ATTENTION AND STUTTERING: DIFFERENTIATING WORD-FORM ENCODING AND WORKING MEMORY DIFFERENCES IN ADULTS WHO STUTTER

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ABSTRACT

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Though motoric, linguistic, and emotional/temperamental factors are commonly thought to contribute to the persistence or development of the stuttering condition in children, how these factors interact to influence the occurrence of moments of stuttering are unclear. Accounting for attentional allocation allows for the differentiation of word-form encoding and working memory processes in adults who stutter. 40 adults who stutter and 42 adults who do not stutter completed three complex working memory span tasks (a working memory capacity measure). These tasks systematically varied in their word-form activation requirements according to psycholinguistic theory. Results indicate that adults who stutter demonstrate working memory capacity differences as a function of word-form encoding influences. These results and the dual-task nature of the tasks allow for the further specification of theories into the origins of moments of stuttering.

This dissertation would not have been possible without my wife, Allison. Without her love, support, and encouragement I would not have completed my PhD program. I would also like to thank Scott. I could ask for nothing more in a mentor or friend.

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INTRODUCTION

This study addresses a long-standing challenge in the field of stuttering: understanding the mechanisms underlying the production of stuttering behaviors. Though motoric, temperamental/emotional, and linguistic factors are thought to contribute to the development and persistence of the stuttering condition (Smith & Kelly, 1997; Smith & Weber, 2017), the ways these factors interact to influence stuttering behaviors are unclear. Theories predict that stuttering behaviors are more likely when "demands are higher" (Adams, 1990; Neilson & Neilson, 1987; Smith & Weber, 2017, p. 16; Starkweather & Gottwald, 1990), yet little empirical evidence exists to support this hypothesis (Manning, 2000b; Yaruss, 2000). What constitutes a *demand* is underspecified (Ratner, 2000; Yaruss, 2000), making it difficult to predict when and under what conditions moments of stuttering will occur. Moreover, motoric, temperamental/emotional, and linguistic factors are often evaluated in isolation (see, Bloodstein & Bernstein Ratner, 2008). Given that people who stutter demonstrate differences in motoric, temperamental/emotional, and linguistic factors (for review, see Conture et al., 2013; Ludlow & Loucks, 2003; Sasisekaran, 2014), further specifying how these factors interact will increase our ability to predict how, when, and why stuttering behaviors occur.

Working memory (Baddeley, 2000, 2003a, 2007; Baddeley & Hitch, 1974; Cowan, 1988, 1999, 2005; Cowan et al., 2014; Logie, 2011, 2016; Logie & Cowan, 2015; Postle, 2006), psycholinguistic (Ferreira & Pashler, 2002; Roelofs, 2008c; Roelofs & Piai, 2011), and motor learning theories (Maxwell et al., 2003; Posner, 1967; Schmidt, 1975) implicate attentional processing as a common process underlying motoric, temperamental/emotional, and linguistic tasks. For example, according to working memory theory, attentional demands are often considered in terms of domain-peripheral (e.g., phonological or visual) and domain-central views, such that when task demands exceed domain-peripheral processing capability, other domain-central attentional resources are used to help complete the task (Logie, 2011, 2016; Logie & Cowan, 2015). Concomitant demands can result in decreased working memory capacity for a specific peripheral domain (Cowan et al., 2014) and decreased system-wide performance (Conty et al., 2010; Kajimura & Nomura, 2016; Markson & Paterson, 2009; Riby et al., 2012; Wang & Apperly, 2017). Capacity is also subject to concomitant processing requirements. For example, when encoding information in multiple vs. single modalities (e.g., visual plus verbal vs. visual alone), capacity decreases (Cowan et al., 2014). Psycholinguistic theory also predicts breakdowns in word-form encoding when attentional allocation is insufficient to increase activation of target word forms over competitors (Roelofs, 2008c; Roelofs & Piai, 2011). Motor-learning theory predicts that attention is necessary for establishing well-learned motor movements necessary for fluent speech (Maxwell et al., 2003; Posner, 1967; Schmidt, 1975), where less well-established motor movements require more attention to execute. Because attentional processing connects these factors, accounting for both system-wide and factor-specific attentional processing can predict system-wide and factor-specific breakdowns.

Further specifying attentional processes will help to connect disparate literatures in stuttering and explain long-standing open questions, such as why differences are observed in people who stutter in some tasks involving language formulation and speech production but not in other tasks involving language formulation and speech production. For example, people who stutter do not differ from people who do not stutter in working memory capacity as measured by simple digit span tasks (Oyoun et al., 2010; Pelczarski & Yaruss, 2016; Sasisekaran & Byrd, 2013; Smith et al., 2012; Spencer & Weber-Fox, 2014), but they do show differences in nonword repetition accuracy (J. D. Anderson et al., 2006; J. D. Anderson & Wagovich, 2010; Byrd et al., 2012, 2017; Hakim & Ratner, 2004; Pelczarski & Yaruss, 2016; Sasisekaran & Weisberg, 2014; Spencer & Weber-Fox, 2014). These findings may suggest that capacity differences emerge only when task difficulty increases: to observe differences in nonword repetition accuracy, the length and complexity of syllable strings must be sufficiently high (Pelczarski & Yaruss, 2016). Another explanation for these findings is that people who stutter recruit domain-central attentional resources sooner (due to domain-peripheral deficits), but the underlying deficit is masked unless the task is sufficiently complex. It is also possible that what may appear to be working memory differences in stuttering (e.g., difficulty maintaining phonological information in an active state) may actually be indicative of word-form encoding deficits given that intention to speak or sub-vocally rehearse is present. Because of these complex interactions between domains, it is difficult to interpret findings in motoric, temperamental, and linguistic domains without first accounting for system-wide engagement of attention. As a first step in accounting for system-wide attentional demands, the proposed study will provide needed information about attentional processing in people who stutter as it relates to working memory and word-form encoding.

1.0 LITERATURE REVIEW

A long history of research evidence has supported the notion that stuttering behaviors have their origin in linguistic, temperamental/emotional, and motoric interactions. For example, Perkins, Rudas, Johnson, & Bell (1976) explored the effects of phonation on stuttering behaviors and rate of speech. They found that speaking (silently and whispering) greatly reduced the frequency of stuttering behaviors and interpreted this as evidence that stuttering behaviors occur due to a discoordination between phonation and respiration. Neilson & Neilson (1987) took a broader approach and included interactions between other systems beyond phonation and respiration, proposing that stuttering behaviors arise due to a mismatch between sensory and motor representations. Neilson & Neilson highlighted how speech production, like other neural functions, has a "limited capacity," such that "fluency will be possible only when the demands on limited resources do not exceed the supply. If the resource limit is reached, fluency will break down" (Neilson & Neilson, 1987, p. 331). In bringing this notion of a limited capacity to the study of stuttering, they described what later became to be called a *Demands and Capacities* Model (DCM). Adams (1990) and Starkweather (1990) used this framework to describe ways in which cognitive, linguistic, emotional/social, and motoric demands might exceed processing capacity of the various system(s) such that breakdowns in the speech production system, or stuttering behaviors, might be more likely to occur.

The DCM remains popular with clinicians as a way to explain stuttering behaviors to clients and families (Manning, 2000a), serving as a component in treatment programs for young children who stutter (de Sonneville-Koedoot, Stolk, Rietveld, & Franken, 2015). Yet, the DCM has been criticized by researchers due to its lack of specificity, circular logic, and lack of predictive ability in the specifying the threshold for a breakdown in fluency (Curlee, 2000; Kelly, 2000; Manning, 2000a, 2000b; Ratner, 2000; Siegel, 2000; Starkweather & Gottwald, 2000; Yaruss, 2000). The notion that any system breaks down when pushed past its operating limitations is self-evident. Moreover, because the DCM cannot specify the levels or conditions in which system(s) break down, the model cannot predict specifically when breakdowns should occur: “If the DCM is to achieve its potential… the problems regarding measurement of either demands and capacities within each of the various domains must be addressed” (Yaruss, 2000, p. 351). Unfortunately, these critiques remain unanswered and are echoed in more current models and theories of stuttering behaviors and the stuttering disorder (see, Smith & Kelly, 1997; Smith & Weber, 2017)—hindering the understanding of why, when, and how stuttering behaviors occur.

Recognizing that group differences are often found between those who stutter and those who do not stutter across many factors on various tasks, Smith and colleagues have more recently proposed the Multifactorial Dynamic Pathways Model (MDP), stating that linguistic, cognitive, motoric, and temperamental systems do not operate in isolation for achieving fluent speech production (Smith & Kelly, 1997; Smith & Weber, 2017). The authors used the analogy of a volcano to describe how stuttering behaviors are related to underlying factors. By observing volcanoes from the surface, one can make seemingly reasonable predictions about the origin and function of volcanoes, such as their size, shape, and locations, and that they erupt with lava at certain times but not at other times. Deeper investigations and ultimate understanding of the underlying mechanisms of volcanoes were elusive until the theory of tectonic plates was developed (Smith & Weber, 2017). According to Smith and colleagues, a similar challenge faces researchers studying stuttering behaviors: full understanding of their origin will require a comprehensive theory that accounts not only for all of the implicated system differences, but also the manner in which they interact. Smith & Weber (2017, p. 2) stated, “disfluencies are the surface behaviors that an integrated, comprehensive theory of the underlying dynamic processes must explain.” Though the MDP posits that various factors interact to influence or cause the persistence of the stuttering disorder in children, the MDP only generally describes how they influence moments of stuttering—that stuttering behaviors are more likely when “linguistic and/or emotional/cognitive demands are higher” (Smith & Weber, 2017, p. 16). This statement is reminiscent of the Demands and Capacities Model, for it does not specify what higher demands are or how they influence moments of stuttering. As such, current stuttering research and clinical work is limited by a lack of understanding of how, when, and why these influencing factors interact to affect the occurrence of stuttering behaviors.

Many researchers have sought to explain differences between people who stutter and those who do not in specific factors or domains, such as motor coordination (Caruso et al., 1988; Usler et al., 2017; Zimmermann, 1980), motor variability (Kleinow & Smith, 2000), non-linguistic auditory processing (Hampton & Weber-Fox, 2008; Kaganovich et al., 2010), phonological encoding skills (J. D. Anderson et al., 2006; J. D. Anderson & Wagovich, 2010; Byrd et al., 2007, 2012, 2017; Coalson et al., 2012; Coalson & Byrd, 2015, 2016, 2017; Hakim & Ratner, 2004; Pelczarski & Yaruss, 2014, 2016; Sasisekaran, 2013; Sasisekaran et al., 2006, 2010, 2013b, 2013a; Sasisekaran & Byrd, 2013; Sasisekaran & Weber-Fox, 2012; Sasisekaran & Weisberg, 2014; Smith et al., 2010; Weber-Fox et al., 2004, 2008), semantic and syntactic processing (Kreidler et al., 2017; Maxfield, 2017; Maxfield et al., 2010, 2013, 2015; Usler & Weber-Fox, 2015; Weber-Fox et al., 2013; Weber-Fox & Hampton, 2008), and temperament (J. D. Anderson et al., 2003; Eggers et al., 2010, 2012; Johnson et al., 2010; Ntourou et al., 2013; Wakaba, 1998). Yet, knowing that there are group differences between people who stutter and people who do not stutter on these factors does not explain how these factors influence moments of stuttering. Further information about how these systems are connected is needed to answer this question.

Research endeavors outside of stuttering have shown that attentional processing underlies all of these domains. As such, attentional processing may affect all of the aspects of language formulation, speech production, and emotional/temperamental functioning that have been implicated in studies and theories about stuttering. For example, attentional processing drives the word-form encoding process (Levelt et al., 1999; Roelofs, 2008c; Roelofs & Piai, 2011). Attentional skills are also a component of a person's temperament profile (Posner & Rothbart, 2007; Rothbart, 2007; Rothbart & Posner, 2015). Attentional processing is fundamental for the creation of working memory representations (Baddeley, 2007; Cowan, 1999). Attentional processing is also necessary for establishing and executing well-learned motor movements necessary for fluent speech (Maxwell et al., 2003; Posner, 1967; Schmidt, 1975). Better understanding attentional processing in domain-peripheral processes may help to specify the interactions of these factors implicated in the origin of stuttering behaviors. For example, current working memory research shows that performance in one or more working-memory domains can be negatively affected by attentional processing demands in one or more different working-memory domains (see Cowan et al., 2014; Doherty & Logie, 2016; Logie & Cowan, 2015; Riby et al., 2012; Wang & Apperly, 2017). Improved understanding of these interactions also has implications for understanding other questions, such as why stuttering behaviors and their experience are variable in time and situation (Constantino et al., 2016; Starkweather, 1987; Tichenor & Yaruss, 2018; Yaruss, 1997), and why a sense of spontaneity, or attending less to the manner of or environment around a moment of speech, often leads to moments of increased fluency or easier stuttering (Constantino & Manning, 2015). Specifying the role of attentional processing in the occurrence of moments of stuttering requires a thorough understanding how cognitive and linguistic domains (e.g., working memory and psycholinguistics) currently instantiate attention according to current theories.

1.1 ATTENTION

1.1.1 Attention and Working Memory

Long-term memory serves as the repository for stable information about one's environment (Huettig et al., 2011). Yet, long-term memory alone is not capable of the processing required for daily-interactions: "in daily life…knowledge often has to be linked to unstable and often rather arbitrary information" (Huettig et al., 2011, p. 142). Working memory is a form of memory that creates a set of on-line representations that "allows for arbitrary objects to be linked to times, places, and each other" (p. 143). Various models of working memory have been proposed (see for review Baddeley, 2012; Constantinidis & Klingberg, 2016), all of which rely on attentional processing.

Among the most widely cited models of working memory is the multi-component model proposed by Baddeley (see Baddeley, 2003a, 2007; Baddeley & Hitch, 1974). Baddeley and Hitch proposed that working memory was too complex to come from a unitary store and that such a model could not account for the transfer of information to long term storage. As a result, they developed the multi-component model of working memory, which posits the existence of distinct, domain-specific sub-systems of working memory: the phonological loop and the visuospatial sketchpad. According to Baddeley and Hitch, each of those subsystems operates independently, and each has its own capacity and processing limitations. Information in these working memory stores can be refreshed or maintained via rehearsal. If rehearsal does not occur, information is subject to decay within a few seconds (Baddeley, 2007). The attentional control system, termed the central executive, allocates attentional resources to each sub-system as needed. By definition, the central executive has no storage capabilities; it only has processing capabilities. Therefore, in Baddeley's original multi-component model all processing, or attentional allocation, was central, and all storage was peripheral (Baddeley & Hitch, 1974). Later experiments and clinical cases did not support such a complete disassociation between central processing and peripheral storage (see discussion in Baddeley, 2012). As a result, Baddeley (2000) 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. This brings the model into more into alignment with other models of working memory, such as the embedded process model (Cowan, 1988, 1999, 2005).

Cowan's (1988, 1999, 2005) embedded processes model of working memory is less compartmentalized in form than Baddeley's. The core of Cowan's model is: "(1) the subsets of elements represented in memory that are in an activated state and (2) a smaller subset of activated memory that is the focus of attention" (Cowan, 2005, p. 37). The focus of attention is very similar to the psycholinguistic notion of enhancement, in that word forms are activated over competitors via attention (see Roelofs, 2008a). In fact, Cowan (1999) stated,

> "Attention was seen as an *enhancement* of the processing of some information to the exclusion of the other, concurrently available information. This effect of attention was viewed as cutting across processing domains and tasks. For example, switching lanes on a highway probably is attention demanding in that it restricts diverse types of information processing, such as those involved in conversation or ongoing thought. In contrast, navigating the vehicle automatically according to well-learned geographical cues probably would not be considered attention demanding…unless it more generally

> restricted the ongoing stream of thought and voluntary actions" (p. 63-64, emphasis added).

The embedded processes model does not treat storage as peripheral and processing as central, as Baddeley's model does. Instead, it recognizes that at least *some* storage is central and *some* processing is peripheral (Cowan et al., 2014; Logie & Cowan, 2015). Still, a debate continues in the working memory literature about how much storage is peripheral, as opposed to central, and how much processing or attentional allocation is central, as opposed to peripheral.

The distinction between central and peripheral components is not merely semantic; the interpretation of fundamental findings in working memory research hinges on this demarcation (Logie & Cowan, 2015). For example, in Baddeley's original multi-component model, both the phonological loop and the visuospatial sketchpad had distinct capacity and processing capabilities. Assuming that the central executive has enough attentional processing resources to drive each slave subsystem, "the number of phonemes stored in working memory should not depend on the number of visuospatial elements stored concurrently, nor vice versa" (Cowan et al., 2014, p. 1807). Current research has challenged this assumption, however. Cowan, Saults, and Blume (2014) conducted a series of dual-task experiments in which participants were asked to encode both verbal and visual information. Tasks required participants to remember different numbers of items with a probe that asked whether one item was different or the same as the group. A chunk is the common term for the unit of working memory storage, which is "a group of elements that are strongly associated with one another and together form a member of a conceptual category" (Cowan et al., 2014, p. 1807; Miller, 1956). Participants were able to encode 3 chunks in each domain alone (total of 6), but only 5 total if asked to do multiple domains concomitantly (Cowan et al., 2014), indicating a decrease in capacity when the central storage mechanism was occupied by concomitant attentional processing. Cowan et al. concluded that working memory storage and processing consists of both peripheral and central components:

> "The central component can be estimated as the portion of memory for stimuli of a certain type (e.g., colors) that have to be shared with stimuli of a second type (e.g., words)…The peripheral component can be estimated as the portion of memory for stimuli of a certain type that does not have to be shared" (Cowan et al., 2014, p. 1806).

This evidence suggests that when a specific working memory sub-system exceeds its capacity (storage) or processing capability (attentional processing) during a given task, central working memory domains are recruited to the possible detriment of concomitant processing (i.e., if another domain-peripheral process is also requiring domain-central attentional resources).

Advanced working memory dual-task measures that contain both processing and storage components are now commonly used in assessments of working memory. Some dual tasks are created in working memory research for particular questions (e.g., determining central and peripheral working memory capacity, see Cowan et al., 2014), while others are used to control where attention is being allocated (e.g., Complex Span Tasks, see Draheim et al., 2018; Foster et al., 2015; Unsworth et al., 2005). Complex span tasks, like simple digit span tasks, require subjects to remember a list of items in serial order (Unsworth & Engle, 2006). Complex span tasks limit the focus of attention, prevent covert-rehearsal, by creating a dual-task with "a storage and a processing component... interweaved between the to-be-remembered stimuli to prevent rehearsal, thus serving as a distractor" (Draheim et al., 2018, p. 2). The dual nature of these tasks requires that participants focus their attention to the processing component of the task (the distractor) and not solely on reinforcing storage of the to-be-remembered stimuli. Other benefits of established assessments, such as the Operation span (OSPAN, Unsworth et al., 2005), are that such tasks have high reliability and external validity, and that they have been used in large samples of typically developed populations, yielding robust measures of central tendency (see

Redick et al., 2012). Many complex span tasks differ in the type of information people are asked to process and recall. The OSPAN requires that subjects remember letters while also processing simple math problems (addition, subtraction, division, multiplication). Subjects alternate between remembering a letter, performing a math problem, and recalling the letter. The Rotation span requires that subjects remember the direction of large or small arrows facing in one of 8 possible directions while also judging whether a displayed letter can be rotated to be a forward-facing letter. Subjects alternate between remembering visual stimuli and making letter-rotation judgments. To complete this letter-rotation-judgment, people must not only attend to and manipulate visuospatial features of a given verbal stimulus, but also perform a verbal memory—retrieval operation, in order to determine whether the rotated verbal stimulus matches a stored representation in long-term verbal memory. The Symmetry Span requires subjects to remember locations of red squares in a 4 x 4 grid while also judging whether a displayed shape is symmetrical along its long axis. Subjects alternate between remembering visual stimuli and processing visual distractors. These dual-tasks limit the recruitment of domain-central attentional resources, thus allowing more accurate investigations into domain-peripheral processing in participants.

Though research into working memory continues to increase, the role that working memory plays in language formulation and language comprehension is on-going. More research has been done connecting working memory to comprehension (e.g., Caplan, 1999; Lewis et al., 2006; McElree et al., 2003; Van Dyke, 2007) than has been done connecting working memory to production (see for review, Martin & Slevc, 2014). This is likely due in part to the fact that working memory's contributions to language comprehension are more intuitive. For example, in order to understand meaning, perceived portions of an utterance or a message must be held active for parsing. The role that working memory plays in language *formulation* is less clear. Theories postulate the existence of buffers that temporarily store selected linguistic representations so they can be correctly arranged and mapped to the motor system for execution (Janssen et al., 2002). Working memory research evidence exists suggesting that working memory span does correlate with discourse quality (Daneman, 1991; Youse & Coelho, 2005), and may predict the accuracy of syntactic encoding (Hartsuiker & Barkhuysen, 2006; Kemper et al., 2009; Scontras et al., 2015). Yet, the role that working memory plays in later stages of word-form encoding (e.g., phonological encoding) in to-be-uttered speech remains largely unspecified in current working memory theories (Martin & Slevc, 2014), though stuttering research has also explored phonological encoding through working memory perspectives (see section 2.2.4). Other fields, such as psycholinguistics, may provide an answer by focusing on one aspect, attentional allocation.

1.1.2 Attention and Word-Form Encoding

Word-form encoding describes the process of preparing a conceptualized message for ultimate production. It involves a series of steps in language formulation that exists after lemma retrieval and before overt articulation (Levelt et al., 1999). Word-form encoding consists of morphemic retrieval, phonological encoding, prosodification, syllabification, and phonetic encoding (Levelt et al., 1999). The process culminates in an articulatory score (Levelt, 2001), or a gestural score (Browman & Goldstein, 1989, 1992), which comprises instructions for the speech production mechanism. The word-form encoding process is commonly thought to be incremental, beginning with conceptualization and ending with linguistic-motor mapping for ultimate production (Levelt et al., 1999), though more current research suggests that many of the processes can begin while other steps are on-going (Munding et al., 2016). Word-form encoding also occurs in an incremental fashion while an utterance is planned for ultimate production (Dell, 1986; Wheeldon & Levelt, 1995). This incrementality allows for portions of a word form (e.g. syllables or phonemes) to be encoded when enough information is present (e.g., initial segments and metrical structure), while other portions are still being retrieved and assembled (Levelt, 1989; Levelt et al., 1999). Importantly, this incremental nature of word-form encoding is not constant—when portions of later word-forms are not well-encoded, the word-form encoding process pauses (Levelt et al., 1999). Models of word-form encoding instantiate word-form encoding via attentional processing, in which activation of word-forms occurs via the summation of the weights of interconnected nodes at different linguistic stages (Dell, 1986; Levelt et al., 1999; Roelofs, 1997, 2008b). This process of connecting similar information is commonly called spreading activation (or activation-spreading, to reflect the order of events in time), connectionism, or parallel distributed processing. Spreading activation, in this sense, means that when a word form or portions of a word form becomes active, the word form activates related representations by measure of similarity. The presence and strength of these connections depend on the rules of the language itself (Wheeldon & Levelt, 1995). In English, each phoneme is connected to other phonemes by virtue of similar features such as place, manner, and voicing (Dell, 1986). For example, the English phonemes /p/ and /b/ share the common features of place and manner but not voice. If the phoneme /p/ were active, /b/ would be partially active by virtue of spreading activation (Dell, 1986). Such activation scales according to connection strength. So, the phoneme /p/ activates /b/ more than /s/, because it shares more features. In a similar manner, activating the semantic representation of *cow* also activates the semantic representation of *horse* more than it activates the semantic representation of *skyscraper,* because cows and horses are both farm animals, mammals, have four legs, etc. These bidirectional connections that enable spreading activation are both formed and activated via enhancement (attentional processing) (Roelofs & Ferreira, 2019; Roelofs & Piai, 2011).

