Behavioral and Neural Indices of Inhibitory Control in Children Who Stutter

by

Isabelle Michaud

Bachelor of Science, Ithaca College, 2021

Submitted to the Graduate Faculty of the

School of Health and Rehabilitation Sciences in partial fulfillment

of the requirements for the degree of

Master of Science in Speech-Language Pathology

University of Pittsburgh

2023

UNIVERSITY OF PITTSBURGH

SCHOOL OF HEALTH AND REHABILITATION SCIENCES

This thesis was presented

by

Isabelle Michaud

It was defended on

March 17, 2023

and approved by

Jason Bohland, Ph.D. CCC-SLP, Department of Communication Sciences and Disorders

Sarah Wallace, Ph.D., CCC-SLP, Department of Communication Sciences and Disorders

Thesis Advisor: Amanda Hampton Wray, Ph.D., CCC-SLP, Department of Communication Sciences and Disorders

Copyright © by Isabelle Michaud

2023

Behavioral and Neural Indices of Inhibitory Control in Children Who Stutter

Isabelle Michaud, BS

University of Pittsburgh, 2023

Purpose: Previous literature has found that children who stutter (CWS) exhibit differences in executive function skills, including inhibitory control, compared to children who do not stutter (CWNS). The current study aimed to determine the similarities and differences between behavioral and neural indices of inhibitory control in both groups of children.

Method: Forty CWS and 36 CWNS, ages 3 to 8 years, completed two inhibition tasks. Twenty CWS and 16 CWNS completed an inhibition task, a Go/No-Go task, while electroencephalography (EEG) was collected to evaluate neural processes underlying inhibitory control. Children also completed Head-Toes-Knees-Shoulders (HTKS), a measure of behavioral self-regulation that assesses inhibitory control and other cognitive processes.

Results: CWS and CWNS performed with similar behavioral accuracy and response times on the inhibitory control tasks (HTKS and Go/No-Go). HTKS accuracy and P2 mean amplitudes elicited by the No-Go condition were found to be significantly correlated for CWS. HTKS accuracy was found to be correlated with P3 mean amplitudes elicited by the Go condition across participants, with the strongest relationship for CWNS. All other correlations were not found to be significant.

Conclusions: These findings suggest that CWS and CWNS perform similarly on tasks involving inhibitory control. In CWS, increased attentional engagement, which is needed to withhold a response during the No-Go condition of the Go/No-Go task, indicated by larger P2 responses, may support stronger performance on HTKS, especially on the complex rule-changing

section. Additionally, when children, across both groups, are able to use their attention more efficiently during tasks with more familiarity, as with the Go condition in the Go/No-Go task, they perform better on all parts of the inhibitory control task (HTKS). Together, these preliminary findings suggest that relationships between behavioral responses and neural processes that regulate inhibition may differ in subtle ways between CWS and CWNS. Replication of this study with a larger sample size is needed to confirm the findings of this study.

Table of Contents

List of Tables

List of Figures

Preface

I would like to take the opportunity to express my gratitude to those who supported me throughout this project. First, thank you to Dr. Mandy Hampton Wray and Erica Lescht for the endless guidance, encouragement, and knowledge shared throughout the past five semesters. I am appreciative of the immense time you dedicated toward scaffolding me through the thesis project. Second, thank you to Dr. Sarah Wallace and Dr. Jason Bohland for being members of my committee. You were integral team members, and I appreciated your feedback and collaboration. Third, thank you to Dr. William Evans for moderating my thesis defense. I am thankful for your kindness and support. Fourth, thank you to Dr. Elif Isbell for providing your time and resources to facilitate my EEG data processing. Lastly, thank you to my friends, family, professors, and clinical instructors for providing motivation to keep going. This project would not have been possible without these individuals.