Multiple lines of research have elaborated the mechanisms by which word-form encoding occurs in people who do not stutter. In a fundamental study, Wheeldon & Lahiri (2002) studied the relationship between the way in which word forms are encoded and how quickly they are produced. They examined whether compound words were treated as one-or-two word forms when they were encoded for production. They found that compound Dutch words (e.g., dagblad) showed shorter naming latencies than two-word phrases that were phonologically similar (e.g., dun boek), showing that the manner in which word-forms are stored dictates how quickly they are produced (Wheeldon & Lahiri, 2002). Other researchers have found evidence supporting that the manner in which word-forms are stored dictates how quickly they are produced in English (Jacobs & Dell, 2014). Together, research shows that the speed of word-form encoding, and therefore translation to the motor system for execution, depends on how semantic, morphological, and phonological information is encoded.

“Enhancement” is the process by which word forms are activated via attentional processing (Roelofs, 2008b, p. 394). If a speaker sees a ball and wants to name it, the person must select the corresponding network of nodes and enhance the activations of the intended-to-speak word forms above other competing word forms (Roelofs, 2008b). Competing word forms are those have also become activated (though not to the same level) through spreading activation. The level at which a word-form representation is considered active is individualized to the situation; there is no set level it must meet in order to be mapped for execution by the motor system. Rather, activation of an intended-to-speak word form must be greater than competitors at the time of selection or errors will be more likely to arise (Levelt et al., 1999; Roelofs, 2008b, 2011, 2014; Roelofs & Piai, 2011). Thus, the level of activation needed for a word form to be active and mapped for execution is a function of the existence of competing word forms, how active they are at the time of selection, and how much speed or accuracy is needed for the task at hand (Roelofs, 2011; Roelofs & Piai, 2011). Word-form encoding is prone to breakdowns when inadequate attentional processing resources are allocated to intended-to-speak word forms (Roelofs & Ferreira, 2019; Roelofs & Piai, 2011). Less enhancement results in less-activated intended-to-speak word forms. This, in turn, leads to greater word-form competition. More ambiguity leads to less clear mappings for the motor system to execute and a correspondingly greater likelihood of disruption in the overall language formulation/speech production process.

Multiple lines of research supports the notion that word-form encoding requires attentional processing (Jongman et al., 2015; Roelofs, 2008c, 2008a; Roelofs & Piai, 2011). While Dell (1986) argued for the continuous spread of activation from lemmas to word forms, other researchers have argued that word forms are activated *only* when there is an intention to speak, even though concepts continually activate lemmas (Levelt et al., 1999). Levelt et al. (1999) refer to this idea as the “great rift” (p. 2), in that only intended-to-speak word forms, or word forms that are sufficiently enhanced, cross this rift for production. Recognizing this debate, Roelofs (2008c) sought to quantify how and when activation spreads from lemma to word forms via attentional processing through a series of experiments using eye gaze measurements to determine the manner in which activation spreads across different linguistic levels during formulation. Participants were asked to name a target picture in the presence of phonologically related, semantically related, or un-related distractors (experiment 1), to name both the picture and the distractor (experiment 2), and to read word-picture stimuli/distractor pairs (experiment 3). Results showed that participants were able to name the target picture faster when it was in the presence of a phonologically or semantically related distractor (experiment 1). Results from experiment 3 showed a facilitative effect of word distractors but not of picture distractors, suggesting that “the amount of activation that cascades from concepts to word forms is limited and attention dependent” (Roelofs, 2008c, p. 363). Roelofs’ findings suggest that activation does not spread continuously from lemmas to word forms (cf. Dell, 1986); rather, it appears that activated lemmas do activate corresponding word forms when intention to speak is not present but only in a “weakly cascading” fashion (Roelofs, 2008c, p. 366). This finding has implications for how linguistic tasks can be used to make claims about the word-form encoding process. For example, a nonword repetition task activates word forms fully, but passive listening or making a rhyme judgment activates those same word forms to a lesser degree. (In section 2.5.2, prior stuttering research is reviewed in light of this finding.) Regardless, attentional allocation is critical for both the speed and efficiency of word-form encoding. Directing attention away from the word-form encoding process increases the likelihood of errors by increasing the ambiguity of which target word-form is the appropriate target. The likelihood of errors are further increased by increasing the time required for mapping the linguistic representations that the motor system will use for execution.

Previous research evidence in psycholinguistics suggests that some stages of word-form production (e.g., lemma activation through phonological word-form selection) are subject to a central bottleneck effect (Ferreira & Pashler, 2002). Ferreira & Pashler (2002) studied whether stages of word-form production were subject to the effects of concurrent processing demands. They conducted a series of experiments in which lemma selection/phonological word-form selection or lemma selection/phoneme selection were manipulated with a concurrent three-tone auditory discrimination task. The logic behind this design was that if a particular portion of the word-form encoding process is subject to the effects of concomitant processing, then one or both stages should be slower than if word-form encoding was done while not under concomitant processing conditions. The authors found that typically developed adults demonstrated a central bottleneck (i.e., a significant effect of the concomitant attentional processing) on the earlier lemma activation/phonological word-form selection but not on the later phoneme selection task. The authors interpreted these results as evidence that earlier stages of word-form encoding but not later stages are subject to the effects of concomitant processing. This finding has further implications for stuttering research. As discussed in section 2.2.3, there is good evidence suggesting that people who stutter exhibit subtle differences in word-form encoding processes and that the later stages of the word-form encoding process in people who stutter are subject to attentional bottlenecks in performance. As such, people who stutter may be subject to the negative effects of concomitant attentional processing during word-form encoding to a greater degree than people who do not stutter.

1.1.3 Attention and Motor Learning

There is a long history of research implicating attentional processing as a necessary factor for learning motor movements. Specifically, a person transitions from using declarative memory when learning a novel motor skill to performing the skill with greater automaticity (Posner, 1967; Schmidt, 1975). As the motor skill becomes more automatic, less attentional processing is needed to maintain performance of the motor skill (Maxwell et al., 2003). Current explanations of motor control assume that motor learning requires internal models and proprioceptive feedback (Guenther et al., 2006; Maxwell et al., 2003; Tourville & Guenther, 2011; Wolpert et al., 1995). There is a bias toward higher cognitive control and proprioceptive feedback for novel motor tasks (Perkell et al., 2000). As internal models are formed and motor actions become automatic, attentional control decreases (Van der Merwe, 2009). Conversely, weaker or less robust internal models may require more attention for the execution of motor tasks. Given that there is theoretical evidence suggesting that people who stutter may have impaired internal models of motor actions (Max, Guenther, et al., 2004), it is probable that speech-motor actions are more attention-demanding in people who stutter. Though an investigation of motor execution is not the primary purpose of this dissertation, section 2.5.3 reviews this aspect of speech production in stuttering research on motor movements to support the validity of the theoretical connection to motor learning and motor execution.

1.1.4 Summary: Attention as a Mediating Factor in Language Formulation and Speech Production

Though past and current theories of the origin of stuttering behaviors implicate the interaction of various processes (Adams, 1990; Neilson & Neilson, 1987; Smith & Weber, 2017; Starkweather & Gottwald, 1990), the mechanism for these system-wide interactions is as yet unspecified. Current theories in motor learning (Maxwell et al., 2003; Posner, 1967; Schmidt, 1975), working memory (Baddeley, 2000, 2003a, 2007; Baddeley & Hitch, 1974; Cowan, 1988, 1999, 2005; Cowan et al., 2014; Logie, 2011, 2016; Logie & Cowan, 2015), and word-form encoding (Roelofs, 2008c; Roelofs & Piai, 2011), all implicate attentional processing as one mediating factor. Moreover, working memory research has shown that attention is not solely a domain-peripheral process that operates in isolation from other domains. Rather, the efficiency of a process that requires attention is a function of how much attentional processing it requires and how much attentional processing concurrent tasks require (Cowan et al., 2014; Logie, 2011, 2016; Logie & Cowan, 2015). As yet, stuttering research has not accounted for domain-central and domain-peripheral attentional processes. Exploring this fluid nature of attention has the potential to answer critical and open questions in stuttering literature—specifically, the mechanisms by which linguistic, cognitive, and temperamental processes increase the likelihood of a breakdown in fluent speech, and whether there are domain-specific differences (e.g., deficiencies in language formulation) between people who stutter and people who do not stutter, as some research suggests (Burger & Wijnen, 1999; Byrd et al., 2007; Coalson & Byrd, 2015; Sasisekaran et al., 2006, 2013a; Sasisekaran & Weber-Fox, 2012; Wijnen & Boers, 1994). By examining stuttering research through the lens of attention, reinterpretations of prior studies can be offered, and novel questions can be asked.

1.2 ATTENTION IN STUTTERING RESEARCH

Multiple lines of research directly or indirectly implicate attention as a factor in the origin of stuttering behaviors, though differences in how the concept of attention is applied exist across the literature. For example, some stuttering research directly highlights the importance of attention by suggesting that there are higher rates of concomitant attentional disorders in children who stutter, or that attentional control is different in children who stutter compared to those who do not (see section 2.5.1). Other research addresses attentional allocation by analyzing performance on linguistic tasks (see section 2.5.2) or motor tasks (see section 2.5.3) to make claims about potential differences in motor and linguistic skills in individuals who stutter. Thus, in stuttering, attention has been investigated as a construct in of itself and through various domain-peripheral lenses.

1.2.1 Neurophysiology of Attention

Some researchers have conceptualized attention as a neurologically based skill to describe efficiency at signal detection, orienting to salient stimuli, or vigilance toward a particular task or state (Posner, 1980; Posner et al., 1980; Posner & Petersen, 1990a). These processes are represented by large, functionally-distinct brain networks formed from different brain regions (Bressler & Tognoli, 2006; Corbetta et al., 2008; Petersen & Posner, 2012; Posner & Petersen, 1990b; Sonuga-Barke & Castellanos, 2007). Most notably, Posner and Peterson (1990a) proposed that attention can be instantiated neurologically into three separate 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). Eggers, De Nil, and Van den Bergh (2012) explored these systems in children who stutter by investigating performance on the attentional network test (ANT; see Fan, McCandliss, Sommer, Raz, & Posner, 2002) with Dutch children between the ages of 4 and 9. Results indicated that the orienting networks of children who stutter were less efficient than those of their peers. Such findings are supported by Chang et al. (2018), who found that connectivity in attentional network areas in children who stutter were significantly different from those in children who do not stutter. Thus, it appears that children who stutter have differences in the underlying neurophysiological bases of attention, though more research is needed in this area. Specifically, it is not clear where the line is between attention as a neurophysiological skill is (e.g., orienting, alerting, and executive control) and attention as a necessary component or bi-product of task-specific processing (e.g., word-form encoding) (for discussion, see Jongman et al., 2015).

1.2.2 Attentional Differences in People who Stutter

Various researchers have investigated ways in which attention may differ between people who stutter and people who do not stutter. Alm & Risberg (2007) examined a range of variables that, in separate studies, have been shown to differ between people who stutter and those who do not. Among many other measures, the authors collected self-report data on childhood attentional deficits and compared the results to temperament as measured by an acoustic startle eyeblink response. The authors found that 41% of the group of adults who stutter self-reported childhood attention scores above the maximum of that of controls, suggesting that children who stutter may have similarities to or aspects of ADHD (see Embrechts et al., 2000; Oyler, 1994). Other research has explored the links between attention and childhood stuttering through parent-reported temperament measures. Temperament is commonly defined as biologically based differences in emotional, motoric, and attentional reactivity (Rothbart, 2007). People who stutter have been shown to have different temperament profiles compared to those who do not stutter (for review, see Conture, Kelly, & Walden, 2013). Specifically, children who stutter are more reactive to and less adaptive to environmental stimuli (Wakaba, 1998) and have greater negative affect (Johnson et al., 2010; Ntourou et al., 2013), decreased attention skills (J. D. Anderson et al., 2003; Eggers et al., 2010; Eggers & Jansson-Verkasalo, 2017), and weaker inhibitory control (Eggers et al., 2010).

Attentional regulation is often considered to be one aspect of temperament. Anderson, Pellowski, Conture, and Kelly (2003) explored the temperament profiles of children who stutter and found that the parents of children who stutter reported that their children were more successful in maintaining attention as measured by the Behavioral Style Questionnaire (BSQ). The authors interpreted the finding of "low distractibility" in terms of temperament, saying, that a child who stutters, "may be less likely to allow external stimulation to divert their attention from disruptions or mistakes in their own speech" (J. D. Anderson et al., 2003, p. 1229). This finding conflicts with previous research suggesting that children who stutter are less successful at maintaining attention than are children who do not stutter (Embrechts et al., 2000). Alm & Risberg (2007) interpreted these seemingly conflicting results as evidence that there are two groups of children with attention deficits: those with hyperactivity and those without hyperactivity. Schwenk, Conture, and Walden (2007) compared children who stutter to those who do not as they attended to environmental stimuli and found that children who stutter shifted attention more frequently than children who do not stutter. They also found that children who stutter were significantly more likely to attend to a moving camera. The authors interpreted these findings as indicating that children are more reactive to environmental stimuli. In a follow-up study to Anderson et al. (2003), Karrass et al. (2006) used the BSQ to examine a slightly different (but largely overlapping, 36%) cohort of older children who stutter and found that children who stutter were less flexible in controlling their attention and less able to shift their attention when needed. More recent research has found similar results in different cohorts of children who stutter (Eggers et al., 2010). Together, these results suggest that children who stutter do have parent-reported attentional differences compared to those who do not stutter as measured by the BSQ.

Other research has explored these parent-reported results by comparing attentional differences to more objective measures. For example, Anderson & Wagovich (2010) correlated results from picture naming and nonword repetition tasks to the results of the BSQ and found that BSQ scores did not predict differences in nonword repetition accuracy. As yet, there is no evidence that attentional skills (particularly, those measured through parent-report such as the BSQ) can predict speech and language performance in children who stutter. Though, parents and teachers have been shown to observe more disfluency in children with poorer attentional regulation (Felsenfeld et al., 2010).

1.2.3 Word-Form Encoding in Stuttering

The idea that stuttering behaviors arise as a result of errors of linguistic formulation has a strong theoretical history in the field. In the Covert Repair Hypothesis (CRH), 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). These repairs directly correspond to proposed monitoring pathways in the word-form encoding system (see Levelt, 1983; Levelt et al., 1999). The ExPlan hypothesis similarly implicates word-form encoding as being at least partially responsible for stuttering behaviors (Howell & Au-Yeung, 2002). The ExPlan hypothesis makes specific predictions as to the nature of repairs of ill-formed linguistic plans via a relationship between planning and motor output speed differences. "The linguistic formulator processes generate a plan (PLAN) and the motor processes execute it (EX)…PLAN and EX take place in parallel and … PLAN is independent of EX" (Howell & Au-Yeung, 2002, p. 6). According to the theory, stuttering behaviors occur when this synchrony is disrupted. For example, *stalling* behaviors occur when an ill-formed linguistic plan is sent to the motor system for execution, while *advancing* behaviors occur the motor system tries to execute too early before it receives a well-formed linguistic plan (Howell & Au-Yeung, 2002). Thus, in both the CRH and ExPlan hypotheses stuttering behaviors are the direct result of either attempts at word-form repairs (CRH) or a linguistic and motor asynchrony (ExPlan). Though research has largely failed to support the central idea of these theories (namely, that stuttering behaviors are the direct results of either repair of or errors of word-form encoding or linguistic-motor mapping; for review, see Brocklehurst, 2008; Melnick, Conture, & Ohde, 2005), there is evidence that people who stutter do have word-form encoding differences compared to those who do not. This evidence comes different lines of research each addressing the underlying question from slightly different theoretical foundations.

1.2.3.1 Evidence from Priming Studies

As typically developing children mature, they transition from encoding words holistically to encoding words incrementally (Walley, 1988, 1993). Encoding holistically means that a speaker formulates an entire word or syllable rather than planning and combining individual sounds (Byrd et al., 2007; Charles-Luce & Luce, 1990). Priming paradigms have been used to investigate this process by virtue of how word forms are represented neurologically. When a particular phoneme or word form is activated with the intention to speak (Levelt et al., 1999; Roelofs, 2008c), spreading activation occurs as a function of the strength of connected word forms (Dell, 1986). Priming is a behavioral technique that takes advantage of these connections. Priming involves a presentation of a stimulus before a target word, where this initial stimulus shares feature(s) with the subsequent word. The feature that is activated for the initial word will remain partially activated while the subsequent word is being planned. For phonological priming, the activation level of a phoneme that has been primed should be greater than that of other non-primed phonemes (Sasisekaran et al., 2006).

Priming paradigms have been used to explore the word-form encoding abilities of children who stutter. The underlying theory is that when a person is presented with a phonologically related prime word, phonological activation spreads and naming latencies decrease (Melnick et al., 2003). Thus, if there were differences in activating a phonological representation in people who stutter, as the CRH predicts (see Postma & Kolk, 1993), a person who stutters would benefit less from priming than a person who does not stutter (Melnick et al., 2003). Wijnen and Boers (1994) and Burger and Wijnen (1999) conducted priming studies in which adults who stutter and adults who do not stutter were asked to utter one word from a set of stimuli as fast as possible in both homogeneous and heterogeneous conditions. Homogeneous conditions were those that began with the same consonant, whereas heterogeneous stimuli were not phonologically related. In both conditions, subjects were given both consonant and consonant-vowel stimuli, and response times were recorded. Average response times of the adults who stutter were longer than those of people who do not stutter in all paradigms in both studies, though primes of CV syllables reduced response times in people who stutter. Though Wijnen and Boers (1994) found a significant priming effect for consonant-only priming conditions, Burger and Wijnen (1999) found no priming effect, suggesting that the group of adults who stutter did have differences in word-form encoding. Melnick et al. (2003, 2005) explored the phonological encoding skills of children through speech reaction time measures in three priming conditions: no prime, homogeneous or phonologically related prime, and heterogeneous or phonologically unrelated prime. No group differences were found in priming effect, suggesting that children who stutter do not have differences in word-form encoding (Melnick et al., 2003). In contrast, Byrd et al. (2007) examined differences in priming between children who stutter and those who do not in three conditions: neutral, holistic, and incremental. The incremental primes contained only the initial onset and part of the nucleus while the holistic prime contained a portion of the onset and all of the nucleus and coda. Children who stutter differed from children who do not stutter in both priming conditions, with children who stutter being faster in the holistic condition than children who do not stutter. The authors interpreted this as evidence that children who do not stutter, aged 3 to 5 years old, shift from holistic to incremental encoding faster than children who stutter; thus, children who stutter are presumed to be late in making this transition (Byrd et al., 2007). Brocklehurst (2008) interpreted the results of Byrd et al. (2007) by highlighting that some of the adults in the older priming studies may still have been encoding words holistically, rather than incrementally. Taken together, these studies provide mixed results as to whether children or adults who stutter have significant differences in responses to priming or an innate difference in their word-form encoding abilities.

1.2.3.2 Evidence from Monitoring Studies

Part of normal language formulation is the monitoring of errors, both overtly and covertly, when they occur during the word-form encoding process (Levelt et al., 1999; Wheeldon & Levelt, 1995). Wheeldon & Levelt (1995) studied how portions of a phonological representation become active by asking subjects to monitor their own internal speech as they formulated it. Native Dutch-speaking participants were asked to remember English/Dutch word pairs, practice those pairs, and produce the Dutch words aloud. In the first experiment, participants heard an auditory description of the sound they had to monitor before hearing an English word. They were then asked to press a button if the Dutch word had the target English sound. Word onsets were responded to more quickly than second syllable onsets, suggesting that these portions of the phonological representation were active before later phonemes. The authors interpreted this as evidence that phonological encoding occurs in an incremental, left-to-right fashion (Wheeldon & Levelt, 1995). In a later experiment of the same study, the authors examined the time course of the activation of the phonological representation by asking participants to monitor consonants in CVC-CVC words. The latency of monitoring of later-occurring consonants greatly increased in across all subjects, suggesting that the encoding of earlier-occurring phonemes/syllables finishes before subsequent phonemes/syllables are encoded (Wheeldon & Levelt, 1995).

The time course of phonological encoding in both children and adults who stutter has been explored through phoneme monitoring. Sasisekaran & Weber-Fox (2012) asked children who stutter and age- and sex-matched peers, aged 7 to 13 years, to complete picture naming, phoneme monitoring, rhyme monitoring, and tone-sequencing tasks. The phoneme monitoring task required silent naming, while the rhyme monitoring task did not. All age cohorts were faster at rhyme monitoring than phoneme monitoring, but significant between-group differences in rhyme monitoring were only seen in younger cohorts (Sasisekaran & Weber-Fox, 2012). The authors interpreted this difference between rhyme and phoneme monitoring performance as evidence that phoneme monitoring is "cognitively more challenging" (Sasisekaran & Weber-Fox, 2012, p. 271). In a follow-up study, Sasisekaran & Byrd (2013) asked children to complete a phoneme monitoring and rhyme judgement task on monosyllabic words, both with silent naming. Results indicated no significant differences in the speed of phoneme monitoring. Yet, upon further analysis, there were age-related differences across the sample, with younger children who stutter showing slower response times than children who do not stutter and older children who stutter showing similar response times to children who do not stutter. The authors interpreted this as evidence that, at least in younger children who stutter, the phoneme monitoring process may be "in overdrive, potentially making up for primary phonological processing difficulty or latency" (Sasisekaran & Byrd, 2013, p. 231).

Sasisekaran, Brady, and Stein (2013a) then studied older children, aged 10-14 years, using bi-syllabic words. They showed that adolescents who stutter were significantly slower than adolescents who do not stutter in phoneme monitoring, though there were no between-group differences in the auditory task. The authors interpreted this pattern as evidence that differences between children who stutter and those who do not on phoneme monitoring are affected by linguistic complexity. Similar findings exist with adults who stutter (Coalson & Byrd, 2015, 2018; Sasisekaran et al., 2006). Adults who stutter have been found to be significantly slower at phoneme monitoring during silent naming than adults who do not stutter (Sasisekaran et al., 2006), and this effect is compounded when metrical aspects of encoding are included in the experimental design (Coalson & Byrd, 2015). In a modified version of the phoneme monitoring task, Coalson and Byrd (2018) examined whether phonological working memory rehearsal was impaired in people who stutter. They added a delay to the phoneme monitoring task, during which the participants were forced to maintain trochaic and iambic nonwords in working memory for a number of seconds. Results indicated that adults who stutter monitored iambic nonwords less accurately than adults who do not stutter. The authors interpreted this finding as evidence that people who stutter have difficulty monitoring the more phonologically demanding condition—iambic nonwords over trochaic nonwords (Coalson & Byrd, 2018). Similarly, Maxfield et al (2016) replicated the study conducted by Ferreira and Pashler (2002) (reviewed above; see section 2.1.2) with people who stutter. Participants were required to name pictures with semantic, phonological, and unrelated distractors while also monitoring a series of pure tones. Whereas Ferreira and Pashler (2002) found that earlier stages of language formulation (e.g., semantics) were susceptible to decreased efficiency while under dual-task conditions in adults who do not stutter, Maxfield et al. (2016) found that the later stages of language formulation (phonological encoding) were susceptible to dual-task effects in adults who stutter. The authors interpret this finding to mean that the language formulation systems in adults who stutter are susceptible to breakdown or less-efficient performance in attention-demanding conditions such as dual-tasks. Overall, results from monitoring studies provide the most compelling evidence that people who stutter have an inherent word-form encoding difference compared to people who not stutter.

1.2.4 Working Memory and Stuttering

Some researchers have approached questions related to working memory from an interference perspective to explore disassociations in concurrent cognitive processing in people who stutter. These investigations have most often involved dual-task paradigms. Other investigations into working memory in people who stutter have been interpreted in terms of Baddeley's (2007) Phonological Loop, in which phonologically related material is stored temporarily in an active state from long term memory. It has been hypothesized that phonological information held active in phonological working memory is then assembled for ultimate production (Gathercole & Baddeley, 1993). In fact, when discussing phonological encoding, Bajaj (2007) stated that "such encoding relies essentially on phonological loop operations" (p. 220). Various tasks have been used to explore phonological working memory in people who stutter, but the most common strategy has been nonword repetition tasks (for review, see Bowers et al., 2018).

1.2.4.1 Dissociations among Concomitant Processing

Dual-task paradigms are a method of investigating performance in two or more domains when system-wide attentional demands increase (Bajaj, 2007). There is a rich history of stuttering research using dual-task conditions (for review; see Bajaj, 2007; Bosshardt, 2006). Some of the prior research has examined the effects of dual-task demands on speech behaviors, and some prior research has examined behaviors outside of speech production. Dual-task experiments involving speech production usually show an increase in stuttering behavior frequency and decreases in performance on the concurrent task. For example, Bosshardt (1999) conducted a dual-task experiment in which people who stutter and people who did not stutter performed a word repetition task and mental calculations both independently and concurrently.

Stuttering frequency increased in the dual-task condition. In a follow-up study, Bosshardt et al. (2002) conducted a dual-task experiment in which people who stutter and people who do not stutter were asked to read phonologically related or un-related words while completing a repetition task. The group of people who stutter showed increased stuttering behaviors while reading words that were phonologically related to the words they were repeating compared to conditions where they were reading words that were phonologically un-related. The authors interpreted this finding as evidence that people who stutter are more susceptible to "cognitive processing interference" (Bosshardt et al., 2002, p. 110).

Similar decreases in performance have been found in experiments outside of speech production. For example, finger-tapping rates of people who stutter have been shown to decrease under dual-task conditions (Brutten & Trotter, 1985, 1986; Greiner et al., 1986; Smits-Bandstra et al., 2006; Sussman, 1982; Webster, 1990). Jones, Fox, & Jacewicz (2012) conducted a novel dual-task study in which people who stutter and people who do not were asked to make rhyme judgments while concurrently performing a memory recall task in three conditions that varied in phonological complexity (no letters, 3 letters, 5 letters). The authors found no significant difference in rhyme judgment accuracy in either group, but reaction times were slower in the group of people who stutter in more phonologically demanding conditions compared to conditions that were less phonologically demanding. The authors interpreted these results as evidence that speech-language processing in people who stutter is more vulnerable to breakdowns in dual-task attention-demanding tasks than in people who do not stutter.

This effect of increased stuttering behaviors while under dual-task conditions is not consistently found in the literature. Eichorn et al (2016) hypothesized that people who stutter should show increased fluency (decreased frequency of stuttering behaviors) when monitoring is limited by dual-task processing. The authors conducted a study in which speech fluency was measured while participants completed various working memory-related tasks. The working memory tasks varied in the type of information (i.e., visual vs linguistic), how many units subjects were required to process (load), and the speed of the processing demand (i.e., short vs long stimulus presentations). Both adults who stutter and those who do not stutter showed similar levels of decreased performance during dual-task conditions. Adults who stutter did demonstrate significantly fewer stuttering behaviors while under all dual-task conditions, though the authors indicated that this effect might have occurred due to decreases in speech rate.

Overall, these studies show that dual-task conditions, speaking or otherwise, tend to increase stuttering behaviors, decrease fluency, and decrease concomitant performance in adults who stutter. Evidence that these findings exist in non-speech production tasks also suggests that these differences are not entirely due to presumed speech-motor difficulties in people who stutter. Still, the mechanisms by which increased working memory demands might increase stuttering behaviors or decrease performance in concurrent tasks is not specified in the stuttering literature.

1.2.4.2 Working Memory Capacity and Quality

Nonword repetition tasks are commonly used in stuttering research to investigate working memory processes (for review, see Bajaj, 2007). Specifically, nonword repetition tasks have been said to directly access the storage component of Baddeley's phonological loop (Gathercole et al., 1994). Nonword repetition tasks have also been used to study the way children learn novel words (Gathercole et al., 1994), because children are exposed to and then must replicate thousands of novel phonological word forms during childhood (Gathercole et al., 1994). Nonword repetition or nonword reading tasks are also used in research because semantics and lexicality are not significantly accessed during the task (Indefrey & Levelt, 2000). That said, nonwords can still engage the word-form encoding system in an attention-demanding way (Roelofs, 2008c).

Indefrey and Levelt (2000) conducted a meta-analysis of 58 word-production studies to determine the time-course and steps of word-form encoding across both behavioral and neuroimaging experiments. The authors found that when people read or repeat nonwords, they access subsequent levels of word-form encoding other than lexicality. These include: phonological code retrieval, phonological encoding, phonetic encoding, and syllabification (Indefrey & Levelt, 2000). Follow-up studies found that regions in the superior temporal gyrus (STG) and the supramarginal gyrus (SMG) are crucial for the earlier steps of phonological code retrieval, while syllabification occurs in left inferior frontal gyrus (IFG) (Indefrey & Levelt, 2004). The whole process of word-form encoding takes approximately 600ms, with phonological code retrieval beginning after 200ms post-stimulus onset (Indefrey & Levelt, 2004). Thus, nonword repetition may be indicative of word-learning *or* linguistic encoding processes, depending on the context in which the task is used.

Ambiguity in the ways in which working memory tasks have been used in stuttering research has led to ambiguity in interpretations of the results of studies of working memory and language formulation skills. For example, research has shown that people who stutter do not differ from people who do not stutter in simple digit span tasks (Oyoun et al., 2010; Pelczarski & Yaruss, 2016; Sasisekaran & Byrd, 2013; Smith et al., 2012; Spencer & Weber-Fox, 2014). This suggests that no simple working memory capacity difference exists between people who stutter and those who do not as measured by simple digit span. Yet, some studies have shown significant differences in nonword repetition accuracy between children who stutter and those who do not (J. D. Anderson et al., 2006; J. D. Anderson & Wagovich, 2010; Hakim & Ratner, 2004; Pelczarski & Yaruss, 2016; Spencer & Weber-Fox, 2014), and between adults who stutter and those who do not (Byrd et al., 2012; Coalson & Byrd, 2017; Sasisekaran & Weisberg, 2014), suggesting that there are subtle working memory capacity differences under some conditions, such as when more complex linguistic information is present. Other studies have not shown group differences on nonword repetition accuracy (Sasisekaran, 2013; Smith et al., 2010, 2012). This working memory research evidence has been interpreted as indicating that nonword repetition tasks measure the quality of information held in Baddeley's phonological loop, while digit span tasks measure capacity (Dollaghan & Campbell, 1998; Pelczarski & Yaruss, 2016). The ambiguity in the stuttering research may be due to the difficulty in controlling for and matching subjects across many domains of language, speech, and cognitive abilities (Sasisekaran, 2014), and in controlling for the linguistic complexity of the stimuli themselves. The ambiguity of the findings may also be due to ceiling effects: to see between-group differences in nonword repetition accuracy, the length and complexity of syllable strings must be sufficiently great (Byrd et al., 2012; Pelczarski & Yaruss, 2016). As working memory storage and processing has been shown to vary depending on both domain-general and domain-specific demands (Cowan et al., 2014), it is also possible that some of the ambiguity in the stuttering research might be due to unaccounted-for variance associated with other working-memory demands.

Complex span tasks (as opposed to simple digit span tasks) are now commonly used in psychology to assess working memory capacity (Unsworth & Engle, 2006, 2007); they are also beginning to be used in stuttering research (see Treleavan et al., 2018). A complex span tasks requires a participant to remember selected stimuli while performing a distractor task (Unsworth

& Engle, 2006), thus limiting the contribution of domain-general attentional resources or the *focus* of attention, to use the terminology of Cowan (Cowan et al., 2014). Complex span tasks also require greater attentional control than simple span tasks (Unsworth & Engle, 2006). Thus, a simple digit span task cannot itself answer questions about the capacity of the domain in question, because when storage or processing capacity in a specific domain is reached, central and potentially shared resources are used to complete the task (Cowan et al., 2014). Thus, though people who stutter show no working memory capacity differences as measured by simple digit span tasks, it is possible that differences in working memory capacity can be detected when measured by complex span tasks. Ultimately, it is difficult to interpret nonword repetition accuracy findings in regard to verbal working memory without first accounting for other possible concomitant attentional processes that may pull attentional resources away from word-form encoding and, ultimately, speech production. It is also difficult to interpret prior nonword repetition accuracy findings, because word-form activation differences may influence nonword repetition performance. In such a case, previously observed nonword repetition differences may be more indicative of word-form encoding differences than of working memory differences.

Other phonological working memory-related tasks have been used in stuttering research to investigate the word-form encoding abilities of people who stutter. Rhyme judgment tasks are tasks in which subjects are asked to make judgments about rhyming agreement or errors. This requires that they hold phonological information active in working memory, as suggested by Baddeley's (2007) phonological loop. In the field of communication science and disorders, such tasks are commonly thought to activate processes underlying the development of phonological encoding, such as segmentation skills in children (Sasisekaran & Byrd, 2013). Some research has shown significant rhyme judgment differences between people who stutter and people who do not stutter (Bosshardt, 2002; Sasisekaran et al., 2006; Weber-Fox et al., 2008), while other research has found no differences (Bosshardt & Fransen, 1996; Weber-Fox et al., 2004). Sasisekaran & Byrd (2013) interpreted the ambiguity of the rhyme judgment research as potentially being explained by including both children who would eventually recover from stuttering and children who would eventually persist in the same experimental conditions. The authors performed a rhyme and segmentation judgment study on older children, aged 7-13, for whom the persistence of stuttering was already known (Sasisekaran & Byrd, 2013). The authors found no group differences in response time in the rhyme and segmentation tasks. Yet, they did discuss a trend for increased time as complexity of stimuli increased (Sasisekaran & Byrd, 2013).

Many recent studies used rhyme judgment performance between groups of people who stutter and those who do not stutter to make claims about the word-form encoding systems of people who stutter. For example, Weber-Fox et al. (2004) interpreted null EEG results from a rhyme judgment task as evidence that adults who stutter do not have deficits with phonological encoding (one step in the word-form encoding process). Though phonologically-related tasks such as rhyme judgments do activate the phonological loop of the multi-component model of working memory (Baddeley, 2007, 2010), it is questionable, from a psycholinguistic perspective, whether this activation is the same that occurs during the word-form encoding process. This is due to the presumption of weaker word form activation when no intention to speak or sub-vocally rehearse is present (See Section 2.1.2). Thus, tasks that activate the phonological loop inform understanding of the phonological loop and not necessarily about the word-form encoding process, and vice versa. It is unclear if working memory capacity differences actually exist in people who stutter apart from the influences of word-form encoding differences, because prior studies of stuttering have not made this seemingly important distinction.

1.2.5 Attention and Motor-Learning

Fluent speech production is the culmination of a complex process that requires precise timing of sensory, conceptual, and motor integration (Guenther et al., 2006; Hickok & Poeppel, 2004, 2007; Max, Guenther, et al., 2004; Tourville & Guenther, 2011). It is automatic, effortless, and achieved by the vast majority of the human population (Starkweather, 1987; Wingate, 1988). Max and colleagues (2004) reviewed the long history of both speech and nonspeech motor research in stuttering and hypothesized that people who stutter may have unstable or insufficiently well-established internal models for speech motor movements. The authors stated, "…an important aspect of the disorder may lie in some children's inability to acquire stable…and correct mappings… between motor commands and sensory consequences" (Max, Guenther, et al., 2004, p. 113). Internal models are the stored representations of motor movements that are learned by repeated execution and refinement over time. As motor movements are learned, fewer errors are generated; this leads to less reliance on feedback control and more reliance on feedforward control (Tourville & Guenther, 2011). The process of repeated execution and refinement leads to greater automaticity (Posner, 1967; Schmidt, 1975) and accuracy (Perkell et al., 2000). Given that speech motor theory postulates that feedforward and feedback motor control components interact to produce well-timed fluent speech (Guenther, 1994; Tourville & Guenther, 2011), a delayed or weak internal model in the feedforward system might lead to an over-reliance on feedback motor control (Max, Guenther, et al., 2004).

Further investigations of this hypothesis have yielded promising findings: biasing the directions into velocities of articulators, or DIVA, model (Tourville & Guenther, 2011) away from feedforward control and toward feedback control yields simulations of stuttering behaviors. Using an updated version of the DIVA model, GODIVA or gradient order DIVA (Bohland et al., 2010), the authors later expanded these findings to explore the role of subcortical influences on the timing of simulated fluent speech movements (Civier et al., 2013). Since attention is necessary to learn motor movements and to generate well-established internal models (Posner, 1967; Schmidt, 1975), it possible that one consequence from people who stutter not having well-established internal models of speech movements is that they must devote more attention when executing these non-well established internal models. Motor research findings support this interpretation. Smith and colleagues have explored the consistency with which people who stutter execute motor movements (see Denny & Smith, 1992; Kelly et al., 1995; Kleinow & Smith, 2000; Olander et al., 2010; Smith et al., 1993, 2010, 2012; Usler et al., 2017; Walsh et al., 2015). Findings generally show that people who stutter are less stable and more variable with speech-related movements than are people who do not stutter. This finding could support the notion that people who stutter have weaker internal models of speech-related movements.

There is mixed evidence that increased phonological complexity of utterances leads to motor differences in people who stutter compared to people who do not stutter. Smith, Sadagopan, Walsh, and Weber-Fox (2010) conducted a nonword repetition task with 17 adults who stutter and 17 adults who do not stutter, in which the consistency of motor movements was measured in relation to nonword complexity. Though both adults who stutter and adults who do not stutter showed no difference in overt nonword repetition accuracy, adults who stutter were significantly less stable and more variable in their speech patterns when length and complexity of nonwords were increased. The authors interpreted these findings as supportive of a multi-dynamic view of stuttering behaviors because increased variability is evidence of a higher likelihood of a breakdown (see Smith & Weber, 2017). Sasisekaran & Weisberg (2014) sought to determine the influence of linguistic factors such as nonword length, phonotactic constraints, and complexity on motor stability. They recorded nonword repetition accuracy and movement variability in 10 adults who stutter and 10 adults who do not stutter. People who stutter showed significantly lower probability of correct responses for longer nonwords and nonwords that were implausible in the native language. In contrast to Smith & Weber (2010), the results from Sasisekaran & Weisberg (2014) indicated that the adults who stutter did not show a significant effect of nonword length on increased movement variability. The authors interpreted this as preliminary evidence that people who stutter are less adaptable or flexible in learning new speech movements.

The central assumption in much of the motor research in stuttering is that if motor stability decreases enough, breakdowns or stuttering behaviors will occur (Smith & Weber, 2017). Specifically, Smith & Weber stated,

> "SLDs [stutter-like disfluencies] occur when the behavior of the dynamic collective moves outside the fluent operating space…we propose that there is an operating range that the speaker must stay within to continue to produce perceptibly fluent speech. When command signals to muscles deviate outside this range, speech is interrupted and we [listeners or observers] perceive SLDs" (Smith & Weber, 2017, p. 16).

Other researchers have questioned whether increased motor variability leads to stuttering behaviors. Jackson et al. (2016) further explored how and why this motor variability occurs. They compared the spatiotemporal index (STI) in conditions where speakers were speaking in front of an audience to conditions where they were speaking by themselves. The authors replicated the previous findings that utterances were highly variable *across* utterances, but also found that speakers were less variable and more stable *within* utterances. The authors interpreted this as evidence that more deterministic (less variable) speaking patterns indicate "a system on the verge of breaking down," in accordance with a dynamical systems perspective (Jackson et al., 2016, p. 1310). Thus, increased variability across utterances may be indicative of a flexible speech motor system that is adapting to speaking demands and that the system becomes more deterministic and rigid during an utterance. This rigidity is believed by some researchers to lead to stuttering behaviors (Jackson et al., 2016).

This debate about whether increased stability or increased variability leads to stuttering behaviors notwithstanding, motor learning theory predicts that more well-formed internal models of speech-related movements should prevent or lead to fewer motor breakdowns (Posner, 1967; Schmidt, 1975). The findings of Jackson et al. support this possibility; it was under audience conditions that the motor systems of speakers who stutter became more rigid and stable (Jackson et al., 2016). Jackson et al. (2016) interpreted this finding as evidence that attention to the social pressure of speaking makes what would otherwise be an automatic action (i.e., speaking) become non-automatic, and this change leads to breakdowns. Though too much attention to what would otherwise be an automatic task certainly causes decreased performance in various domains (see Kal et al., 2013), the question is whether or not speech motor movements are automatic in people who stutter in the first place (Civier et al., 2010; Max, Maassen, et al., 2004). Because speech-motor actions may require more attention to execute in people who stutter compared to people who do not stutter, speech-motor execution should be subject to the increased effects of concomitant processing, thereby leading to increased chances of breakdown/delays in speech-motor movements.

1.2.6 Summary: Attention and Stuttering

Researchers have explored attention in individuals who stutter in various ways: as a disorder, as a neurophysiological construct that differentiates people who stutter from people who do not stutter, and as an aspect of temperament. Research has also explored attention as a construct that underlies other processing tasks, such as word-form encoding, the creation of working memory representations, and motor learning. In each case, such exploration has been conducted through factor-specific lenses. Considering the many ways that attention can be instantiated allows for consideration of novel questions that connect different aspects of stuttering research. Specifically, considering attentional demands both in terms of a domain-specific view (e.g., linguistic encoding during word formulation) and a domain-general view (e.g. other concomitant processing requirements) may allow for breakdowns in speech to be predicted. This possibility addresses a critical gap in stuttering research knowledge, for it is currently unknown when or why specific moments of stuttering will occur (Brocklehurst et al., 2013; Manning, 2000a; Postma & Kolk, 1993; Smith & Weber, 2017; Vasic & Wijnen, 2005). It is possible that by accounting for attentional allocation in more nuanced ways, the occurrence of stuttering behaviors can be explained. As a first step in this process, it is necessary to account for ambiguity in a key area of attention-related stuttering research, that is, whether previously but inconsistently observed differences in working memory abilities in people who stutter (e.g., differences in nonword repetition accuracy) occur because of a true underlying working memory deficit or if they occur as a function of word-form encoding influences on the task.

1.3 RESEARCH QUESTION, HYPOTHESES, AND INTERPRETATIONS

The purpose of this dissertation is to determine whether people who stutter have working memory capacity differences, independent of word-form encoding influences, compared to people who do not stutter. There are two important considerations that are necessary to address this question. These are addressed below.

First, prior research evidence has shown that people who stutter do not differ from those who do not stutter on simple digit span tasks. Given that simple digit span does not account for domain-peripheral, domain-central storage, and attentional components, it is unclear whether domain-central components are being recruited that might mask domain-peripheral deficits. As such, people who stutter may have working memory capacity differences in one or more domains that are only detectible when measured by complex span tasks (tasks that limit the amount of domain-central contributions when processing exceeds domain-peripheral abilities, see section 2.1.1). Using such tasks addresses the finding that people who stutter show working memory capacity differences only when linguistic processing demands are great. Specifically, because people who stutter only demonstrate nonword repetition differences when linguistic demands are high (e.g., more phonologically complex nonwords), it is possible that the recruitment of domain-central attentional resources masks working memory capacity differences in when demands are low (e.g., less phonologically complex nonwords).

Secondly, use of these tasks allows for the inherent amount of word form activation to be measured and accounted for in the experimental paradigm (see section 2.1.2). Each of the Complex Span tasks outlined above (see section 2.1.1) contains a natural hierarchy of word-form activation (highest: Operation Span, lowest: symmetry span). This hierarchy is further detailed below (3.4.3). This hierarchy allows word-form encoding influences to be accounted for when evaluating whether adults who stutter have working memory capacity differences.

If differences are found between people who stutter and those who do not in working memory capacity as measured by complex span tasks, then the manner in which these differences occur would support various interpretations, depending on the pattern of differences that are observed. These different interpretations can be revealed through the research question and hypotheses presented below.

Research Question: Do adults who stutter have working memory capacity differences compared to adults who do not stutter independent from the influences of word-form activation?

Hypothesis #1: One possible outcome is that people who stutter will not show working memory capacity differences as measured by any of three complex span tasks (OSPAN, Rotation, and Symmetry). Such a finding would suggest that working memory capacity does not differentiate people who stutter and those who not.

Hypothesis #2: A second possible outcome is that people who stutter will show differences across the complex span tasks as a function of the amount of word form activation each tasks requires. There is a hierarchy of word form activation across the three complex span tasks from highest activation (OSPAN) to least activation (Symmetry). Should group performance mimic this hierarchy, that would provide evidence that word-form activation differences are manifesting themselves as working memory differences. OSPAN only contains single letters, and it is not overly complex in regard to linguistic demands. Should this outcome occur, the findings would not only address ambiguity between phonological working memory and word-form encoding in prior stuttering research, but also provide evidence that people who stutter demonstrate word-form encoding differences with simple word forms when domain-central attentional resources are limited.

Hypothesis #3: A third possible outcome is that people who stutter will perform significantly lower than people who do not stutter across all of the tasks, regardless of the level of inherent word-form activation differences across the tasks. This outcome would suggest that working memory differences—independent of word-form encoding factors—differentiate people who stutter from those who do not stutter. This would indicate a need for novel investigations into the working memory skills of people who stutter, because it would call into question prior interpretations of working memory differences in people who stutter.

The research question will be investigated using a mixed experimental design in which participants will complete complex working memory span tasks that vary in the type of information (visual vs linguistic; e.g., OSPAN, Symmetry Span, Rotation Span) and in processing/distractor components. All findings may connect an as-yet disparate literature on attention-related factors thought to differentiate people who stutter and affect the occurrence of stuttering behaviors. This foundation will serve as a basis for future investigations into how attention is allocated in people who stutter in various tasks.

2.0 METHODS

2.1 POWER ANALYSES

A power analysis was conducted to estimate sample sizes needed to answer the research questions. The primary analysis was be done via linear models for the maximum likelihood of detecting effects (Bates et al., 2014); however, it was not possible to simulate models to predict sample size, because no published research exists 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. Thus, a power analysis was conducted based on a one-way ANOVA to determine the upper bound of subjects needed to detect effects with published means and SDs of the OSPAN (see Redick et al., 2012). A power of .80 and an alpha of .05 were chosen. Effect sizes were calculated from various hypothetical means that a group of people who stutter might have, based on the published means and SDs of the OSPAN (M=57.36, SD=13.65). Samples sizes were calculated for medium and large effect sizes via an ANOVA. To differentiate people who stutter from people who do not stutter on the OSPAN task via an ANOVA approach, a projected sample size of 63 participants per group would be necessary to detect a medium effect (.5), while a sample size of 25 would be necessary to detect a large effect (.8). Because the ultimate analysis will be more robust with linear mixed effect models (Brysbaert & Stevens, 2018), the power to detect differences, should they exist, may be higher in the actual analyses. Thus, the analysis may detect a smaller effect, should one exist, with a sample size of 25 subjects per group. Because of this, a projected sample size of 25 subjects per group was chosen as an initial targeted sample size (i.e., the N required to detect a large effect size in the ANOVA), though more subjects were ultimately recruited.

2.2 PARTICIPANTS

Participants were 40 adults who stutter and 42 adults who do not stutter, all 18 years of age or older. Both groups (people who stutter and those who do not) were recruited to ensure an approximately equal sex ratio and average age. Recruitment was successful regarding age in that age did not significantly differentiate the groups, $t(58.5) = -1.50$, $p = .14$. The sex ratio in both groups was approximately equal with approximately twice as many males as females in each group. See Table 1 for details.