1.0 Introduction

Developmental stuttering is a neurologically-based disorder characterized by disfluent speech patterns (i.e., part- or monosyllabic whole-word repetitions, blocks, and prolongations), secondary or concomitant behaviors (e.g., involuntary movements, muscle tensing), and psychological or affective reactions (e.g., feelings of shame, fear, avoidance; Yairi & Seery, 2015). Eighty-five percent of children who stutter (CWS) begin during the preschool years, typically prior to age 4 years (Yairi & Seery, 2015). While all preschool-aged children experience typical speech disfluencies (e.g., phrase repetitions, revisions, interjections), about 5% experience stuttering-like disfluencies (SLDs; Yairi & Seery, 2015). Early stuttering is primarily marked by sudden onset with heterogeneous, moderate-severe speech disfluencies (Yairi & Seery, 2015). Typically, about 3-15% of total words are disfluent in children or adults who stutter, meaning the majority of speech is fluent (Yairi & Seery, 2015). According to Yairi and Seery (2015), approximately 75% of CWS recover naturally (i.e., without speech-language treatment) between 2 to 4 years post onset. There are several predictive factors that may be involved in the persistence of stuttering, including age (i.e., older onset), biological sex (e.g., male), family history of stuttering, and severity of SLDs (Yairi & Seery, 2015).

While research is ongoing regarding the exact causes of stuttering, several theories have been recognized and accepted. In general, stuttering causes are multifactorial, meaning they are influenced by a variety of genetic and environmental factors (Yairi & Seery, 2015). For example, researchers have found that some CWS have abnormal basal ganglia-thalamocortical (BGTC) networks that interrupt the timing and coordination of speech muscles (Chang & Guenther, 2020). A well-known theory, called the Multifactorial Dynamic Pathways Theory of Stuttering, proposes that the underlying cause of stuttering is a genetic predisposition toward an unstable speech motor system combined with environmental interactions that influence epigenetic expression (Smith & Weber, 2017). Factors including speech, language, and emotional abilities are believed to impact speech disfluencies. Together, these behavioral, psychological, and environmental responses lead to epigenetic changes in neural structures that may result in stuttering-like disfluencies (Smith & Weber, 2017; Yairi & Seery, 2015). This theory hypothesizes that children who recover from stuttering develop compensatory strategies for disfluencies, while those who persist are continually impacted by the above cycle (Smith & Weber, 2017).

Aligned with this theory, many factors, including linguistic, cognitive, emotional, sensory, and motor processing, are proposed to be involved in the development and persistence of childhood stuttering (Anderson & Ofoe, 2019; Ofoe et al., 2018; Yairi & Seery, 2015). With regard to cognitive processes, it has been hypothesized that CWS may exhibit weaker executive functioning compared to children who do not stutter (CWNS), including inhibition, cognitive flexibility, and attention skills (Anderson & Ofoe, 2019; Anderson & Wagovich, 2017; Eggers et al., 2013; Ofoe et al., 2018). Grammar et al. (2014) defines executive functions as cognitive skills that are essential for "purposeful, future-oriented behavior that allow for flexible adaptation to changing task demands, including regulation of attention, inhibition of inappropriate responses, coordination of information in working memory, and organization and planning of adaptive behavior" (p.94). In typically developing preschool-aged children, executive function skills experience rapid development (Simpson & Carroll, 2019), as they are continually influenced by genetic and environmental factors (Diamond, 2013). In CWS, executive function differences may contribute to the variability among individuals who stutter (Anderson & Ofoe, 2019). In other words, differences observed in speech, language, emotional, sensory, or motor development and function in CWS may in part result from differences in executive function skills (Anderson & Ofoe, 2019).

1.1 Inhibitory Control

The present study will focus on one skill within the domain of executive function, inhibition. The aim is to extend our current understanding of inhibitory control by examining the relationship between behavioral and neural mechanisms in CWS. Currently, the connection between these different measures is unclear, with contradictory findings in the literature. This is in part due to limited literature involving inhibition-related tasks analyzed using event-related brain potentials (ERP) in CWS. To our knowledge, there are limited studies directly comparing behavioral and ERP data in CWS and CWNS. Within the reviewed research, conflicting results are most likely due to variations in sample size, stimulus modality, age range, and types of inhibition involved in the task.

There are several definitions and types of inhibition that have been evaluated within the stuttering literature. Garon et al. (2008) described inhibition as the ability to ignore irrelevant stimuli or suppress a prepotent (i.e., dominant) response, which is known as simple response inhibition, with a more appropriate (i.e., less dominant) response, which is known as complex response inhibition. In simpler terms, inhibitory control is the ability to subside, interrupt, or delay an action (Clark, 1996; Eggers et al., 2013; Johnstone et al., 2007). This skill is crucial for functioning within natural environments and completing everyday tasks (Johnstone et al., 2007), in addition to establishing efficient, goal-directed behavior (Jonkman, 2006). With this being said, inhibitory control is one of the later developing higher-order functions (Dustman et al., 1996;

Johnstone et al., 2007). As children continue to develop through late adolescence, their inhibition abilities improve exponentially (Dustman et al., 1996).