Self-help and history of therapy history was determined by yes/no questions, though participants were asked to describe these experiences. Participants described a range of therapy experiences—some based on increasing fluency/not stuttering and others based on achieving effective communication. 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), hearing deficits, and other speech-language disorders. See Table 1 for full demographic information.

Table 1 Demographic Information

Demographic Variable	Stutter	NonStutter
	Raw Number or M (SD)	
Age	27.05 (11.2)	24.07 (5.86)
Sex		
Female	12	11
Male	30	29
Prefer not to say/Missing Data	0	0
Concomitant Disorder		
ADHD/ADD	5	2
ADHD/ADD and Depression	1	1
Racial Category		
American Indian or Alaskan Native	0	1
Asian American	5	5
Black or African American	6	0
Native Hawaiian or other Pacific Islander	0	0
Caucasian	28	36
Other	0	0
Prefer not to say/Missing Data	1	0
Ethnicity		
Hispanic or Latino	0	2
Not Hispanic or Latino	40	40
History of stuttering therapy		
Yes	24	n/a
No	16	n/a
Prefer not to say/Missing Data	0	n/a
History of self-help or support		
Yes	11	n/a
No	29	n/a
Prefer not to say/Missing Data	0	n/a
Highest educational experiences		
Elementary School	0	0
High School Graduate	1	3
Some College	18	22
College Graduate	10	9
Graduate School	10	8

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. Participants were recruited via IRBapproved methods—fliers posted in and around Michigan State University, past participation in other research projects, local and national stuttering associations, referral by other Michigan-based researchers and clinicians, and word-of-mouth recruitment by local people who stutter and those who do not stutter.

2.3 INCLUSION CRITERIA

Inclusion and grouping criteria were based on person-centered definitions. Participants were assigned to the group of adults who stutter (S) if they self-reported to be a person who stutters. This allowed participation regardless of the amount of observable stuttering behavior they exhibited during a particular speaking situation. Participants were assigned to the group of adults who do not stutter (N) if they self-reported not to be (or have a history of being) a person who stutters. No participant reported being a person who did not stutter while giving the impression of being a person who actually stuttered based on clinical observation (e.g., exhibiting a perceptually high number of disfluencies during the study). No participant reported being a person who stutters while giving the impression of not being a person who stutters. Thus, no subjects were excluded from the study in this way. Four people responded to 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.

2.4 MEASURES

2.4.1 Speech and Cognitive Measures

Various speech and cognitive baseline measures were completed by participants. Inclusion of these random effects was assessed in determining best model fit. In an attempt to account for individual differences in cognitive ability, each subject 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).

The potential negative impact of stuttering on communication a subject who stutters might have was measured via the Overall Assessment of the Speaker's Experience of Stuttering (OASES, Yaruss & Quesal, 2016). No minimum quality of life impact was required in order to allow for participation by people who have different backgrounds and experiences with stuttering. The OASES has been shown to be a reliable and stable measure of the impact stuttering has on a person's life (Yaruss & Quesal, 2006, 2016). It assesses stuttering impact via the WHO's International Classification of Functioning, Disability, and Health (ICF, WHO, 2001).

In order to address whether both groups of subjects were comparable in gross phonological skills, one subtest of the original Comprehensive Test of Phonological Processing (CTOPP) and three subtests of the updated CTOPP (CTOPP-2, Wagner et al, 2013) were conducted with all participants. In accordance with previous stuttering literature (see Coalson & Byrd, 2017), the word segmentation, forward digit span, nonword segmentation, and nonword repetition subtests were given. It was not expected that people who stutter as a group would differ on these tasks from the group of people who do not stutter (Coalson & Byrd, 2017), but including these tasks attempted to address baseline group functioning in regards to phonological processing.

2.4.2 Temperament and Perseverative Thinking Measures

Given the aims of this study, data on various domains shown to require attentional allocation and storage of information were collected in addition to the baseline demographic measures described above. For example, growing research suggests that cognitive processes, such as repetitive negative thinking (Curci et al., 2013; Hubbard, Hutchison, Hambrick, et al., 2016; Joormann et al., 2011; Levens et al., 2009; Owens et al., 2012; Tichenor & Yaruss, 2019b) and temperament (M. C. Anderson & Levy, 2009; Bomyea & Amir, 2011) require attentional processing. As such, measures of temperament (Adult Temperament Scale, ATQ, Evans & Rothbart, 2007) and repetitive negative thinking (Perseverative Thinking Questionnaire, PTQ, Ehring et al., 2011) were taken to capture individual differences in attentional allocation.

2.4.3 Complex Working Memory Span Tasks

Complex span tasks (e.g., OSPAN, Rotation span, and Symmetry span) are widely used in cognitive psychology to assess working memory capacity and predict behaviors across a plethora of domains that rely on executive control (e.g., domain central resources, for review, see Conway et al., 2005). The first complex span task was the reading span task developed by Daneman & Carpenter (1980). The original OSPAN was developed to explore whether the processing component needed to be strategy specific (e.g., reading strategies in the reading span task, see Turner & Engle, 1989). Numerous researchers have used these complex span tasks on thousands of participants in various populations (Redick et al., 2012). Redick et al. (2012) combined data from three labs that used various complex span tasks from 2004 to 2009 and evaluated the psychometric properties of tasks across approximately 6000 research subjects. More recent research has attempted to make these tasks more efficient and more applicable to a broader range of researchers and populations, with revisions being made to shorten administration time or to increase reliability (see Draheim et al., 2018; Foster et al., 2015; Oswald et al., 2014; Unsworth & Engle, 2007). The tasks for this study came from Draheim et al. (2018), who examined the psychometric proprieties of the tasks to improve differentiation between people with higher and lower working memory capacities. In particular, the standard version of the OSPAN has difficulty differentiating individuals with average vs. higher capacity. Draheim et al. (2018) revised the tasks with increased set sizes to differentiate people at the higher end of working memory abilities, while also allowing optional numbers of blocks (i.e., sets of experimental conditions). Each task allows for 1 to 3 blocks to be given. Research evidence has shown that shortening the tasks and reducing the number of trials does not significantly decrease measure validity (Foster et al., 2015), so subjects completed 2 blocks in this study rather than 3. Block (1 or 2) was incorporated as a possible random effect in the models.

Given that the main research question was to ascertain whether the group of people who stutter differ from the group of people who do not stutter in working memory capacity as a function of the type of information they are asked to retain (e.g., visual, verbal) while accounting for word-form activation, the following automated computer-based tasks were chosen: the Operational Span (OSPAN), the Rotation Span, and the Symmetry Span (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 distractor used. Per psycholinguistic theory (see, Roelofs, 2008c), word forms are most active in the OSPAN task while there is the least amount of word form activation in the symmetry span task, which is a purely visual task. The rotation span task contains only weakly cascading activation in the distractor task (rotated orthographic letters). All automated tasks also control for attention to task. The training procedure at the start of each task measured the time required to complete both the task to-be-remembered and the distractor. A time limit of the training time multiplied by a standard deviation of 2.5 was then imposed during the task to ensure construct validity. This ensured that working memory performance was not compensated for by increased time (Conway et al., 2005). The tasks also provided measures of the accuracy and speed of distractor tasks as well as average response time.

Multiple 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, the 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 items across partial scores (Unsworth et al., 2005, 2009). More recent research has explored practice effects that might occur over multiple blocks of tasks. Draheim et al. (2018) evaluated the properties of the complex span tasks in relation patterns of subject performance to address the concern that subjects might be responding differently to earlier presented items in earlier blocks than later items and blocks due to "strategies, the building of proactive interference, or that they are not sufficiently practiced on the task during the first block" (Draheim et al., 2018, p. 5). The authors found evidence that practice effects *were* influencing responses in later blocks. Other researchers have found that limiting the number of blocks negligibly decreases predictive ability on fluid intelligence (Foster et al., 2015). Current recommendations are to measure working memory capacity with multiple instances of the complex span tasks to provide a more complete measure of a person's working memory ability (Draheim et al., 2018; Foster et al., 2015; Unsworth et al., 2009). These recommendations were followed by using multiple complex span tasks and limiting the number of blocks completed to two.

2.4.4 The Attention Network Test (ANT)

Fan et al. (2002) developed the Attention Network Test (ANT) as a way of assessing the neurophysiological attentional networks proposed by Posner and colleagues (see Petersen & Posner, 2012; Posner & Petersen, 1990b). 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 to evaluate all three attentional networks (i.e., Orienting, Alerting, and Executive Control) (Fan et al., 2002; Posner, 1980). Subjects 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 cues (Fan et al., 2002). The ANT task has been used in hundreds of studies (MacLeod et al., 2010), and has been successfully used to measure attentional network functioning in various populations (e.g., Johnson et al., 2008; Urbanek et al., 2009). There is research evidence that the high vs. low working memory span subjects do differ in their Executive Control networks (Redick & Engle, 2006). As such, it was possible that the ANT might help disambiguate differences in adults who stutter if working memory capacity differences exist.

2.5 INSTRUMENTATION

All data collection occurred automatically via the complex span tasks provided by the Engle Lab at GA Tech (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 in the Spartan Stuttering Lab in the Oyer Speech and Language Building on the campus of Michigan State University. Some data collection occurred off-site at various regional research institutions (e.g., The University of Michigan). When data collection occurred off-site, all tasks and procedures were the same as described above.

2.6 DATA COLLECTION

2.7 PROCEDURES

Participants completed all tasks in the Spartan Stuttering Lab or, when data collection occurred off-site, in a quiet room. Participants completed all demographic and pen- and paper-based assessments described above. They then completed two blocks on each of the three complex span tasks chosen for this study (OSPAN, Rotation Span, and Symmetry Span). The order of the complex span tasks was randomized across participants. The order of the tasks was included among possible random effects in the linear mixed effect model. In total, the three tasks required approximately 30-60 minutes with other questionnaires and assessments requiring 45-60 minutes. Thus, total study time for each participant was between 75-120 minutes.

2.8 MEASUREMENT RELIABILITY

Given that the measures in this study were fully automated (OSPAN, Rotation Span, and Symmetry Span) or self-report measures (OASES, ATQ, PTQ), no inter- or intra-rater reliability was conducted.

2.9 PLANNED ANALYSES

The current study sought to determine: (a) if people who stutter have working memory capacity differences compared to people who do not stutter as measured by complex span tasks; and (b) if people who stutter have differences in some specific working memory domains as inconsistently suggested by some prior literature (e.g., verbal vs. visual). Linear mixed effect models were run using lme4 (Bates et al., 2014), a package developed for statistical computing package R (R Core Team, 2019). Since each subject completed two blocks of each complex span task, the two partial span scores were transformed into z-scores for comparison across blocks and across complex span tasks. This yielded six complex span partial z-scores (2 blocks each across 3 complex span tasks). These partial-span z-scores were the primary outcome variables of interest, because they accounted for partial-credit in how well the representations of items to-be-remembered were maintained. These were psychometrically preferable to absolute span scores for a variety of reasons. First, partial span scores contain more variance than absolute scores, allowing for better differentiation between individuals (Conway et al., 2005). Partial span score was predicted from group (people who stutter or people who do not stutter) and complex span task (OSPAN, Rotation Span, Symmetry Span). The fixed effects were group (categorical variable with 2 levels) and complex span task (categorical variable with 3 levels). Random intercept of participant was added to account for subject-by-subject idiosyncratic variation in the model. A random slope of complex span task was also added to account for the probability that effects of complex span varied individually among participants. Other random effect variables were iteratively incorporated in models (e.g., ANT scores, ATQ scores, TONI-4 score, PTQ score, Blocks, order in which the participant completed the complex span tasks, etc.) from least maximal to most maximal. Models were compared via the likelihood ratio test to determine the maximum random effects structure.

3.0 RESULTS

The primary research question asked whether adults who stutter demonstrate working memory differences independent of word-form encoding influences. Results are first presented for baseline measures (e.g., temperament, nonverbal intelligence, phonological processing, etc.). Results for the linear mixed-effect models follow.

3.1 GROUP DIFFERENCES ON BASELINE MEASURES

Table 3 contains descriptive statistics for TONI-4 scores. TONI-4 scores did not significantly differ between the group of participants who stutter and the group of participants who do not stutter (*t*(75.77) = .56, *p* = .58), indicating that the groups did not significantly differ in nonverbal intelligence. See Table 2 and 8 for more details. No correction for multiple comparisons was done on baseline measures given the overall non-significant findings. Instead, confidence intervals are presented in Table 8 to aide interpreting the test statistics (see, Rothman, 1990; Saville, 1990).

Table 2 Descriptive Statistics for Groups on Test of Nonverbal Intelligence – 4 (TONI-4)

Group	Mean	SD	Median	Min	Max	Skew	Kurtosis
N	104.12	8.62	105	87	124	0.29	-0.69
S	102.95	8.41	103.5	87	125	0.27	-0.67

Note: N = People who do not stutter, S = People who Stutter

Table Caption: Table 2 contains descriptive statistics for the Test of Nonverbal Intelligence.

Similarly, there were no significant differences across groups in in the CTOPP measures: word segmentation, *t*(72.72) = -.25, *p* = .81; forward digit span, *t*(72.42) = .70, *p* =.49; nonword repetition, *t*(77.43)= 1.01, *p* =.32; and nonword segmentation, *t*(73.35)= .52, *p* = .61. These data indicate that both groups of participants were comparable in both nonverbal intelligence and phonological processing skills as measured by the TONI-4 and the CTOPP, respectively. See Table 3 and 8 for more details.

Table 3 Descriptive Statistics for Groups on the Comprehensive Test of Phonological Processing (CTOPP)

Measure	Group	Mean	SD	Median	Min	Max	Skew	Kurtosis
Word Segmentation	N	19.88	0.77	20	15	20	-6.03	35.14
Word Segmentation	S	19.93	0.47	20	17	20	-5.86	33.15
Forward Digit Span	N	12	2.27	11	8	17	0.5	-0.6
Forward Digit Span	S	12	2.75	11	6	18	0.44	-0.35
Nonword Repetition	N	10.79	2.27	11	6	16	0.16	-0.21
Nonword Repetition	S	10.65	1.98	11	6	15	0.07	-0.56
Nonword Segmentation	N	15.98	2.04	16	8	19	-1.61	3.7
Nonword Segmentation	S	15.7	2.16	16	9	18	-1.15	1.17

Note: N = People who do not stutter, S = People who Stutter

Table Caption: Table 3 contains descriptive statistics for the Comprehensive Test of Phonological Processing.

Participants who stutter demonstrated a range of OASES scores, representing very mild to very severe adverse impact related to stuttering. These values are comparable to published norms (see, Yaruss & Quesal, 2016), but no statistical comparisons on the four OASES sub-scores or OASES total scores were made due to the comparatively small sample size of the present study compared to published normative data. See Table 5 and 8 for more details.

Table 4 Descriptive Statistics for Groups on the Overall Assessment of the Speaker's Experience of Stuttering (OASES)

Measure	Group	Mean	SD	Median	Min	Max	Skew	Kurtosis
General Information	S	3.09	0.71	3.06	1.65	4.44	-0.22	-1.03
Reactions to Stuttering	S	2.74	0.86	2.55	1.21	4.69	0.36	-0.71
Communication in Daily Situations	S	2.44	0.77	2.36	1.16	4.56	0.33	-0.12
Quality of Life	S	1.93	0.81	1.68	1	4.21	1.01	0.28
Total Score	S	2.6	0.76	2.41	1.28	4.55	0.48	-0.38

Note: N = People who do not stutter, S = People who Stutter

Table Caption: Table 4 contains descriptive statistics for the Overall Assessment of the Speaker's Experience of Stuttering.

Participants who stutter and participants who do not stutter demonstrated no statistically significant differences on the Perseverative Thinking Questionnaire (PTQ) ($t(72.74) = -1.39$, $p =$

.17), meaning that groups were comparable in the frequency in which they engaged in Repetitive Negative Thinking. This finding is consistent with prior research showing that people who stutter do not exhibit greater RNT than people who do not stutter (Tichenor & Yaruss, 2019b). See Table 5 and 8 for more details. Descriptive Statistics for Groups on Perseverative Thinking Questionnaire (PTQ)

Table 5 Descriptive Statistics for Groups on Perseverative Thinking Questionnaire (PTQ)

Group	Mean	SD	Median	Min	Max	Skew	Kurtosis
N	24.43	9.64	26.5	4	50	-0.13	-0.15
S	28.23	10.89	27	8	46	0.05	-1.16

Note: N = People who do not stutter, S = People who Stutter

Table Caption: Table 5 contains descriptive statistics for the Perseverative Thinking Questionnaire

Some Adult Temperament Questionnaire (ATQ) scores did statistically differ between groups: Negative Affect *t*(72.13) = -2.23, *p* = .03; while others did not: Effortful Control *t*(66.24) = 1.26, *p* = .21; Extraversion/Surgency *t*(75.41) = -.11, *p* = .91; and Orienting Sensitivity *t*(70.69) = -.38, *p* = .71. This indicates that the sample of adults who stutter did not significantly differ from the group of adults who did not stutter on most aspects of temperament with the exception of Negative Affect. See Table 6 and 8 for more details.

Table 6 Descriptive Statistics for Groups on the Adult Temperament Questionnaire (ATQ)

Measure	Group	Mean	SD	Median	Min	Max	Skew	Kurtosis
Negative Affect	N	3.76	0.64	3.79	2.46	5.65	0.29	0.15
Negative Affect	S	4.03	0.74	4.15	2.15	5.65	-0.6	0.07
Effortful Control	N	4.51	0.77	4.47	2.95	6.42	0.08	-0.35
Effortful Control	S	4.26	0.97	4.16	2.16	6.79	0.16	0.02
Extraversion/Surgency	N	4.42	0.69	6	3.24	6.59	0.16	0.02
Extraversion/Surgency	S	4.39	0.68	4.24	3.29	6.29	0.7	0.04
Orienting Sensitivity	N	4.56	0.78	4.57	3	6.73	0.26	0.13
Orienting Sensitivity	S	4.64	0.86	0.89	2.93	6.27	0.05	-0.91

Note: N = People who do not stutter, S = People who Stutter

Table Caption: Table 6 contains descriptive statistics for the Adult Temperament Questionnaire.

Similarly, Attention Network Test scores did not statistically differ between groups: Alerting *t*(77.12) = -.24, *p* = .80; Orienting *t*(77.20) = .98, *p* = .33; and Conflict *t*(77.81) = -.15, *p* = .88. See Figure 1 for ANT data visualization. Overall, these findings indicate that groups were comparable in Alerting, Orienting, and Executive Control networks. See Table 7 and 8 for more details.

Table 7 Descriptive Statistics for Groups on the Attention Network Test (ANT)

Measure	Group	Mean	SD	Median	Min	Max	Skew	Kurtosis
Alerting	N	38.69	29.38	37	-31	119	0.23	0.34
Alerting	S	43.98	30.92	40	-13	145	1.02	1.86
Orienting	N	42.57	27.21	42.5	-13	110	0.36	0.03
Orienting	S	37.1	20.65	33	35.94	85	0.41	-0.11
Executive Control	N	130.9	39.48	124.5	78	210	0.62	-0.74
Executive Control	S	129.4	33.6	131	74	212	0.45	-0.45

Note: N = People who do not stutter, S = People who Stutter

Table Caption: Table 7 contains descriptive statistics for the Attention Network Test

Figure 1 Group Attention Network Test Performance

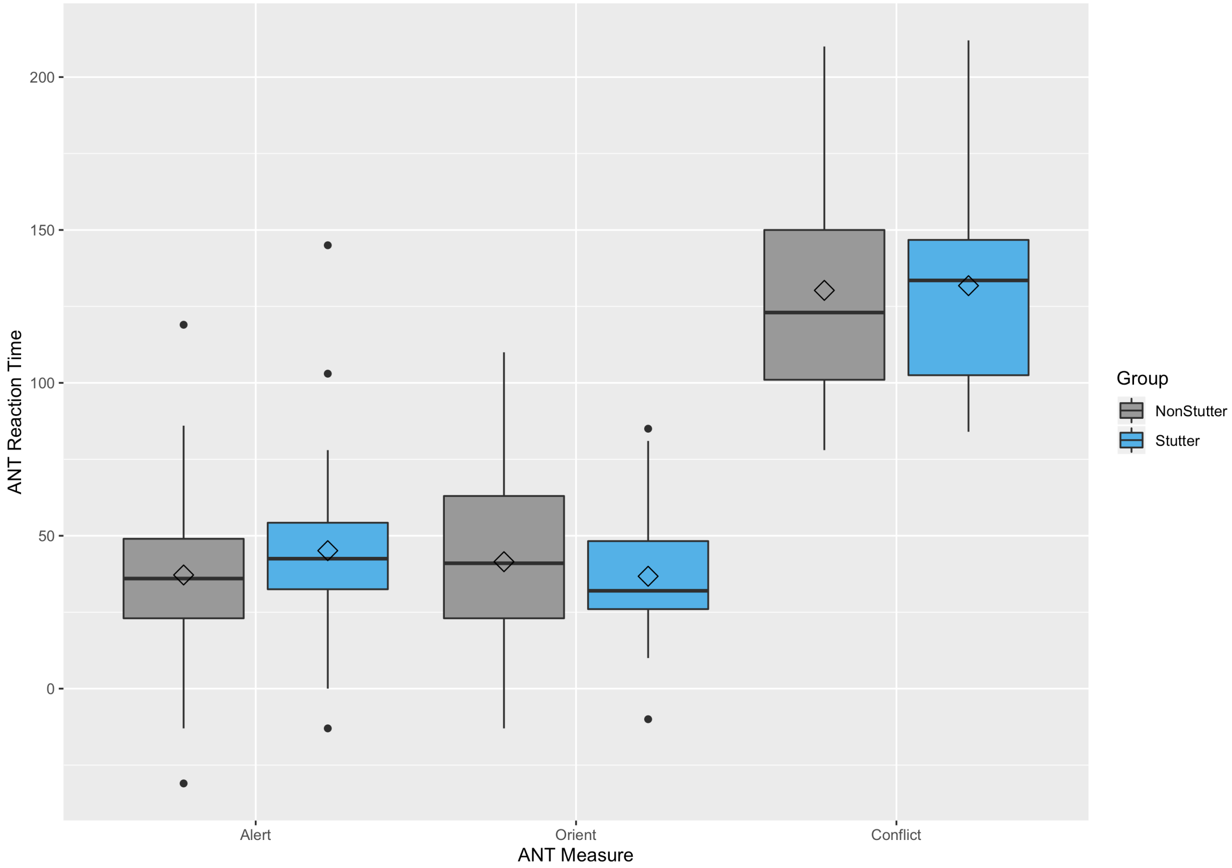

Figure Caption: ANT Reaction times are plotted by task and group. The dots represent outliers (1.5 IQR outside of the median) and the diamonds represent medians. There were no significant between-group differences.

Table 8 Test Statistics for Groups on Baseline Measures

Measure	*df*	*t*	p	CI (95%, lower)	CI (95%, upper)
TONI-4	75.77	0.56	0.58	-2.76	0.58
CTOPP: Word Segmentation	72.72	-0.25	0.81	-0.32	0.25
CTOPP: Forward Digit Span	72.42	0.70	0.49	-0.73	1.51
CTOPP: Nonword Repetition	77.43	1.01	0.32	-0.44	1.36
CTOPP Nonword Segmentation	73.35	0.52	0.61	-0.71	1.20
Perseverative Thinking Questionaire	72.74	-1.39	0.17	-7.93	1.41
ATQ: Negative Affect	**72.13**	**-2.23**	**0.03**	**-0.64**	**-0.04**
ATQ: Effortful Control	66.24	1.26	0.21	-0.15	0.65
ATQ: Extraversion/Surgency	75.41	-0.11	0.91	-0.32	0.29
ATQ: Orienting Sensitivity	70.69	-0.38	0.71	-0.44	0.30
ANT: Alerting	77.12	-0.24	0.80	-14.19	11.12
ANT: Orienting	77.20	0.98	0.33	-5.42	15.98
ANT: Executive Control	77.81	-0.15	0.88	-17.25	14.80

Bolded indicates significant effects

Table Caption: Table 8 contains test statistics for all of the baseline measures taken from published assessments in the study: Test of Nonverbal Intelligence (TONI-4), Comprehensive Test of Phonological Processing (CTOPP), Perseverative Thinking Questionnaire (PTQ), Adult Temperament Questionnaire (ATQ), Attention Network Test (ANT).

In order to evaluate the correlations among these baseline measures, a correlation matrix was created and plotted for both groups of subject.

Figure 2 Correlation of Baseline Measures by in the S Group

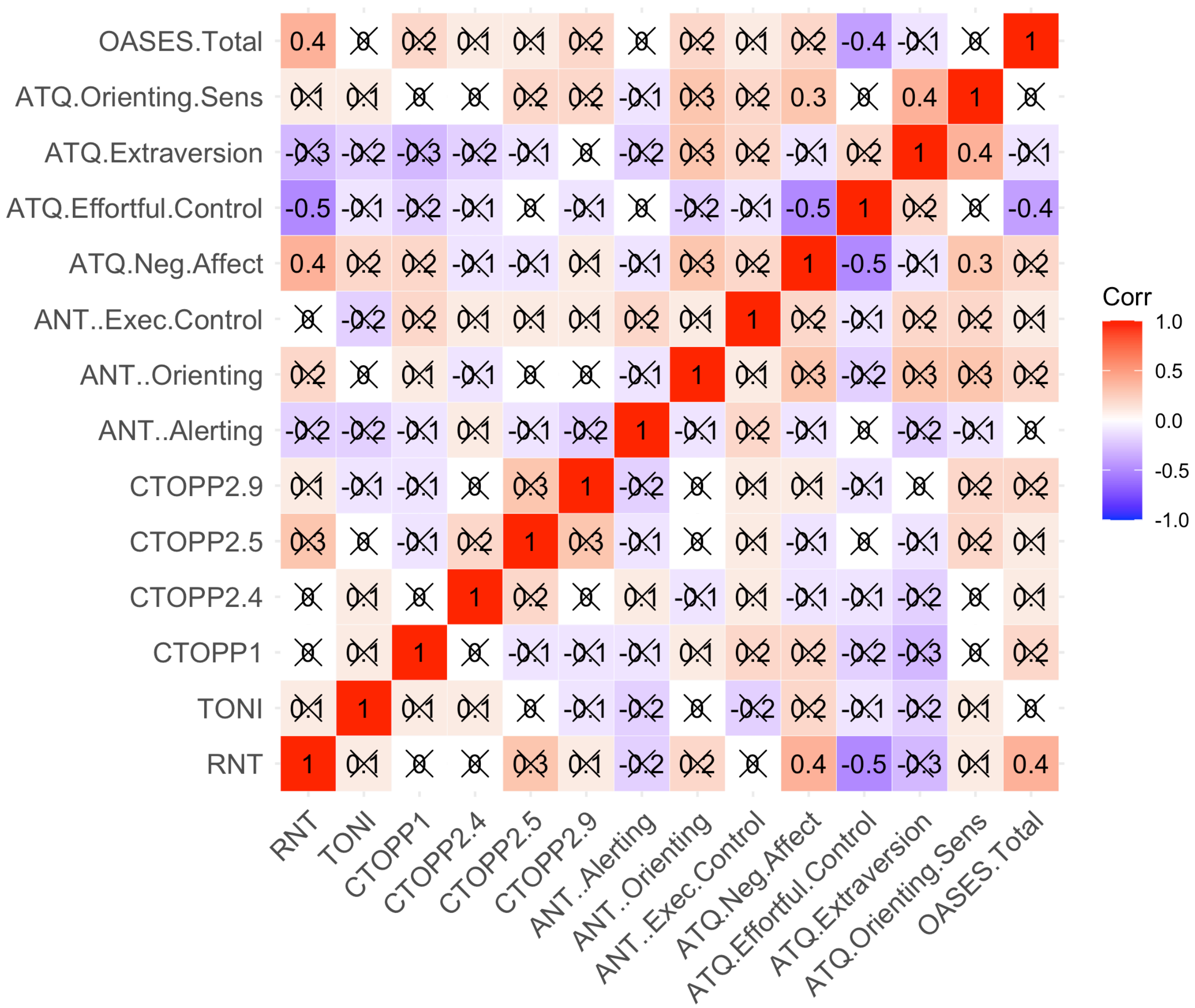

Figure Caption: Figure 2 contains correlations of baseline measures in the S Group. Inignificant correlations are crossed out. More positiive correlations are colored red and more negative correlations are colored blue.

The baseline measures in the group of people who stutter showed the highest correlations between the PTQ (RNT measure) and Negative Affect and total OASES score. The lowest correlations were between Negative Affect and Effortful Control.

Figure 3 Correlation of Baseline Measures by in the N Group

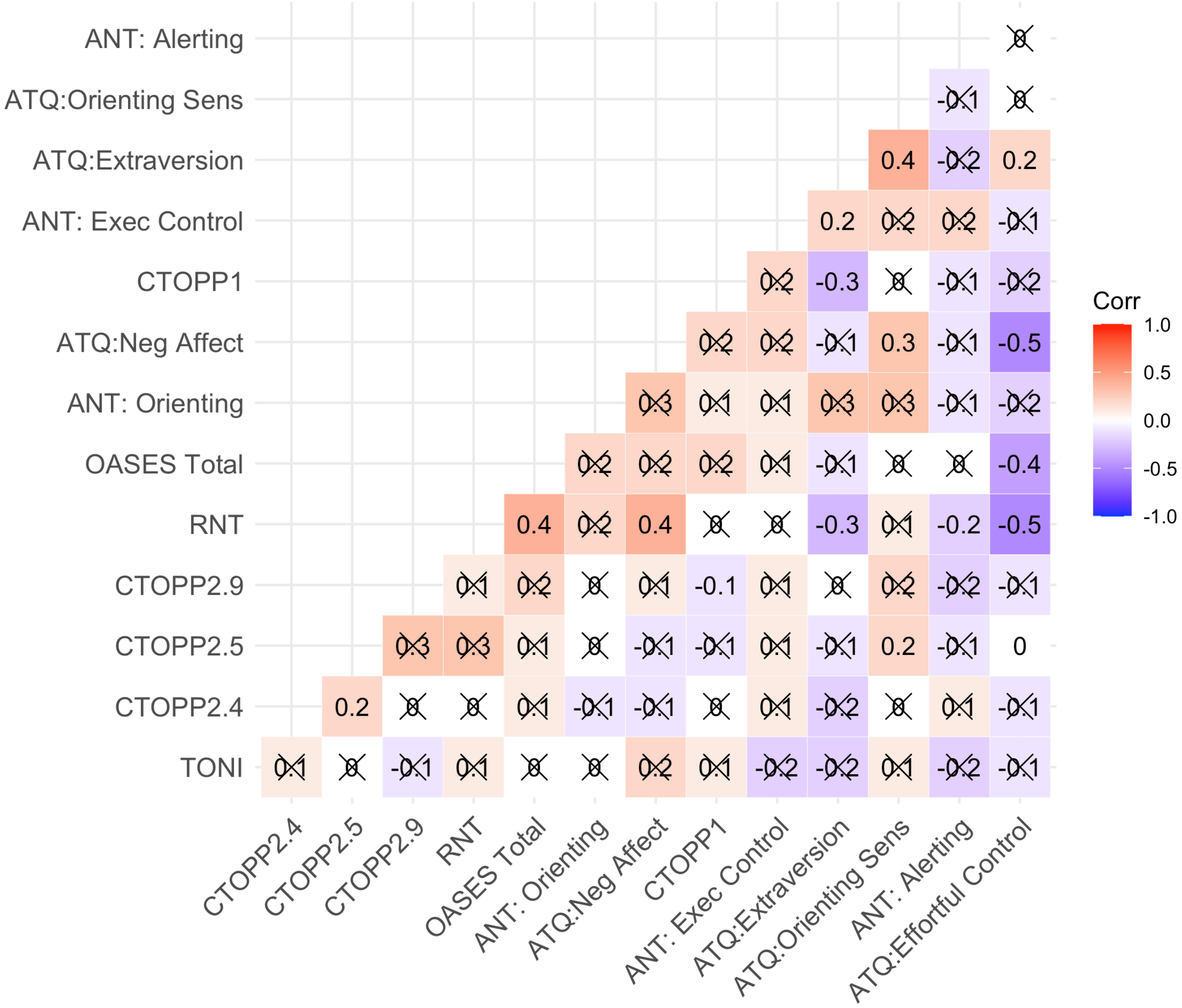

Figure Caption: Figure 3 contains correlations of baseline measures in the N Group. Inignificant correlations are crossed out. More positiive correlations are colored red and more negative correlations are colored blue.

The baseline measures in the group of people who do not stutter (N group) showed the highest correlations among CTOPP tests, Effortful Control, and Orienting Sensitivity. As with the S group, the lowest correlations were between Negative Affect and Effortful Control in the N group.

3.2 GROUP DIFFERENCES ON COMPLEX SPAN TASKS

Descriptive statistics were calculated for raw performance on each block across the three complex span tasks for both people who stutter and adults who do not stutter. See Tables 10-12 for details. Means across all blocks and tasks were descriptively lower for the group of adults who stutter than they were for the group of adults who do not stutter. Groups were not statistically significant from one another on the OSPAN $t(76) = 2.00$, $p = .05$; the Rotation Span $t(74.79) = 1.46$, $p = .15$, or on the Symmetry Span $t(72.39) = .98$, $p = .33$.

Table 9 Descriptive Statistics for Partial Span Scores on OSPAN Task

Group	Block	Mean	SD	Median	Min	Max	Skew	Kurtosis
N	1	25.36	9.98	27	4	41	-0.59	-0.51
S	1	21.27	9.65	22	4	42	-0.1	-0.97
N	2	26.24	9.69	28.5	1	41	-0.99	0.38
S	2	21.92	10.39	23	3	40	-0.23	-1.19

Note: N = People who do not stutter, S = People who Stutter

Table Caption: Table 9 contains descriptive statistics for the OSPAN Task

Table 10 Descriptive Statistics for Partial Span Scores on Rotation Span Task

Group	Block	Mean	SD	Median	Min	Max	Skew	Kurtosis
N	1	11.86	4.12	12	2	19	-0.41	-0.29
S	1	10.84	4.65	10	2	22	0.21	-0.49
N	2	12.24	5.26	11.5	0	24	-0.07	-0.47
S	2	10.3	5.03	10	2	21	0.31	-0.81

Note: N = People who do not stutter, S = People who Stutter

Table Caption: Table 10 contains descriptive statistics for the Rotation Span Task

Table 11 Descriptive Statistics for Partial Span Scores on Symmetry Span Task

Group	Block	Mean	SD	Median	Min	Max	Skew	Kurtosis
N	1	14.28	5.23	13	2	27	0.37	-0.08
S	1	13.22	6.02	14	0	25	-0.14	-0.58
N	2	14.37	6.09	14	1	27	-0.07	-0.84
S	2	13.11	5.56	13	0	26	-0.27	0.21

Note: N = People who do not stutter, S = People who Stutter

Table Caption: Table 11 contains descriptive statistics for the Test of Nonverbal Intelligence.

All raw scores from participants and tasks were transformed into z-scores to allow comparison across complex span tasks. These raw group distributions of z-scores across tasks can be seen in Figure 4 plotted by group. The data visually indicate that partial span scores tended to be lower for the group of adults who stutter compared to the group of adults who do not stutter across all three tasks.

Figure 4 Complex Span Task Performance in Z-scores By Group

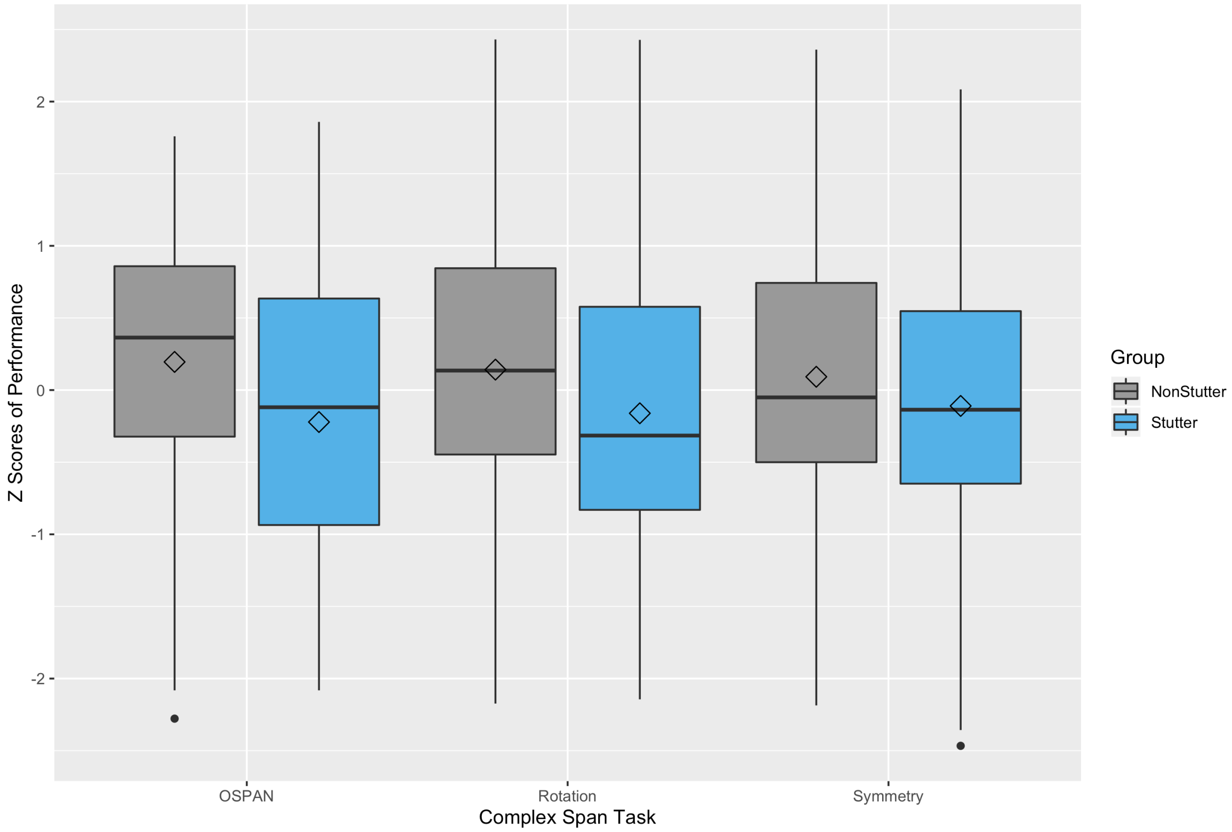

Figure Caption: Complex Span Z-scores are plotted by task and group. The dots represent outliers and the diamonds represent medians. The whiskers represent maximum and minum values (excluding outliers)

Given that the complex span tasks require concomitant processing (e.g., math problems, determining whether letters can be meaningfully rotated, or judging whether a shape is symmetrical along its long axis), accuracy measures were taken for all subjects. These raw accuracy measures are presented below in Figure 5.

Figure 5 Concomitant Task Accuracy By Group

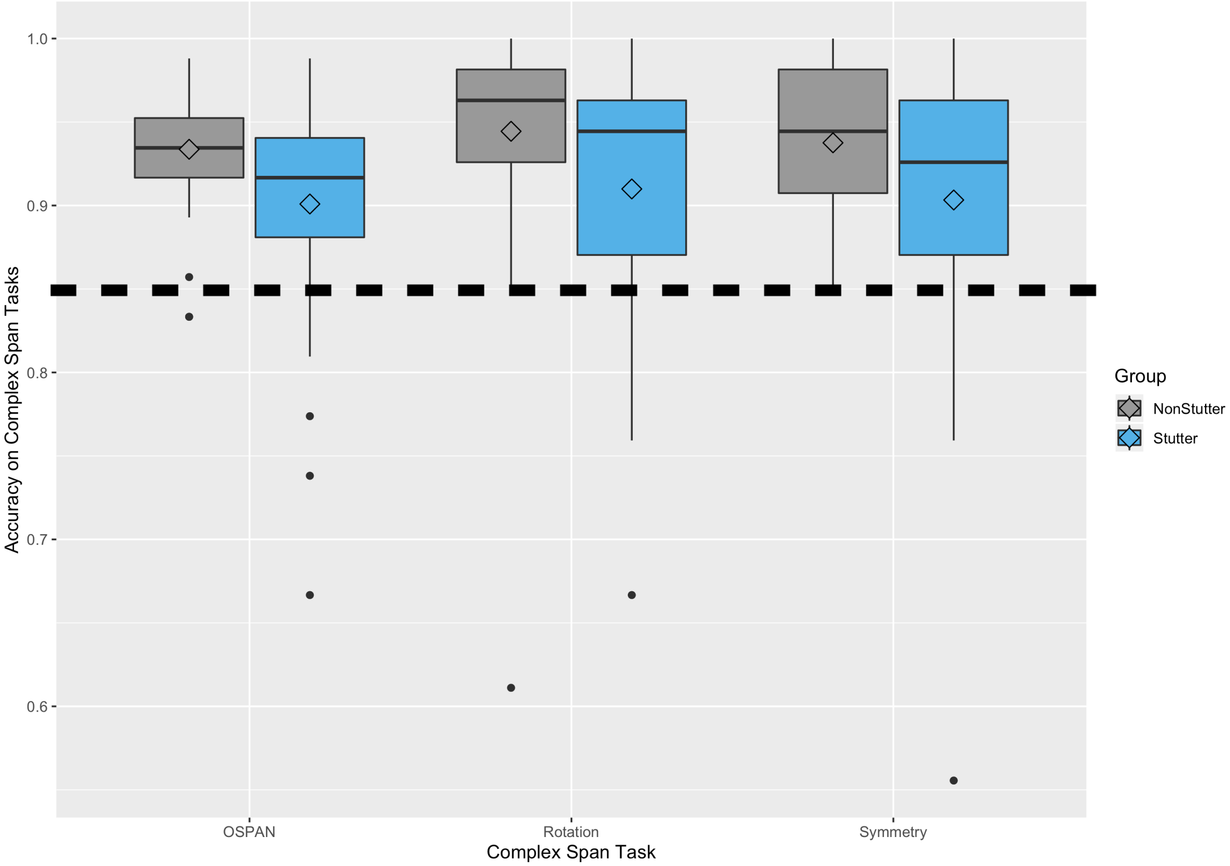

Figure Caption: Complex Span accuracy performance is plotted by task and group. The dots represent outliers and the diamonds represent medians. The whiskers represent maximum and minum values (excluding outliers). The dashed horizontal line represents the usual cut-off criterion imposed to ensure measure validity.

The hashed line on the 85% level indicates the typical cut-off point used to determine whether subjects are faithfully engaging in the complex span task. Typically, data from subjects who fail to meet this criterion are discarded (Draheim et al., 2018; Unsworth et al., 2005). However, since the a priori hypothesis of this study was that people who stutter would have more difficulty in the complex span task(s), data were not removed in this way. Partial data from only one subject who did not stutter (Subject 83) were removed for one task (Rotation Span) due to an accuracy of .60 and a partial span score greater than five z-scores, indicating that the participant sacrificed accuracy on the concomitant task to aid retention. Complete data from two subjects who stutter (Subject 6 and Subject 21) were excluded for failing to meet criterion levels on *any* of the three complex span tasks and failing to participate faithfully in the tasks (e.g., checking their phones during the experiment). Note that no data from either subject were used in any analyses. No other data were removed for subjects who failed to meet accuracy criterion because their partial span scores were within 2.5 z-scores from zero.

Patterns in the data suggest that, as a group, people who stutter had more difficulty maintaining accuracy on the concomitant tasks during the complex span tasks. To confirm this, a Chi-Square test was completed to test the hypothesis that subject accuracy on the concomitant task was independent of subject group status. Results indicated that the relationship between accuracy and group was significant, (X^2 (30) = 87.75, $p < .001$, $V = .43$). Thus, as a group, people who stutter were less likely to meet the accuracy criterion across all complex span tasks than were the group of people who did not stutter and this effect was medium to large (Cohen, 1988). This pattern of difficulty was distributed across the three complex span tasks. Five adults who stutter did not meet criterion in the OSPAN and Symmetry Span. Seven adults who stutter did not meet criterion in the Rotation Span. Comparatively, only two adults who did not stutter failed to meet criterion in the OSPAN and one failed to meet criterion in the Symmetry Span.

3.3 LINEAR MIXED EFFECT MODELS PREDICTING COMPLEX SPAN PERFORMANCE

In order to evaluate whether adults who stutter demonstrate working memory differences independent of word-form encoding influences, it was necessary to determine whether group status, complex span task, or their interaction, significantly predicted partial-span z-scores. An initial model (Model 1) comprising a fixed effect of group, complex span task, and their interaction was built with a random intercept of subject. A second model (Model 2) was built adding a random slope of complex span task. This allowed for subject performance to vary across the tasks. This random slope also allowed for the possibility that individual subjects may perform better or worse 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 did Model 1. Sixteen other models were constructed using possible random intercepts of Order (because subjects took the complex span tasks in randomized orders), Block, Age, Sex, concomitant ADHD/Depression self-reports, and various baseline measures (e.g., TONI score, PTQ scores, Attention Network Variables, and Temperament Factors) to maximize the random effect structure. These models did not significantly improve fit compared to Model 2. Results for Model 2 are presented in Table 12. Note that dummy coding (treatment coding) was used in all linear mixed effect models, with the group of people who stutter on the OSPAN as the intercept.

Table 12 Mixed Effects Analyses of Random and Fixed Factors influence on Complex Span Z Score performance (DV)

Predictors	Fixed Effects				Random Effects	
	Co-efficient	Std. Error	t value	p	Variance	Std. Deviation
Intercept (S Group on OSPAN)	-0.222	0.147	-1.506	0.136	0.663	0.814
N Group on OSPAN	0.408	0.202	2.024	0.046	*n/a*	*n/a*
GroupS:ComplexSpanRotation	0.061	0.159	0.381	0.705	0.662	0.814
GroupS:ComplexSpanSymmetry	0.105	0.149	0.707	0.481	0.532	0.729
GroupN:ComplexSpanRotation	-0.091	0.219	-0.418	0.677	*n/a*	*n/a*
GroupN:ComplexSpanSymmetry	-0.200	0.203	-0.982	0.329	*n/a*	*n/a*
Residual	*n/a*	*n/a*	*n/a*	*n/a*	0.277	0.526

* shaded cells indicate significant effects

Data from Model 2 directly support Hypothesis #2 which stated that working memory capacity differences (as measured by partial span scores) would mimic the inherent hierarchy of word-form activation present across the three complex span tasks. When participants who stutter completed the OSPAN (the intercept in Model 2), the OSPAN partial-span z-score was estimated to be -.22. The first predictor in the model (GroupN:OSPAN) was the predicted difference in mean partial-span z-score on the OSPAN between people who stutter and people who do not stutter. Not being a person who stutters increased partial-span z-scores by .41, giving an estimated mean of .19 partial-span z-scores (-.22 plus .41). This effect is significant *t*(79.57) = -2.02, *p* = .046, *d* = .28. The effect size of this difference is 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 from the OSPAN predicted partial-span z score in people who stutter were not statistically significant from their OSPAN predicted performance.