Similar to the purpose of executive functions in general, inhibition skills play a valuable role in the development of other cognitive abilities, including learning, attention, emotional regulation, perception, and motor activity (Clark, 1996; Johnstone et al., 2005). Individuals with stronger inhibition skills have the ability to remain focused by resisting impulses and suppressing distractions (Diamond, 2013). For example, children with lower inhibition skills may have difficulty separating internal or external stimuli from tasks at hand, especially when an unanticipated environmental change occurs (Ofoe et al., 2018). Similarly, children with decreased inhibitory control may have difficulty stopping an activity after being instructed to stop (Garon et al., 2008). With regard to stuttering, according to Ofoe et al. (2018), the complex functions of inhibition may impact the ability of CWS to effectively “suppress the production of incorrect speech plans during speech monitoring” (p.1642).

Inhibition skills are used throughout all aspects of everyday life. Children with reduced inhibitory control have increased difficulty successfully regulating their emotions (Carlson & Wang, 2007; Eggers et al., 2013). According to Eggers et al. (2013), this may lead to increased emotional arousal responses during stress-inducing situations. In general, it is common for anxiety-provoking environments or situations to increase the frequency of stuttering (Yairi & Seery, 2015). Eggers et al. (2013) also stated, “lower [inhibitory control] impedes [CWS’s] ability to withhold their responses long enough to consider the complexities of a specific situation and to engage appropriate social skills” (p.8). CWS with lower inhibition skills may have difficulty suppressing prepotent responses within everyday environments (e.g., home, school, community; Eggers et al., 2013).

According to Garon et al. (2008) and Simpson and Carroll (2019), there are several types of inhibition that can be analyzed through a variety of behavioral or neural tasks: prepotent response inhibition, resistance to distractor interference, and resistance to proactive interference. Prepotent response inhibition can be divided into (a) simple response inhibition and (b) complex response inhibition. Simple response inhibition involves responding to one signal and withholding responses from a different signal (Garon et al., 2008; Ofoe et al., 2018; Simpson & Carroll, 2019). Complex response inhibition involves suppressing a dominant response and performing a subdominant response (Garon et al., 2008; Ofoe et al., 2018). In other words, these tasks are more demanding on working memory because they require participants to select between multiple responses (Simpson & Carroll, 2019). Generally, complex tasks have greater prepotency, typically because the expected stimulus-response pattern occurs prior to rule switching, which requires increased inhibitory strength (Simpson & Carroll, 2019). Inhibitory strength refers to the "ability to overcome increasingly large differences in activation of the to-be-inhibited and to-be-produced response" (Simpson & Carroll, 2019, p.1462). Resistance to distractor interference refers to the ability to ignore irrelevant stimuli within the external environment (Ofoe et al., 2018). Resistance to proactive interference refers to the ability to ignore irrelevant information from disrupting current task performance (Ofoe et al., 2018).

Within the literature, it is still unclear whether inhibitory control is composed of single or several processes (Vuillier et al., 2016). Vuillier et al. (2016) propose that inhibitory control has two separate component processes that emerge and develop differently: interference suppression and response inhibition. Interference suppression refers to "resisting interference from irrelevant or misleading information" (Vuillier et al., 2016, p.2). Stroop and Flanker paradigms demonstrate interference suppression because irrelevant information must be ignored (Vuillier et al., 2016).

Rule change tasks, such as the Dimension Change Card Sort task and Head-Toes-Knees-Shoulders (HTKS), may require interference suppression skills as well. Response inhibition refers to "stopping a prepotent response" (Vuillier et al., 2016, p.2). Go/No-Go and Stop Signal paradigms require response inhibition because participants must withhold responses completely (Vuillier et al., 2016). Vuillier et al. (2016) believe that interference suppression develops later than response inhibition (Vuillier et al., 2016). Despite the separation between these types of inhibition, both are likely involved in all inhibitory control-related tasks (Vuillier et al., 2016).