The data for people who do not stutter indicated an opposite pattern of results. Note that because these variables were dummy coded, comparison is still people who stutter taking the OSPAN. There was a predicted decrease of .09 in partial-span z-scores for people who not stutter on the Rotation Span Task. Adding this decrease to the predicted OSPAN vs. Rotation Span difference for people who do not stutter (.06 - .09 = -.03) indicates a predicted mean of .15 partial-span z-scores on the Rotation Span Task for people who stutter (.18 - .03 = .15). There was also a predicted decrease of .20 partial-span z-scores for people who do not stutter on the Symmetry Span Task. Adding this decrease to the predicted OSPAN vs. Symmetry Span difference for people who do not stutter (.11 - .20 = -.09) indicates a predicted mean of -.11 (.18 - .09 = -.27). Neither of these decreases were significantly different from the baseline condition (people who stutter taking the OSPAN). These data indicated that people who stutter only demonstrate working memory capacity differences (e.g., lower partial span scores) in the more linguistically demanding condition (e.g., OSPAN with most word-form activation). Figure 4 visualizes the effects of the fixed effects (Group and Complex Span Task). Visual inspection of Figure 4 supports the formal interpretation of Model 2 above, indicating that the most robust difference in complex span task occurred on the OSPAN. The group partial span scores most closely matched in the Symmetry Span task, with adults who stutter performing slightly lower in the Rotation Span compared to adults who do not stutter. See Figure 4 for details.

Figure 6 Visualization of Fixed Effects

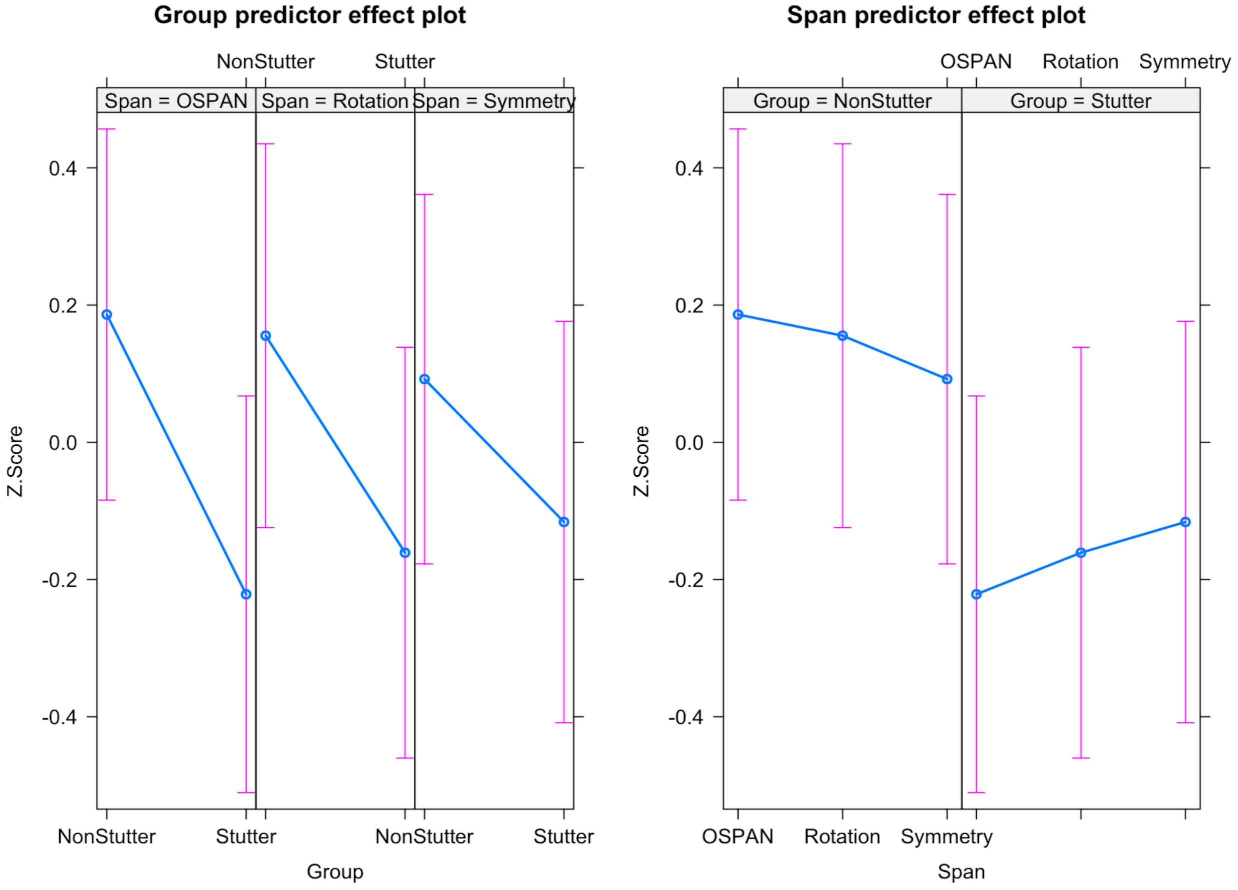

Figure 6 visualizes the Model 2 predicted fixed effects of Group (Adults who Stutter and Adults who do not Stutter) and Complex Span Task (OSPAN, Rotation, Symmetry)

3.4 MULTIPLE LINEAR REGRESSION OF ATTENTION-RELATED CONSTRUCTS ON MEAN OSPAN PARTIAL SPAN SCORE.

Given that past research evidence has shown that individuals with high vs. low working memory capacities can be differentiated by performance on attention-related tasks, such as the ANT (see, Redick & Engle, 2006), multiple linear regressions were performed to determine whether group status, task performance (e.g., PTQ total score, Effortful Control profile, or Attention Network Test reaction time), or their interactions could predict OSPAN partial span scores. A new variable was created from the mean of the OSPAN partial span scores on blocks 1 and 2 to capture average working memory partial span performance on the two blocks participants completed. This variable was used as the outcome variable in the multiple linear regression equations discussed below.

Two multiple linear regression models (Models 1 and 2, respectively) were built to explore the effect of Repetitive Negative Thinking (RNT) and Effortful Control on mean OSPAN partial span score. Neither RNT ($F(3,75) = 1.797$, $p < .155$, $R^2 = .07$, $R^2_{\text{Adjusted}} = .03$, $f^2 = .07$) nor Effortful Control ($F(3,74) = 2.346$, $p < .080$, $R^2 = .09$, $R^2_{\text{Adjusted}} = .05$, $f^2 = .10$) explained a significant amount of the variance of mean partial span OSPAN scores. Similarly, three multiple linear regression models (Models 3-5) were built to explore the effects of the Alerting, Orienting, and Executive Control networks on mean OSPAN partial span score. Neither Alerting ($F(3,75) = 1.359$, $p < .265$, $R^2 = .05$, $R^2_{\text{Adjusted}} = .01$, $f^2 = .05$) nor Orienting ($F(3,75) = 1.685$, $p < .177$, $R^2 = .063$, $R^2_{\text{Adjusted}} = .026$, $f^2 = .07$) explained a significant amount of the variance of mean partial span OSPAN scores. The Executive Control network explained a significant amount of the variance on mean OSPAN partial span score ($F(3,75) = 2.894$, $p < .041$, $R^2 = .10$, $R^2_{\text{Adjusted}} = .07$, $f^2 = .12$), which indicated a small to medium effect size. See Table 13 for further details on specific regression variables.

Table 13 Multiple Linear Regressions of ANT, RNT, and Effortful Control on Median OSPAN Partial Score

Model	Variable	*B*	*SE B*	β	τ	*p*
Repetitive Negative Thinking (RNT)						
	RNT	*0.07*	*3.88*	0.08	0.472	*0.639*
	People who Stutter	*-6.51*	*0.15*	-0.35	-1.140	*0.258*
	Interaction	*0.07*	*0.2*	0.13	0.362	*0.718*
Effortful Control						
	Effortful Control	*3.20*	*1.79*	0.31	1.787	*0.078*
	People who Stutter	*14.95*	*10.55*	0.82	1.417	*0.161*
	Interaction	*-4.23*	*2.37*	-1.03	-1.786	*0.078*
Alerting Network						
	Orienting	0.00	0.05	0.00	-0.050	0.965
	People who Stutter	-4.31	3.62	-0.23	-1.189	0.238
	Interaction	0.00	0.07	0.01	0.040	0.972
Orienting Network						
	Alerting	0.05	0.05	0.14	0.979	0.331
	People who Stutter	-2.01	4.08	-0.11	-0.494	0.623
	Interaction	-0.05	0.09	-0.13	-0.571	0.570
Executive Network						
	Executive Control	0.05	0.04	0.20	1.423	0.159
	People who Stutter	11.76	7.91	0.63	1.490	0.141
	Interaction	**-0.12**	**0.06**	**-0.91**	**-2.090**	**0.040**

*Bolded cells indicate significant effects

The significant interaction of people who stutter and Executive Control network scores to predict OSPAN partial scores was expected given past research evidence showing that individuals with higher vs. lower OSPAN scores differ in the efficiency of their Executive Control networks (Redick & Engle, 2006). Figure 5 illustrates this significant interaction. People who stutter who had slower reaction times (lower efficiency) in Executive Control conditions in the ANT demonstrated lower mean OSPAN partial scores while people who stutter with faster reaction times (higher efficiency) in Executive Control conditions in the ANT demonstrated higher mean OSPAN partial scores.

Figure 7 ANT Executive Control Prediction of Mean OSPAN Partial Span Scores

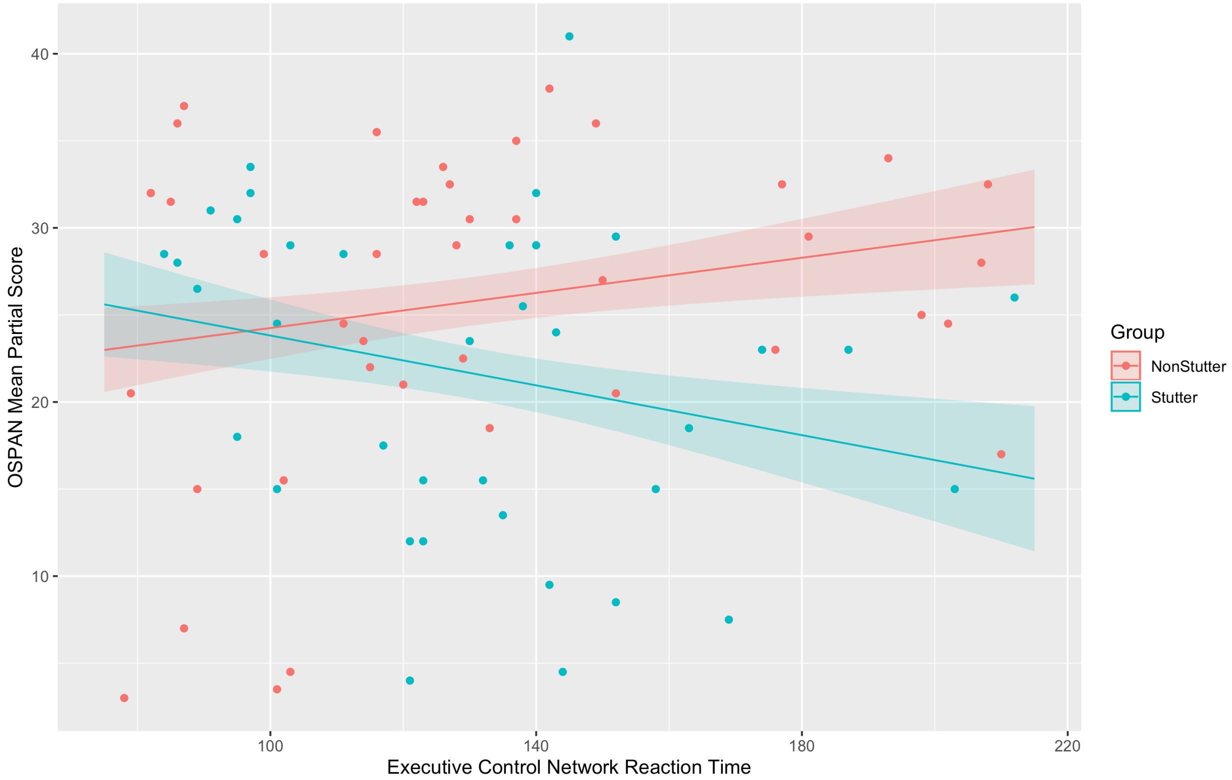

Figure 7 visualizes the Model 2 predicted fixed effects of Group (Adults who Stutter and Adults who do not Stutter) and Complex Span Task (OSPAN, Rotation, Symmetry)

Because Executive Control was significantly predictive of OSPAN partial span scores, a post-hoc analysis was done to determine whether Executive Control, group, or the interaction could predict Rotation and Symmetry Span Scores. Mean Rotation and Symmetry span scores were calculated in the same fashion as mean OSPAN scores. Results indicated that Executive Control, group status, and their interaction explained a significant amount of the variance on mean partial Rotation Span scores ($F(4.37,75) = 3.001$, $p < .04$, $R^2 = .11$, $R^2_{\text{Adjusted}} = .07$, $f^2 = .12$), though no predictors themselves in the model were significant. Executive Control, group status, and their interaction did not explain a significant amount of the variance on mean partial Symmetry Span scores ($F(5.16,75) = 1.634$, $p < .19$, $R^2 = .06$, $R^2_{\text{Adjusted}} = .03$, $f^2 = .06$).

4.0 DISCUSSION

This study examined working memory capacity in adults who stutter and adults who do not stutter using complex span working memory tasks. Results indicated that participants who stutter exhibited working memory capacity differences as a function of word-form encoding influences, meaning that the word form activation requirements inherent in each of the three complex span tasks paralleled the working memory capacities of the group of people who stutter across the tasks. Specifically, the group of people who stutter were predicted to perform significantly lower on the OSPAN than were the group of people who not stutter. This difference represented a small to medium effect size. Though the group of people who stutter did not significantly increase their performance on the Rotation or Symmetry span tasks (with respect to their OSPAN performance), the increasing pattern of performance corresponds to the decreasing word-form encoding demands of those tasks (*most* word-form activation in OSPAN, *some* in the Rotation span task, *least* in the Symmetry Span task). Though this finding implicates word-form encoding as a meaningful difference in adults who stutter, the finding that the group of people who stutter also had significantly more difficulty maintaining the accuracy criterion on the concomitant task in each of the complex span tasks suggests that people who stutter may be more globally affected by concomitant attentional processing.

The finding that performance on working memory capacity measures (partial span scores) of the adults who stutter in this study paralleled the hierarchy of word-form activation inherent in the tasks (i.e., *highest* activation with OSPAN, *partial* or *weakly cascading* activation with Rotation Span, and *lowest* activation with Symmetry Span) is meaningful because it differentiates word-form encoding and working memory processes in adults who stutter. It is also meaningful because the word forms in the OSPAN were simple (single orthographic letters) as compared to more complex word forms (such as multisyllabic nonwords or more syntactically or semantically-complex word-forms commonly comprising connected speech). The finding that working memory capacity differences were found with simple word forms compared with more phonologically complex word-forms, such as nonwords, suggests that these word-form encoding differences do not exist only as a function of phonological complexity, as past research in stuttering has suggested (J. D. Anderson et al., 2006; see, J. D. Anderson & Wagovich, 2010; Byrd et al., 2012; Coalson & Byrd, 2017; Hakim & Ratner, 2004; Pelczarski & Yaruss, 2016; Sasisekaran & Weisberg, 2014; Spencer & Weber-Fox, 2014). The finding further specifies the growing evidence that people who stutter demonstrate word-form encoding differences. More compelling evidence that people who stutter have word-form encoding differences comes from tasks that fully activate word forms (e.g., phoneme monitoring, see Section 2.2.3.2) than tasks that only partially activate word forms (e.g., rhyme judgement, see Section 2.2.4.2). Thus, considering the task demands on word form activation lends support to the notion that people who stutter do have difficulty with word-form encoding.

Considering the inherent requirements of word-form encoding-related tasks also differentiates past research evidence in stuttering regarding word-form encoding and working memory. This differentiation between word-form encoding and working memory is meaningful to stuttering research because past research has often attempted to answer word-form encoding questions from the perspective of working memory (see section 2.2.4). For example, Weber-Fox et al. (2004) interpreted null EEG results from a rhyme judgment task (a task that activates the Phonological Loop in Baddeley's multi-component model) as evidence that adults who stutter do not have deficits with phonological encoding (one step in the word-form encoding process). The impetus for such work stems from Baddeley and colleagues' early work specifying the

Phonological Loop and the role it plays in language acquisition (Gathercole & Baddeley, 1993). Yet, Baddeley himself has more recently indicated that decades of research show that Phonological Loop processing is different from language formulation and speech production processes: “while the [phonological] loop has almost certainly evolved from mechanisms for speech perception and production, the fact that patients with grossly impaired phonological short term memory may have normal speech perception and production argues for a separate system…” (Baddeley, 2010, p. 139). Because there are data showing that individuals with severely impaired phonological working memory can and do have normal language formulation and speech production abilities (see case examples and discussion in Baddeley, 2012), phonological loop processing itself does not equate with language formulation and speech production processes (Baddeley, 2010), though phonological loop processes do play a role in language acquisition (for review, see Baddeley, 2003b). This distinction is meaningful to stuttering research because it implicates word-form encoding and not working memory as an important difference between individuals who stutter and individuals who do not stutter (see sections 2.2.3 and 2.2.4). This also further clarifies past stuttering research findings. More compelling results that people who stutter have word-form encoding differences have been found using tasks that activate word forms to higher degrees (e.g., phoneme monitoring, see Coalson & Byrd, 2015, 2018; Sasisekaran & Byrd, 2013; Sasisekaran & De Nil, 2006; Sasisekaran & Weber-Fox, 2012) as compared to tasks that partially activate word forms (e.g., rhyme judgment, see Bosshardt et al., 2002; Bosshardt & Fransen, 1996; Weber-Fox et al., 2004, 2008). Thus, in order to investigate word-form encoding abilities of people who stutter, the degree to which experimental tasks activate word forms must be considered. The traditional view in stuttering research that the later stages of word-form encoding, and in particular phonological encoding, rely “essentially on phonological loop operations” (Bajaj, 2007, p. 220) is not supported by psycholinguistic theory or the data in this study.

The data in this study were collected via dual-task paradigms that limit the contribution of domain-central attentional resources when domain-peripheral processing exceeded domain-peripheral abilities, to use the terminology of Cowan and colleagues (see section 2.1.1). The finding that adults who stutter demonstrated significantly decreased working memory capacity as a function of the influences of word-form encoding suggests that adults who stutter may need to recruit domain-central attentional resources *sooner* (due to domain-peripheral deficits in word-form encoding) than people who do not stutter in order to maintain accuracy, speed, and precision when formulating language. These findings suggest that the allocation of attention in cognitive-linguistic tasks is particularly important for determining cognitive-linguistic differences between people who stutter and people who do not stutter. The finding also helps to further specifying how moments of stuttering may ultimately be triggered: domain-central attentional resources might be further limited in people who stutter due to deficiencies in other peripheral domains, such as motor execution (see section 2.1.3).

The finding that Executive Control network efficiency scores in the group of people who stutter significantly predicted OSPAN performance (the task where subjects were required to most activate word-forms) highlights the possibility that adults who stutter may be more prone to dissociations in attentional processing when word-form encoding demands are present than are adults who do not stutter. Specifically, participants who stutter with higher Executive Control network efficiency were predicted to have higher capacity measures in the OSPAN, while participants who stutter with lower Executive Control network Efficiency were predicted to have lower capacity measures as measured by the OSPAN. Though this effect was not found with the

Rotation and Symmetry span performance, it is possible that participants who stutter did not need to recruit domain-central attentional resources to maintain accuracy and performance while performing the Rotation and Symmetry span tasks. In other words, because participants who stutter had the lowest working memory capacity scores on the OSPAN, it is likely that in this task alone were subjects more likely to recruit domain-central resources.

The findings in this study further specify theories into the origin of moments of stuttering. Many historical theories implicate differences in language formulation as the origin of stuttering behaviors—as errored input to the motor system (e.g., ExPlan, see Howell & Au-Yeung, 2002) or as the result of covert repairs of an errored linguistic plan (e.g., CRH, see Postma & Kolk, 1993). Research has largely failed to support portions of the central tenets of these theories; namely, that stuttering behaviors are the *direct* results of linguistic-motor mapping (ExPlan) or of errors of word-form encoding (CRH). Yet, data from this study support one underlying hypothesis of the both the CRH and the ExPlan, which suggest that people who stutter demonstrate word-form encoding differences/errors that may delay or impair motor execution. This can further specify the commonly accepted tenet that moments of stuttering occur when demands in linguistic, motoric, and emotional/temperamental factors are high (Adams, 1990; Neilson & Neilson, 1987; Smith & Weber, 2017; Starkweather & Gottwald, 1990). Data from this study suggest that the factor influencing the occurrence of moments of stuttering may not be increased system-wide demands. Rather, moments of stuttering might occur when domain-central attentional allocation cannot supplement the demands of a *domain-peripheral system* (e.g., language formulation) that is prone to inefficiency and breakdown (see section 2.1.2 for discussion of enhancement). Such a view is supported by the experiences and reports of people who stutter. Tichenor & Yaruss (2018, 2019c) described that, to people who stutter, the *direct* result of attempting to speak is experienced not as prototypical stuttering (or stutter-like) behaviors (e.g., prolongations, repetitions, or blocks), but as the sensation of being out of control or feeling stuck. The loss of control as experienced by people who stutter may result from underlying attentional allocation deficiencies in the interaction of processes that sub-serve speech formulation and language production. Word-form encoding differences may be one possible contributing factor to the loss of control.

4.1 DETANGLING INDIVIDUAL DIFFERENCES AND VARIABILITY IN STUTTERING BEHAVIORS

Individual differences in attentional processing, combined with moment-by-moment demands, may help to explain why there are individual differences in how often moments of stuttering occur and why moments of stuttering are variable. Stuttering behaviors have long been observed to be highly variable in time and place (Constantino et al., 2016; Johnson et al., 2009; Starkweather, 1987; Van Riper, 1982). Constantino et al (2016) systematically documented wide ranges in stuttering frequency, duration, and physical concomitants over days and weeks in multiple subjects. This long-observed variability of stuttering behaviors is both frustrating to individuals who stutter and theoretically meaningful (Tichenor & Yaruss, 2018). The data and theory discussed in this study suggest that stuttering behaviors may not be variable per se, but occur when domain-peripheral processing cannot be supplemented with domain-central attentional resources. By accounting for the ways specific individuals who stutter allocate attention in a moment-by-moment basis, moments of stuttering may be predicted and variability may be explained via limitations in attentional processing.

Limitations in domain central attentional resources can occur in numerous ways. For example, personal speaking goals and preferences have been shown to influence whether a person who stutters chooses to hide or mask moments of stuttering from occurring (Constantino et al., 2017; Constantino & Manning, 2015; Tichenor & Yaruss, 2019a). As such, a person who has a lower tolerance for errors or mistakes in language formulation or speech production may set unrealistic or unattainable thresholds for language formulation or speech production, as some researchers have hypothesized. For example, Brocklehurst, Lickley, and Corley (2013) described the Variable Release Threshold Hypothesis (VRT) which states that moments of stuttering occur when people who stutter set unrealistically high targets for the release of linguistic information to the motor system for execution. These unrealistically high targets occur due to past negative experiences with stuttering. Under such constraints, the word-form encoding system would require more enhancement (attentional allocation) of the intended-to-speak word form in order for it to be translated to the motor system for execution (Roelofs, 2008c; 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. Data from this study support such a possibility: participants who stutter who exhibited lower Executive Control network efficiency scores demonstrated significantly lower OSPAN partial span scores compared to participants who stutter who exhibited higher Executive Control network efficiency scores. This may indicate that people who stutter with lower Executive Control network efficiency were not be able to supplement domain peripheral processing demands in word-form encoding to the same degree as people with higher efficiency Executive Control networks. Thus, individual differences in Executive Control network efficiency may predispose some people who stutter to more frequent moments of stuttering than others by virtue of deficiencies in the ability to inhibit distractors in attention.