1.1.1 Inhibition-Related Tasks

Behavioral measures are valuable because they efficiently evaluate cognitive abilities through direct-response structured tasks in a short period of time (Toplack et al., 2013). Several behavioral tasks are designed to assess inhibition skills in children, including Go/No-Go or Stop-Signal tasks, card sorting or Stroop-like paradigms, Mistaken Gift or Gift Delay Tasks, and HTKS tasks. Each of these measures differ in many ways, including the type of inhibition assessed, the type of task, modality (i.e., auditory, visual), required response (i.e., verbal, nonverbal, manual), and relative difficulty. For example, Go/No-Go, stop-signal, or gift delay tasks evaluate inhibition of an initial prepotent response (i.e., ability to stop an ongoing response) and HTKS or Stroop-like tasks investigate protection from self-initiated responses caused by conflicting interference (Eggers et al., 2013). The present study will examine performance on the Zoo task, a visual Go/No-Go task that assesses simple response inhibition and requires a nonverbal, manual response. Additionally, I examined performance on the HTKS task, which is an auditory stimulus-response task that assesses complex response inhibition and resistance to proactive interference and requires a nonverbal, manual response. These two tasks are beneficial for the current study because they do not require a verbal response. This is important because speech disfluencies may have impacted the ability for CWS to respond to stimuli.

Go/No-Go tasks are used with children and adults to assess inhibition via behavioral or neural analysis. This task involves two sets of stimuli: Go signals that require a response (e.g., press button or verbally respond) and No-Go signals that require withholding a response (Johnstone et al., 2005). The strength of inhibitory control required can be manipulated by increasing the strength of response priming or preparation (Jonkman, 2006). This is accomplished by increasing the number of Go stimuli or presenting warning signals (Jonkman, 2006). Several response patterns have been recognized within the literature, including false alarms and misses. False alarms refer to the failure of inhibiting responses to No-Go stimuli and misses refer to the failure of responding to a Go stimuli (Eggers et al., 2013). False alarms have been found to reflect impulsivity and response control (Christ et al., 2001), while misses reflect focused attention and concentration (Trommer et al., 1988).

The HTKS task is a measure of behavioral self-regulation that assesses cognitive flexibility, inhibitory control, and working memory in younger children, typically between the ages of 4 and 8 years (Cameron Ponitz et al., 2008; McClelland et al., 2014). This task involves participants following auditorily presented directions and completing a non-verbal task (e.g., “touch your shoulders”). There are three sections with different rules that require children to respond in different ways than the previous instructions (e.g., “touch your head when I say ‘touch your toes’”). This is related to inhibitory control because participants are required to inhibit their natural response while initiating the correct task command (Cameron Ponitz et al., 2008; McClelland et al., 2014). This task is believed to engage several other components of executive function in addition to inhibition as well (McClelland et al., 2014). Some studies propose that

HTKS primarily assesses response inhibition (Fuhs & Day, 2011; McClelland et al., 2014), while others suggest it is primarily correlated with cognitive flexibility and working memory (McClelland et al., 2007; Wanless et al., 2013). Although it may engage multiple executive function skills, this measure is psychometrically sound (i.e., reliable, valid), brief, economically practical, and has been found to significantly predict growth in many academic outcomes in CWNS (McClelland et al., 2014).

For the present study, a Go/No-Go task will be used to examine both behavioral and electroencephalography (EEG) responses, specifically by analyzing time- and stimulus-locked ERPs. ERPs are an index of the brain's electrical activity in response to cognitive, motor, or sensory stimuli. Specifically, they provide detailed temporal information about neural responses to a given stimulus (Luck, 2014). ERPs can be used to examine a variety of neural processes, including inhibitory control.

The current study involves both behavioral and neural inhibition measures in CWS and CWNS for several reasons. First, valuable information can be extracted from each individually and with comparison. For example, behavioral measures allow for direct observation of inhibition skills within a structured environment over a short period of time (Toplack et al., 2013). Both ERP and behavioral paradigms can provide functionally significant information that is relevant in clinical settings with children who stutter. ERPs will be used as an avenue for further analyzing inhibitory control because there are certain aspects which cannot be directly derived from behavioral means alone (Jonkman, 2006; Piispala et al., 2016). Specifically, response preparation, conflict monitoring, stimulus expectation, and response inhibition have been associated with specific ERP components (Jonkman, 2006). Comparing the results of neural and behavioral measures of inhibitory control in CWS and CWNS will reveal valuable similarities and differences. For example, which group performs better on each task? Which ERP components are most prominent during the Go/No-Go task and how does this compare to HTKS results? The current study will attempt to answer each of these questions. To our knowledge, there are limited published studies that have performed this direct comparison. Upon successful completion, the results will provide insights into the significant neural processes involved during Go/No-Go tasks and the clinical relevance revealed from HTKS for CWS.