There are several theoretically and clinically relevant ways that limitations in domain-central attentional resources can occur on a moment-by-moment basis that may explain the variability in moments of stuttering individuals experience. In daily life, concomitant processing demands fluctuate moment-by-moment and situation-to-situation. Such increases in moment-by-moment concomitant processing demands may limit the pool of domain-central attentional resources, leading to an increased occurrence of breakdowns in language formulation and speech production that may lead to moments of stuttering. There are limits to how many central attentional resources can supplement domain-peripheral performance when task demands are high in multiple areas (see section 2.1.1). For example, Cowan, Saults, and Blume (2014) determined that when a person attempts to maintain verbal and visual information in an active state, working memory capacity is significantly decreased compared to the situation in which a person is required to maintain only verbal or visual information in an active state. Thus, concomitant processing may increase competition for domain-central attentional resources when multiple peripheral demands require them. This has implications for explaining why moments of stuttering are variable in time and across situation. Attentional demands are fluid, ever-changing, and situationally specific. Though a specific person who stutters may have trait characteristics that predispose them to deficiencies in attentional allocation (e.g., more frequently engaging in RNT, a lower Executive Control network efficiency, etc.), situation specific demands may limit domain central attentional resources when speaking requires them. Thus, the long-observed variable nature of moments of stuttering may be the observed down-stream result of both individual differences (e.g., word-form encoding, Executive Network efficiency, etc.) and traits that develop due to experiences in life (e.g., adverse stuttering impact, Repetitive Negative Thinking, etc.).

4.2 FUTURE DIRECTIONS

The possibility that word-form encoding may be a natively impaired process in people who stutter has further implications for research into speech production differences. The word-form encoding process is a critical and necessary step in speech production—where linguistic information serves as an input to the motor system (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 errorless (Posner, 1967; Schmidt, 1975; Tourville & Guenther, 2011). Researchers have theorized that children and adults who stutter may not develop the necessary internal models for fluent speech production (Max, Guenther, et al., 2004), which makes them more reliant on feedback control (Civier et al., 2010). Data from the present study highlight word-form encoding differences one potential cause of this inability to develop well-formed internal models and subsequent reliance on feedback control. In other words, the effect of a word-form encoding system that is less efficient would naturally result in linguistic output that is more slowly translated to the motor system for execution. The result of ambiguous input to a motor system may predispose it to both developing less well-formed internal models and, subsequently, relying more on feedback control.

Current models of speech motor control (The Dual Stream Model, see Hickok & Poeppel, 2007, 2016; Directions into Velocities of Articulators, see Tourville & Guenther, 2011) and language formulation (WEAVER++, Levelt et al., 1999; Roelofs, 1997, 2015) are well-specified and have resulted in a better understanding of speech production and language formulation (for review, see Hickok, 2014; Roelofs & Ferreira, 2019). Yet, the transition of linguistic information to speech production can be more specified in both literatures. Underspecifying this interaction results in researchers in both domains oversimplifying psycholinguistic or speech motor constructs. For example, Hickock (2014) has recently argued for the direct mapping of lemmas to motor programs, despite the fact that WEAVER++ models the input of motor actions as a phonological word comprising syllables and appropriate stress patterns (Roelofs, 2015). In a like manner, so too is WEAVER++ unable to account for motor control constructs, such as feedforward/feedback motor control (see Tourville & Guenther, 2011). Critical questions regarding the origin of stuttering require further specification of this interaction. A better understanding may depend on future research on language formulation and speech motor control to improve existing models to better specify the interaction of both domains.

Research evidence outside of stuttering has shown that other concomitant cognitive processes, such as rumination or Repetitive Negative Thinking (RNT), come at a cost to attentional allocation (Hubbard, Hutchison, Turner, et al., 2016). Hubbard et al (2016) used the Reading Span task and a second modified version of the Reading Span (one that encouraged RNT to occur) to explore working memory capacity in individuals with dysphoria—a condition where it is common to engage in RNT. The authors found that, as a group, people with and without dysphoria did not have significantly different working memory capacities; but, when engaged in the modified Reading Span task (a task that encouraged RNT), participants with dysphoria showed significantly decreased working memory capacities. The authors interpreted this as evidence that depressive thoughts come at a cost to working memory capacity, which can be reduced in situations where individuals who are prone to such thoughts attend to them repetitively (i.e., RNT). Research evidence has shown that many people who stutter who are negatively impacted (see, Tichenor & Yaruss, 2019c; Yaruss & Quesal, 2004) also engage more frequently in RNT (Tichenor & Yaruss, 2019b). Because data from this study show that individuals who stutter demonstrate working memory capacity differences when word-form encoding is required, individuals who are more negatively impacted and engage in higher levels of RNT may also be predisposed to limitations in domain central attentional resources and, as a result, more frequent moments of stuttering. Though RNT was not a significant predictor of working memory capacity in this study, it is likely that the OSPAN, Rotation Span, and Symmetry Span did not engage RNT. Further research should replicate the study by Hubbard et al (2016) with people who stutter to determine the effect of RNT on working memory capacity for how a person copes with the stuttering condition may predispose them to breakdowns in language formulation and speech production.

The Executive Control network has historically been considered to be responsible for resolving conflict (Eggers et al., 2012; Posner & Petersen, 1990a), though more recent research evidence has shown that the Executive Control network may be comprised of multiple networks focused on different mechanisms of top-down control, conflict resolution on responses, emotional control, and the development of self-regulation (for review, see Petersen & Posner, 2012; Posner & Petersen, 1990a). The Executive Control network also has an anatomical basis involving the anterior cingulate gyrus, anterior insula, parts of the prefrontal cortex, and basal ganglia (Posner & Fan, 2008). Because data from this study suggest that the group of adults who stutter significantly differ in the efficiency of the Executive Control networks compared to adults who do not stutter, the efficiency of the Executive Control network in adults who stutter may be innately compromised. Such a possibility is supported by recent research evidence showing that children who stutter demonstrate significantly lower Orienting network efficiency compared to children who do not stutter (Eggers et al., 2012). Growing research outside of stuttering suggests that children transition from relying primarily upon the Orienting network in infancy and preschool years to Executive Control as they age (Petersen & Posner, 2012; Posner et al., 2012). Importantly, this age period is also when stuttering most often develops (Yairi & Ambrose, 1999). Thus, the occurrence of stuttering in children may be closely linked to a delay in shifting from predominately relying on the Orienting network to the Executive Control network. Future research should explore this potential relationship by examining the development of attentional control in children who stutter.

Lastly, growing research evidence is implicating Effortful Control profiles (see, Evans & Rothbart, 2007) as an important individual difference marker in how someone experiences stuttering (Kraft et al., 2014; Tichenor & Yaruss, 2019b). Effortful Control is "the ability to inhibit a dominant response to perform a subdominant response, to detect errors, and to engage in planning" (Rothbart & Rueda, 2005, p. 3). Though Effortful Control did not significantly predict mean OSPAN scores in this study (p = .08), future research into Effortful Control and Executive Control is needed because they are closely related and overlapping constructs (for review, see Petersen & Posner, 2012). Individuals with higher levels of Effortful Control can "more flexibly approach situations they fear and inhibit actions they desire" (Rothbart & Rueda, 2005, p. 3). Furthermore, Effortful Control and Executive Control directly relate to another important construct in childhood stuttering; namely, Emotional Regulation (Rothbart & Rueda, 2005). Effortful Control directly depends on Emotional Regulation, which has been implicated in a number of growing studies with children who stutter in both predicting children who will recovery from children who do not recover from stuttering (Johnson et al., 2010; Karrass et al., 2006; Ntourou et al., 2013), and in predicting stuttering severity (Arnold et al., 2011). Thus, future research should explore the development of Effortful Control and Executive Control through the lens of Emotional Regulation in children who stutter because all may predict how a person reacts to being out of control or stuck during moments of stuttering (see, Tichenor & Yaruss, 2019a, 2019c).

4.3 LIMITATIONS

The strengths of this study highlight limitations that should be considered. Subjects in this study were similar in terms of age, sex ratio, and education (See Table 1). Yet, both groups of people who stutter and people who do not stutter were mostly young, educated, Caucasian, and from the United States of America. Future research should explore these working memory capacity tasks in groups of people who stutter from more diverse backgrounds. Furthermore, results in this study come from 42 adults who stutter and 40 who do not stutter. Given the power analysis (see section 3.1), the study may have been underpowered to detect the actual differences that may exist in the population. Though significant differences were found between predicted OSPAN scores between people who stutter and people who do not and the effect size was small-to-medium, a larger sample of subjects may find a larger effect size for this apparent difference. Future research should expand these findings in this study with more subjects. Lastly, because data in this study come from adults at a single point in time, future research should expand these findings to ascertain whether they apply to children who stutter. At present, it is unclear how working memory differences may exist developmentally or whether children who stutter may also demonstrate working memory deficits as a function of word-form encoding influences. Lastly, care should be taken in applying these working memory capacity differences across the tasks to different tasks or conditions. For example, the word forms in the OSPAN are simple orthographic letters. More realistic and complex word forms may decrease working memory capacity to greater degrees than was found in this study.

4.4 SUMMARY

This study provides data further specifying previously observed working memory differences in adults who stutter. Because the working memory capacities paralleled the hierarchy of word-form activation across the complex span tasks, the data suggest that adults who stutter demonstrate working memory deficits as a function of word-form encoding influences. Because this effect was found with relatively simple word-forms (i.e., single orthographic letters), the data show that working memory differences in adults who stutter do not only exist as a function of linguistic complexity, as past research has suggested. Executive Control network efficiency also significantly predicted mean partial score in the OSPAN (the task with the highest word-form encoding influences), meaning that people who stutter who have slower reaction times (lower efficiency) in Executive Control demonstrated lower mean OSPAN partial scores while people who stutter with faster reaction times (higher efficiency) in Executive Control demonstrated higher mean OSPAN partial scores. The complex span tasks in this study were dual-tasks that limited the contribution of domain central attentional resources when/if needed. Thus, the data suggest that moments of stuttering may occur when domain-peripheral processing (e.g., word-form encoding) cannot be supplemented with domain-central domain attentional resources (e.g., Executive Control). This finding further specifies past and more recent theories regarding the origins of moments of stuttering, while also helping to explain individual differences both between and within people who stutter.

REFERENCES

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., Pellowski, M. W., Conture, E. G., & Kelly, E. (2003). Temperamental Characteristics of Young Children Who Stutter. *Journal of Speech Language and Hearing Research*, *46*(5), 1221. https://doi.org/10.1044/1092-4388(2003/095)

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.

Anderson, M. C., & Levy, B. J. (2009). Suppressing unwanted memories. *Current Directions in Psychological Science*, *18*(4), 189–194. https://doi.org/10.1111/j.1467-8721.2009.01634.x

Arnold, H. S., Conture, E. G., Key, A. P. F., & Walden, T. (2011). Emotional reactivity, regulation and childhood stuttering: A behavioral and electrophysiological study. *Journal of Communication Disorders*, *44*(3), 276–293. https://doi.org/10.1016/j.jcomdis.2010.12.003

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. (2003a). Working memory: looking back and looking forward. *Nature Reviews Neuroscience*, *4*(10), 829–839. https://doi.org/10.1038/nrn1201

Baddeley, A. (2003b). Working memory and language: An overview. *Journal of Communication Disorders*, *36*(3), 189–208. https://doi.org/10.1016/S0021-9924(03)00019-4

Baddeley, A. (2007). *Working Memory, Thought, and Action*. Oxford University Press.

Baddeley, A. (2010). Working memory. *Current Biology*, *20*(4), R136-40. https://doi.org/10.1016/j.cub.2009.12.014

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.

Bates, D., Maechler, M., Bolker, B., & Walker, S. (2014). lme4: Linear mixed-effects models using Eigen and S4. *R Package Version*, *1*(7).

Bloodstein, & Bernstein Ratner, N. (2008). *A handbook on stuttering* (6th ed.). Thomson/Delmar Learning.

Bohland, J. W., Bullock, D., & Guenther, F. H. (2010). Neural representations and mechanisms for the performance of simple speech sequences. *Journal of Cognitive Neuroscience*, *22*(7), 1504–1529. https://doi.org/10.1162/jocn.2009.21306

Bomyea, J., & Amir, N. (2011). The effect of an executive functioning training program on working memory capacity and intrusive thoughts. *Cognitive Therapy and Research*, *35*(6), 529–535. https://doi.org/10.1007/s10608-011-9369-8

Bosshardt, H. G. (1999). Effects of concurrent mental calculation on stuttering, inhalation and speech timing. *Journal of Fluency Disorders*, *24*(1), 43–72.

Bosshardt, H. G. (2002). Effects of concurrent cognitive processing on the fluency of word repetition: Comparison between persons who do and do not stutter. *Journal of Fluency Disorders*, *27*(2), 93–114. https://doi.org/10.1016/S0094-730X(02)00113-4

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

Bosshardt, H. G., Ballmer, W., & De Nil, L. F. (2002). Effects of Category and Rhyme Decisions on Sentence Production. *Journal of Speech, Language, and Hearing Research*, *45*, 844–857.

Bosshardt, H. G., & Fransen, H. (1996). Online sentence processing in adults who stutter and adults who do not stutter. *Journal of Speech and Hearing Research American Speech-Language-Hearing Association*, *39*(August), 785–797. https://doi.org/10.1044/jshr.3904.785

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.

Browman, C. P., & Goldstein, L. (1989). Articulatory gestures as phonological units. *Phonology*, *6*(2), 201. https://doi.org/10.1017/S0952675700001019

Browman, C. P., & Goldstein, L. (1992). Articulatory Phonology: An Overview. *Phonetica*, *49*(3–4), 155–180.

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

Brutten, G. J., & Trotter, A. C. (1985). Hemispheric interference: A dual-task investigation of youngsters who stutter. *Journal of Fluency Disorders*, *10*(2), 77–85. https://doi.org/10.1016/0094-730X(85)90016-6

Brutten, G. J., & Trotter, A. C. (1986). A dual-task investigation of young stutterers and nonstutterers. *Journal of Fluency Disorders*, *11*(4), 275–284. https://doi.org/10.1016/0094-730X(86)90015-X

Brysbaert, M., & Stevens, M. (2018). Power Analysis and Effect Size in Mixed Effects Models : A Tutorial. *Journal of Cognition*, *1*(1), 1–20.

Burger, R., & Wijnen, F. (1999). Phonological encoding and word stress in stuttering and nonstuttering subjects. *Journal of Fluency Disorders*, *24*(2), 91–106. https://doi.org/10.1016/S0094-730X(98)00028-X

Byrd, C. T., Coalson, G. A., Yang, J., & Moriarty, K. (2017). The effect of phonetic complexity on the speed of single-word productions in adults who do and do not stutter. *Journal of Communication Disorders*, *69*(June), 94–105. https://doi.org/10.1016/j.jcomdis.2017.06.009

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., 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.

Caplan, D. (1999). Working Memory and Sentence Comprehension. *Neurobiology of Language*, *1999*, 633–645. https://doi.org/10.1080/00103629409369211

Caruso, A. J., Conture, E. G., & Colton, R. H. (1988). Selected temporal parameters of coordination associated with stuttering in children. *Journal of Fluency Disorders*, *13*(1), 57–82. https://doi.org/10.1016/0094-730X(88)90028-9

Chang, S.-E., Angstadt, M., Chow, H. M., Etchell, A. C., Garnett, E. O., Choo, A. L., Kessler, D., Welsh, R. C., & Sripada, C. (2018). Anomalous network architecture of the resting brain in children who stutter. *Journal of Fluency Disorders*.

Charles-Luce, J., & Luce, P. A. (1990). Similarity neighborhoods of words in young children's lexicons. *Journal of Child Language*, *17*(1990), 205-215 ST-Similarity neighborhoods of words in.

Civier, O., Bullock, D., Max, L., & Guenther, F. H. (2013). Computational modeling of stuttering caused by impairments in a basal ganglia thalamo-cortical circuit involved in syllable selection and initiation. *Brain and Language*, *126*(3), 263–278.

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. (2016). Phonetic complexity of words immediately following utterance-initial productions in children who stutter. *Journal of Fluency Disorders*, *47*, 56–69. https://doi.org/10.1016/j.jfludis.2015.10.002

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

Coalson, G. A., Byrd, C. T., & Davis, B. L. (2012). The influence of phonetic complexity on stuttered speech. *Clinical Linguistics & Phonetics*, *26*(7), 646–659. https://doi.org/10.3109/02699206.2012.682696

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., Leslie, P., Quesal, R. W., & 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

Constantino, C., & Manning, W. H. (2015). Beyond Stuttering and Fluency: the Possibilyt of Spontaneous Speech. In *American Speech Language and Hearing Association*.

Constantino, C., Manning, W. H., & Nordstrom, S. N. (2017). Rethinking covert stuttering. *Journal of Fluency Disorders*, *53*, 26–40. https://doi.org/10.1016/j.jfludis.2017.06.00

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

Conty, L., Gimmig, D., Belletier, C., George, N., & Huguet, P. (2010). The cost of being watched: Stroop interference increases under concomitant eye contact. *Cognition*, *115*(1), 133–139. https://doi.org/10.1016/j.cognition.2009.12.005

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. (1988). Evolving Conceptions of Memory Storage, Selective Attention, And Their Mutual Constraints Within the Human Information-Processing System. *Psychological Bulletin*, *104*(2), 163–191. https://doi.org/10.1037/0033-2909.104.2.163

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. (2005). *Working Memory Capacity*. Psychology Press. https://doi.org/10.4324/9780203342398

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

Curci, A., Lanciano, T., Soleti, E., & Rimé, B. (2013). Negative emotional experiences arouse rumination and affect working memory capacity. *Emotion*, *13*(5), 867–880. https://doi.org/10.1037/a0032492

Curlee, R. F. (2000). Demands and capacities or demands and performance? *Journal of Fluency Disorders*, *25*, 329–336. https://doi.org/10.1016/S0094-730X(00)00081-4

Daneman, M. (1991). Working Memory as a Predictor of Verbal Fluency. *Journal of Psycholinguistic Research*, *20*(6), 445–464.

Daneman, M., & Carpenter, P. (1980). Individual Differences in Working Memory and Reading. *Journal of Verbal Learning and Verbal Behavior*, *19*, 450–466.

de Sonneville-Koedoot, C., Stolk, E., Rietveld, T., & Franken, M.-C. (2015). Direct versus Indirect Treatment for Preschool Children who Stutter: The RESTART Randomized Trial. *Plos One*, *10*(7), e0133758. https://doi.org/10.1371/journal.pone.0133758

Dell, G. S. (1986). A spreading-activation theory of retrieval in sentence production. *Psychological Review*, *93*(3), 283.

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

Doherty, J. M., & Logie, R. H. (2016). Resource-sharing in multiple-component working memory. *Memory and Cognition*, *44*(8), 1157–1167. https://doi.org/10.3758/s13421-016-0626-7

Dollaghan, C., & Campbell, T. F. (1998). Nonword Repetition and Child Language Impairment. *JSLHR Journal of Speech, Language, and Hearing Research JSLHR Journal of Speech, Language, and Hearing Research American Speech-Language-Hearing Association*, *41*(5), 1136–1146. https://doi.org/10.1044/jslhr.4105.1136

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

Eggers, K., De Nil, L. F., & Bergh, B. R. H. V. den. (2010). Temperament dimensions in stuttering and typically developing children. *Journal of Fluency Disorders*, *35*(4), 355–372. https://doi.org/10.1016/j.jfludis.2010.10.004

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)

Eggers, K., & Jansson-Verkasalo, E. (2017). Auditory Attentional Set-Shifting and Inhibition in Children Who Stutter. *Journal of Speech Language and Hearing Research*, *60*(11), 3159. https://doi.org/10.1044/2017_JSLHR-S-16-0096

Ehring, T., Zetsche, U., Weidacker, K., Wahl, K., Schönfeld, S., & Ehlers, A. (2011). The Perseverative Thinking Questionnaire (PTQ): Validation of a content-independent measure of repetitive negative thinking. *Journal of Behavior Therapy and Experimental Psychiatry*, *42*(2), 225–232. https://doi.org/10.1016/j.jbtep.2010.12.003

Eichorn, N., Marton, K., Schwartz, R. G., Melara, R. D., & Pirutinsky, S. (2016). Does Working Memory Enahnce or Interfere with Speech Fluency in Adults who Do and Do Not Stutter? Evidence from a Dual-Task Paradigm. *Journal of Speech, Language, and Hearing Research*, *59*, 415–429.

Embrechts, M., Ebben, H., Franke, P., & Van De Poel, C. (2000). Temperament: A comparison between chidlren who stutter and children who do not stutter. In H. G. Bosshardt, J. S. Yaruss, & H. F. M. Peters (Eds.), *Proceedings of the 3rd world congress on fluency disorders* (pp. 557–562). Nimegan 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.

Evans, D. E., & Rothbart, M. K. (2007). Developing a model for adult temperament. *Journal of Research in Personality*, *41*(4), 868–888. https://doi.org/10.1016/j.jrp.2006.11.002

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.

Felsenfeld, S., Van Beijsterveldt, C. E. M., & Boomsma, D. I. (2010). Attentional Regulation in Young Twins With Probable Stuttering, High Nonfluency, and Typical Fluency. *Journal of Speech Language and Hearing Research*, *53*(5), 1147. https://doi.org/10.1044/1092-4388(2010/09-0164)

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.

Gathercole, S. E., Willis, C. S., Baddeley, A. D., & Emslie, H. (1994). The Children's Test of Nonword Repetition: A Test of Phonological Working Memory. *Memory*, *2*(2), 103–127. https://doi.org/10.1080/09658219408258940

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

Greiner, J. R., Fitzgerald, H. E., & Cooke, P. A. (1986). Speech fluency and hand performance on a sequential tapping task in left- and right-handed stutterers and nonstutterers. *Journal of Fluency Disorders*, *11*(1), 55–69. https://doi.org/10.1016/0094-730X(86)90004-5

Guenther, F. H. (1994). A Neural Network Model Of Speech Acquisition And Motor Equivalent Speech Production Running title: Speech acquisition and motor equivalence. *Biological Cybernetics*, *72*, 43–53. https://doi.org/10.1007/BF00206237

Guenther, F. H., Ghosh, S. S., & Tourville, J. A. (2006). Neural modeling and imaging of the cortical interactions underlying syllable production. *Brain and Language*, *96*(3), 280–301.

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

Hampton, A., & Weber-Fox, C. (2008). Non-linguistic auditory processing in stuttering: Evidence from behavior and event-related brain potentials. *Journal of Fluency Disorders*, *33*(4), 253–273. https://doi.org/10.1016/j.jfludis.2008.08.001

Hartsuiker, R. J., & Barkhuysen, P. N. (2006). Language production and working memory: The case of subject-verb agreement. *Language and Cognitive Processes*, *21*(1–3), 181–204. https://doi.org/10.1080/01690960400002117

Hickok, G. (2014). The architecture of speech production and the role of the phoneme in speech processing. *Language, Cognition and Neuroscience*, *29*(1), 2–20.

Hickok, G., & Poeppel, D. (2004). Dorsal and ventral streams: a framework for understanding aspects of the functional anatomy of language. *Cognition*, *92*(1), 67–99.

Hickok, G., & Poeppel, D. (2007). The cortical organization of speech processing. *Nature Reviews Neuroscience*, *8*(5), 393–402.

Hickok, G., & Poeppel, D. (2016). Neural Basis of Speech Perception. In *Neurobiology of Language*. Elsevier Inc. https://doi.org/10.1016/B978-0-12-407794-2.00025-0

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. (2016). 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

Indefrey, P., & Levelt, W. J. M. (2000). The Neural Correlates of Language Production. In M. Gazzaniga (Ed.), *The new cognitive neurosciences* (pp. 845–865). MIT press.

Indefrey, P., & Levelt, W. J. M. (2004). The spatial and temporal signatures of word production components. *Cognition*, *92*(1), 101–144.

Jackson, E., Tiede, M., Beal, D., & Whalen, D. H. (2016). The Impact of Social–Cognitive Stress on Speech Variability, Determinism, and Stability in Adults Who Do and Do Not Stutter. *Journal of Speech, Language, and Hearing Research*, *59*(6), 1295–1314.

Jacobs, C. L., & Dell, G. S. (2014). 'Hotdog', not 'hot' 'dog': The phonological planning of compound words. *Language, Cognition and Neuroscience*, *29*(4), 512–523. https://doi.org/10.1080/23273798.2014.892144

Janssen, P., Roelofs, A., & Levelt, W. J. M. (2002). Inflectional frames in langauge production. *Language & Cognitive Processes*, *17*(6), 569–591.

Johnson, K. A., Karrass, J., Conture, E. G., & Walden, T. (2009). Influence of stuttering variation on talker group classification in preschool children: Preliminary findings. *Journal of Communication Disorders*, *42*(3), 195–210. https://doi.org/10.1016/j.jcomdis.2008.12.001

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

Johnson, K. A., Walden, T. A., Conture, E. G., & Karrass, J. (2010). Spontaneous reuglation of emtions in preschool children who stutter: preliminary findings. *Journal of Speech, Language, and Hearing Research*, *53*, 1478–1495.

Jones, R., Fox, R. A., & Jacewicz, E. (2012). The Effects of Concurrent Cognitive Load on Phonological Processing in Adults who Stutter. *Journal of Speech, Language, and Hearing Research: JSLHR*, *55*, 1862–1865.

Jongman, S. R., Roelofs, A., & Meyer, A. S. (2015). Sustained attention in language production: An individual differences investigation. *Quarterly Journal of Experimental Psychology*, *68*(4), 710–730. https://doi.org/10.1080/17470218.2014.964736

Joormann, J., Levens, S. M., & Gotlib, I. H. (2011). Sticky thoughts: Depression and rumination are associated with difficulties manipulating emotional material in working memory. *Psychological Science*, *22*(8), 979–983. https://doi.org/10.1177/0956797611415539

Kaganovich, N., Hampton Wray, A., & Weber-Fox, C. (2010). Non-linguistic auditory processing and working memory update in pre-school children who stutter: An electrophysiological study. *Developmental Neuropsychology*, *35*(6), 712–736. https://doi.org/10.1080/87565641.2010.508549

Kajimura, S., & Nomura, M. (2016). When we cannot speak: Eye contact disrupts resources available to cognitive control processes during verb generation. *Cognition*, *157*, 352–357. https://doi.org/10.1016/j.cognition.2016.10.002

Kal, E. C., Van Der Kamp, J., & Houdijk, H. (2013). External attentional focus enhances movement automatization: A comprehensive test of the constrained action hypothesis. *Human Movement Science*, *32*(4), 527–539. https://doi.org/10.1016/j.humov.2013.04.001

Karrass, J., Walden, T. A., Conture, E. G., Graham, C. G., Arnold, H. S., Hartfield, K. N., & Schwenk, K. A. (2006). Relation of emotional reactivity and regulation to childhood stuttering. *Journal of Communication Disorders*, *39*(6), 402–423. https://doi.org/10.1016/j.jcomdis.2005.12.004

Kelly, E. (2000). Modeling stuttering etiology: Clarifying levels of description and measurement. *Journal of Fluency Disorders*, *25*(4), 359–368. https://doi.org/10.1016/S0094-730X(00)00085-1

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

Kemper, S., Schmalzried, R., Herman, R., Leedahl, S., & Mohankumar, D. (2009). The effects of aging and dual task demands on language production. *Aging, Neuropsychology, and Cognition*, *16*(3), 241–259. https://doi.org/10.1080/13825580802438868

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.

Kraft, S. J., Ambrose, N., & Chon, H. (2014). Temperament and environmental contributions to stuttering severity in children: The role of Effortful Control. *Seminars in Speech and Language*, *35*(2), 80–94. https://doi.org/10.1055/s-0034-1371753

Kreidler, K., Hampton Wray, A., Usler, E., & Weber, C. (2017). Neural Indices of Semantic Processing in Early Childhood Distinguish Eventual Stuttering Persistence and Recovery. *J Speech Lang Hear Res*, *60*(11), 3118–3134. http://dx.doi.org/10.1044/2017_JSLHR-S-17-0081

Levelt, W. J. M. (1983). Monitoring and self-repair in speech. *Cognition*, *14*(1), 41–104.

Levelt, W. J. M. (1989). Speaking: From intention to articulation. *MA: The MIT Press, Cambridge*.

Levelt, W. J. M. (2001). Spoken word production: A theory of lexical access. *Proceedings of the National Academy of Sciences*, *98*(23), 13464–13471. https://doi.org/10.1073/pnas.231459498

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.

Levens, S. M., Muhtadie, L., & Gotlib, I. H. (2009). Rumination and Impaired Resource Allocation in Depression. *Journal of Abnormal Psychology*, *118*(4), 757–766. https://doi.org/10.1037/a0017206

Lewis, R. L., Vasishth, S., & Van Dyke, J. A. (2006). Computational principles of working memory in sentence comprehension. *Trends in Cognitive Sciences*, *10*(10), 447–454. https://doi.org/10.1016/j.tics.2006.08.007

Logie, R. H. (2011). The Functional Organization and Capacity Limits of Working Memory. *Current Directions in Psychological Science*, *20*(4), 240–245. https://doi.org/10.1177/0963721411415340

Logie, R. H. (2016). Retiring the central executive. *Quarterly Journal of Experimental Psychology*, *69*(10), 2093–2109. https://doi.org/10.1080/17470218.2015.1136657

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

Ludlow, C. L., & Loucks, T. (2003). Stuttering: a dynamic motor control disorder. *Journal of Fluency Disorders*, *28*, 273–295.

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

Manning, W. H. (2000a). SPECIAL SECTION THE DEMANDS AND CAPACITIES MODEL. *Journal of Fluency Disorders*, *25*, 317–319.

Manning, W. H. (2000b). The Demands and Capacities Model. *Journal of Fluency Disorders*, *25*, 377–383.

Markson, L., & Paterson, K. B. (2009). Effects of gaze-aversion on visual-spatial imagination. *British Journal of Psychology*, *100*(3), 553–563. https://doi.org/10.1348/000712608X371762

Martin, R. C., & Slevc, L. R. (2014). Language Production and Working Memory. *The Oxford Handbook of Language Production*, *June*, 1–33. https://doi.org/10.1093/oxfordhb/9780199735471.013.009

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.

Max, L., Maassen, B., Kent, R., Peters, H. F., Van Lieshout, P., & Hulstijin, W. (2004). Stuttering and internal models for sensorimotor control: A theoretical perspective to generate testable hypotheses. *Speech Motor Control in Normal and Disordered Speech*, 357–387.

Maxfield, N. D. (2017). Semantic and Phonological Encoding Times in Adults Who Stutter: Brain Electrophysiological Evidence. *Journal of Speech Language Hearing and Research*, 1–18.

Maxfield, N. D., Huffman, J. L., Frisch, S. A., & Hinckley, J. J. (2010). Neural correlates of semantic activation spreading on the path to picture naming in adults who stutter. *Clinical Neurophysiology*, *121*(9), 1447–1463. https://doi.org/10.1016/j.clinph.2010.03.026

Maxfield, N. D., Morris, K., Frisch, S. A., Morphew, K., & Constantine, J. (2015). Real-time processing in picture namign in adults who stutter: ERP Evidence. *Clinical Neurophysiology*, *126*(2). https://doi.org/10.1038/nrm2621

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

Maxfield, N. D., Pizon-Moore, A., Frisch, S. A., & Constantine, J. (2013). Exploring semantic and phonological picture-word priming in adults who stutter using event-related potentials. *Clinical Neurophysiology*, *70*(4), 646–656. https://doi.org/10.1002/ana.22528.

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

McElree, B., Foraker, S., & Dyer, L. (2003). Memory structures that subserve sentence comprehension. *Journal of Memory and Language*, *48*, 67–91.

Melnick, K. S., Conture, E. G., & Ohde, R. N. (2003). Phonological priming in picture naming of young children who stutter. *Journal of Speech Language and Hearing Research*, *46*(December), 1428–1443. https://doi.org/10.1044/1092-4388(2003/111)

Melnick, K. S., Conture, E. G., & Ohde, R. N. (2005). Phonological Encoding in Young Children Who Stutter. In R. J. Hartsuiker, R. Bastiaanse, A. Postma, & F. Wijnen (Eds.), *Phonological encoding and monitoring in normal and pathological speech* (pp. 102–115). Psychology Press.

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

Munding, D., Dubarry, A. S., & Alario, F. X. (2016). On the cortical dynamics of word production: a review of the MEG evidence. *Language, Cognition and Neuroscience*, *31*(4), 441–462. https://doi.org/10.1080/23273798.2015.1071857

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

Ntourou, K., Conture, E. G., & Walden, T. A. (2013). Emotional reactivity and regulation in preschool-age children who stutter. *Journal of Fluency Disorders*, *38*(3), 260–274. https://doi.org/10.1016/j.jfludis.2013.06.002

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.

Oswald, F. L., McAbee, S. T., Redick, T. S., & Hambrick, D. Z. (2014). The development of a short domain-general measure of working memory capacity. *Behavior Research Methods*, *47*(4), 1343–1355. https://doi.org/10.3758/s13428-014-0543-2

Owens, M., Koster, E. H. W., & Derakshan, N. (2012). Impaired filtering of irrelevant information in dysphoria: An ERP study. *Social Cognitive and Affective Neuroscience*, *7*(7), 752–763. https://doi.org/10.1093/scan/nsr050

Oyler, M. E. (1994). *Vulnerability in Stuttering Children*. University of Colorado.

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. (2014). Phonological encoding of young children who stutter. *Journal of Fluency Disorders*, *39*, 12–24.

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

Perkell, J. S., Guenther, F. H., Lane, H., Matthies, M. L., Perrier, P., Vick, J., Wilhelms-Tricarico, R., & Zandipour, M. (2000). A theory of speech motor control and supporting data from speakers with normal hearing and with profound hearing loss. *Journal of Phonetics*, *28*(3), 233–272. https://doi.org/10.1006/jpho.2000.0116

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 * Each reproduced movement was Interval .— The effect of recall in- terval was analyzed separately for each condition and interpolated task . The. *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., & Fan, J. (2008). Attention as an organ system. In J. Pomerantz (Ed.), *Topics in Integrative Neuroscience.* (pp. 31–61). Cambridge University Press.

Posner, M. I., & Petersen, S. (1990a). The attention system of the human brain. *Annual Review of Neuroscience*, *13*, 25–42. https://doi.org/10.1146/annurev.ne.13.030190.000325

Posner, M. I., & Petersen, S. E. (1990b). 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., Rothbart, M. K., Sheese, B. E., & Voelker, P. (2012). Control Networks and Neuromodulators of Early Development. *Developmental Psychology*, *48*(3), 827–835.

https://doi.org/10.1037/a0025530

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

Postle, B. R. (2006). Working memory as an emergent property of the mind and brain. *Neuroscience*, *139*(1), 23–38. https://doi.org/10.1016/j.neuroscience.2005.06.005

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. (2019). *R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria*.

Ratner, N. B. (2000). Performance or capacity, the model still requires definitions and boundaries it doesn't have. *Journal of Fluency Disorders*, *25*(4), 337–346. https://doi.org/10.1016/S0094-730X(00)00083-8

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

Riby, D. M., Doherty-Sneddon, G., & Whittle, L. (2012). Face-to-face interference in typical and atypical development. *Developmental Science*, *15*(2), 281–291. https://doi.org/10.1111/j.1467-7687.2011.01125.x

Roelofs, A. (1997). The WEAVER model of word-form encoding in speech production. *Cognition*, *64*(3), 249–284. https://doi.org/10.1016/S0010-0277(97)00027-9

Roelofs, A. (2008a). Attention, gaze shifting, and dual-task interference from phonological encoding in spoken word planning. *Journal of Experimental Psychology. Human Perception and Performance*, *34*(6), 1580–1598. https://doi.org/10.1037/a0012476

Roelofs, A. (2008b). Attention to spoken word planning: Chronometric and neuroimaging evidence. *Linguistics and Language Compass*, *2*(3), 389–405. https://doi.org/10.1111/j.1749-818X.2008.00060.x

Roelofs, A. (2008c). 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. (2011). Attention, exposure duration, and gaze shifting in naming performance. *Journal of Experimental Psychology: Human Perception and Performance*, *37*(3), 860–873. https://doi.org/10.1037/a0021929

Roelofs, A. (2014). Integrating psycholinguistic and motor control approaches to speech production: where do they meet? *Language, Cognition and Neuroscience*, *29*(1), 35–37. https://doi.org/10.1080/01690965.2013.852687

Roelofs, A. (2015). Modeling of phonological encoding in spoken word production: From Germanic languages to Mandarin Chinese and Japanese. *Japanese Psychological Research*, *57*(1), 22–37. https://doi.org/10.1111/jpr.12050

Roelofs, A., & Ferreira, V. S. (2019). The Architecture of Speaking. In P. Hagoort (Ed.), *Human Language: From Genes and Brains to Behavior* (pp. 35–51). MIT press.

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

Rothbart, M., & 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

Rothbart, M., & Rueda, M. R. (2005). The Development of Effortful Control. In U. Mayr, E. Awh, & S. Keele (Eds.), *Developing Individuality int he human brain: A trib ute to Michael I. Posner* (pp. 167–188). American Psychiatric Association.

Rothman, K. J. (1990). No adjustments are needed for multiple comparisons. *Epidemiology*, *1*(1), 43–46. https://doi.org/10.1097/00001648-199001000-00010

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. (2014). Exploring the link between stuttering and phonology: A review and implications for treatment. *Seminars in Speech and Language*, *35*(2), 95–113. https://doi.org/10.1055/s-0034-1371754

Sasisekaran, J., Brady, A., & Stein, J. (2013a). 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., Brady, A., & Stein, J. (2013b). A preliminary investigation of phonological encoding skills in children who stutter. *Journal of Fluency Disorders*, *38*(1), 45–58.

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. (2006). Phoneme monitoring in silent naming and perception in adults who stutter. *Journal of Fluency Disorders*, *31*(4), 284–302. https://doi.org/10.1016/j.jfludis.2006.08.001

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., Smith, A., Sadagopan, N., & Weber-Fox, C. (2010). Nonword repetition in children and adults: Effects on movement coordination. *Developmental Science*, *13*(3), 521–532. https://doi.org/10.1111/j.1467-7687.2009.00911.x

Sasisekaran, J., & Weber-Fox, C. (2012). Cross-sectional study of phoneme and rhyme monitoring abilities in children between 7 and 13 years. *Applied Psycholinguistics*, *33*(02), 253–279. https://doi.org/10.1017/S0142716411000348

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

Saville, D. J. (1990). Multiple comparison procedures: The practical solution. *American Statistician*, *44*(2), 174–180. https://doi.org/10.1080/00031305.1990.10475712

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

Schwenk, K. A., Conture, E. G., & Walden, T. A. (2007). Reaction to background stimulation of preschool children who do and do not stutter. *Journal of Communication Disorders*, *40*(2), 129–141. https://doi.org/10.1016/j.jcomdis.2006.06.003

Scontras, G., Badecker, W., Shank, L., Lim, E., & Fedorenko, E. (2015). Syntactic complexity effects in sentence production. *Cognitive Science*, *39*(3), 559–583. https://doi.org/10.1111/cogs.12168

Siegel, G. M. (2000). Demands and capacities or demands and performance? *Journal of Fluency Disorders*, *25*(4), 321–327. https://doi.org/10.1016/S0094-730X(00)00081-4

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

Smits-Bandstra, S., De Nil, L., & Rochon, E. (2006). The transition to increased automaticity during finger sequence learning in adult males who stutter. *Journal of Fluency Disorders*, *31*(1), 22–42. https://doi.org/10.1016/j.jfludis.2005.11.004

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.

Starkweather, C. W. (1987). *Fluency and Stuttering*. Prentice-Hall.

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

Starkweather, C. W., & Gottwald, S. R. (2000). The Demands and Capacities Model: Response to Siegel. *Journal of Fluency Disorders*, *25*, 369–375.

Sussman, H. M. (1982). Contrastive patterns of intrahemispheric interference to verbal and spatial concurrent tasks in right-handed, left-handed and stuttering populations. *Neuropsychologia*, *20*(6), 675–684. https://doi.org/10.1016/0028-3932(82)90067-7

Tichenor, S. E., & Yaruss, J. S. (2018). A Phenomenological Analysis of the Moment of Stuttering. *American Journal of Speech-Language Pathology*, *27*, 1180–1194. https://doi.org/10.1044/2018_AJSLP-ODC11-17-0192

Tichenor, S. E., & Yaruss, J. S. (2019a). 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. (2019b). Repetitive Negative Thinking, Temperament, and Adverse Impact in Adults Who Stutter. *American Journal of Speech-Language Pathology*.

Tichenor, S. E., & Yaruss, J. S. (2019c). Stuttering As Defined By People Who Stutter. *Journal of Speech, Language, and Hearing Research*, *62*, 4356–4369. https://doi.org/https://doi.org/10.1044/2019_JSLHR-19-00137

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.

Treleavan, S., Allen, M. A., & Coalson, G. A. (2018). *Verbal Versus Visuospatial Working Memory in Adults who Stutter*.

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

Usler, E., Smith, A., & Weber, C. (2017). A Lag in Speech Motor Coordination During sentence production is associated with stuttering persistence in young children. *American Journal of Speech-Language Pathology*, *60*, 1–15. https://doi.org/10.1044/2016

Usler, E., & Weber-Fox, C. (2015). Neurodevelopment for syntactic processing distinguishes childhood stuttering recovery versus persistence. *Journal of Neurodevelopmental Disorders*, *7*(1), 4. https://doi.org/10.1186/1866-1955-7-4

Van der Merwe, A. (2009). A theoretical framework for the characterization of pathological speech sensorimotor control. In M. Mcneil (Ed.), *Clinical Management of Sensorimotor Speech Disorders* (Second, pp. 3–18). Thieme.

Van Dyke, J. A. (2007). Interference effects from grammatically unavailable constituents during sentence processing. *Journal of Experimental Psychology: Learning Memory and Cognition*, *33*(2), 407–430. https://doi.org/10.1037/0278-7393.33.2.407

Van Riper, C. (1982). *The nature of stuttering*. Prentice Hall.

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.

Wakaba, Y. (1998). Research on temperament of children who stutter with early onset. In E. C. Healey & H. F. M. Peters (Eds.), *Stuttering: procedings of the second world congress on fluency disorders* (Vol 2.). University Press Nijmegen.

Walley, A. (1988). Spoken word recognition by young children and adults. *Cognitive Development*, *3*, 137–165.

Walley, A. (1993). The Role of Vocabulary Development in Children′s Spoken Word Recognition and Segmentation Ability. In *Developmental Review* (Vol. 13, Issue 3, pp. 286–350). https://doi.org/10.1006/drev.1993.1015

Walsh, B., Mettel, K. M., & Smith, A. (2015). Speech motor planning and execution deficits in early childhood stuttering. *Journal of Neurodevelopmental Disorders*, *7*(1), 27. https://doi.org/10.1186/s11689-015-9123-8

Wang, J. J., & Apperly, I. A. (2017). Just one look: Direct gaze briefly disrupts visual working memory. *Psychonomic Bulletin & Review*, *24*(2), 393–399. https://doi.org/10.3758/s13423-016-1097-3

Weber-Fox, C., & Hampton, A. (2008). Stuttering and Natural Speech Processing of Semantic and Syntactic Constraints on Verbs. *Journal of Speech Language and Hearing Research*, *51*(5), 1058. https://doi.org/10.1044/1092-4388(2008/07-0164)

Weber-Fox, C., Hampton Wray, A., & Arnold, H. (2013). Early childhood stuttering and electrophysiological indices of language processing. *Journal of Fluency Disorders*, *38*(2), 206–221. https://doi.org/10.1016/j.jfludis.2013.01.001

Weber-Fox, C., Spencer, R. M., Spruill, J. E., & Smith, A. (2004). Phonologic Processing in Adults Who StutterElectrophysiological and Behavioral Evidence. *Journal of Speech, Language, and Hearing Research*, *47*(6), 1244–1258. http://jslhr.pubs.asha.org/article.aspx?articleid=1781507

Weber-Fox, C., Spruill, J. E., Spencer, R., & Smith, A. (2008). Atypical neural functions underlying phonological processing and silent rehearsal in children who stutter. *Developmental Science*, *11*(2), 321–337. https://doi.org/10.1111/j.1467-7687.2008.00678.x

Webster, W. G. (1990). Evidence in bimanual finger-tapping of an attentional component to stuttering. *Behavioural Brain Research*, *37*(2), 93–100. https://doi.org/10.1016/0166-4328(90)90084-R

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

Wheeldon, L. R., & Lahiri, A. (2002). The minimal unit of phonological encoding: Prosodic or lexical word. *Cognition*, *85*(2), B31–B41. https://doi.org/10.1016/S0010-0277(02)00103-8

Wheeldon, L. R., & Levelt, W. J. M. (1995). Monitoring the Time Course of Phonological Encoding. *Journal of Memory and Language*, *34*, 311–334.

WHO. (2001). *The International Classification of Functioning, Disabiliyt, and Health (ICF)*. World Health Organization.

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

Wingate, M. E. (1988). *The Structure of Stuttering*. R.R. Donnelley and Sons.

Wolpert, D. M., Ghahramani, Z., & Jordan, M. I. (1995). An internal model for sensorimotor integration. *Science-AAAS-Weekly Paper Edition*, *269*(SEPTEMBER). http://www.ufjf.br/especializacaofisioto/files/2010/03/Leitura-5.pdf

Yairi, E., & Ambrose, N. (1999). Early Childhood Stuttering IPersistency and Recovery Rates. *Journal of Speech, Language, and Hearing Research*, *42*(5), 1097–1112. https://doi.org/doi.org/10.1044/jslhr.4205.1097

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. (2000). The role of performance in the demands and capacities model. *Journal of Fluency Disorders*, *25*(4), 347–358. https://doi.org/10.1016/S0094-730X(00)00084-X

Yaruss, J. S., & Quesal, R. (2004). Stuttering and the international clasification of functioning, disability, and health (ICF): an update. *Journal of Communication Disorders*, *37*, 35–52. https://doi.org/10.1016/S0021-9924(03)00052-2

Yaruss, J. S., & Quesal, R. (2006). Overall assessment of the speaker's experience of stuttering (OASES): Documenting multiple outcomes in stuttering treatment. *Journal of Fluency Disorders*, *31*, 90–115. https://doi.org/10.1016/j.jfludis.2006.02.00

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

Yaruss, J. S., & Reardon-Reeves, N. (2017). *Early Childhood Stuttering Therapy: A Practical Guide*. Stuttering Therapy Resources, Inc.

Youse, K. M., & Coelho, C. A. (2005). Working memory and discourse production abilities following closed-head injury. *Brain Injury*, *19*(12), 1001–1009. https://doi.org/10.1080/02699050500109951

Zimmermann, G. (1980). Stuttering: a disorder of movement. *J Speech Hear Res*, *23*(1), 122–136. https://doi.org/10.1044/jshr.2301.122