1.2 Inhibition in Children Who Do Not Stutter (CWNS)

The existing literature has limited information regarding typical development of response inhibition and preparation, making it difficult to understand involvement with various developmental disorders (Johnstone et al., 2007; Jonkman et al., 2003). Most studies have been conducted with typically developing adult participants rather than children. Generally, it is understood that younger children have delayed development of inhibitory control (Johnstone et al., 2005; Jonkman, 2006; Jonkman et al., 2003). While there are discrepancies within our current understanding, some believe children begin to display inhibition improvements between the ages of 3 and 6 years, with reduced advancement after the age of 7 years (Johnstone et al., 2007). Others believe significant development occurs during late childhood and early adolescence due to structural development of the frontal cortex (Jonkman, 2006; Sowell et al., 1999).

1.2.1 Behavioral Measures of Inhibition

Behavioral data from children completing Go/No-Go tasks revealed valuable information on inhibitory skills. Overall, as the age of participants increased to adulthood, performance efficiency and accuracy improved (Grammer et al., 2014; Johnstone et al., 2005; Jonkman, 2006). Younger participants had slower response times, more false alarms, higher periods of inattention, increased impulsivity, and lower percentages of correct responses (Johnstone et al., 2005, Jonkman et al., 2003; Vuillier et al., 2016). Interestingly, Johnstone et al. (2005) found that children had slower response times (i.e., button presses) for correct Go stimuli and incorrect No-Go stimuli. The researchers hypothesized that this was due to increased attention allocation to No-Go stimuli (Johnstone et al., 2005). Similarly, Vuillier et al. (2016) found that children had slower response times for Go trials compared to adults.

HTKS serves as an additional behavioral paradigm to assess inhibitory control skills, in addition to other cognitive processes, in children. Participants are required to suppress their habitual responses to commands and initiate the correct, unnatural response (McClelland et al., 2014). Difficulty increases throughout the task because rules are switched, requiring further use of inhibitory control. Studies assessing performance on HTKS in CWNS are limited, but research has concluded that accuracy of performance improves with advancing age (Cameron Ponitz et al., 2008). There are several factors that can influence performance, including socioeconomic status, classroom considerations, cultural influences, and self-regulation skills, (Cameron Ponitz et al., 2008; Gonzales et al., 2021). Numerous studies have suggested that HTKS is a valid and reliable method for assessing inhibitory control, cognitive flexibility, and working memory (Cameron Ponitz et al., 2008; Gonzales et al., 2021; Hee et al., 2018; McClelland et al., 2014).

1.2.2 Neural Measures of Inhibition

As mentioned previously, several aspects of executive function (e.g., inhibition) have been measured by specific ERP components. Generally, ERP components, or waveforms, are labeled based on the signal's polarity and latency, negative (N) or positive (P) peaks at a given timepoint, such as P300, a positive waveform that peaks ~300 ms after a stimulus is presented (Luck, 2014). Studies of typically developing individuals have revealed that N1, P2, N2 and P3 are the main ERP components consistently elicited by the Go/No-Go paradigm (Donkers & van Boxtel, 2004; Falkenstein et al., 1999; García-Larrea et al., 1992; Johnstone et al., 2005; Johnstone et al., 2007; Jonkman, 2006; Jonkman et al., 2003; Kok, 1986; Nieuwenhuis et al., 2003; Piispala et al., 2016; Piispala et al., 2017; Pliszka et al., 2000; Smith, 2011; Vuillier et al., 2016). Accumulating evidence suggests that N2 and P3 are related to separate aspects of inhibitory processing (e.g., degree and success of inhibition; Falkenstein et al., 2002; Johnstone et al., 2005). The N1 and P2 have been found to be related to attention (Luck, 2014; Wongupparaj et al., 2018). Figure 1 illustrates relevant ERP components as derived from ongoing EEG data (Luck et al., 2000).

N1 is often observed when participants complete Go/No-Go paradigms (Johnstone et al., 2005; Johnstone et al., 2007). N1 is believed to reflect attention and discrimination abilities during various tasks (Luck, 2014). Johnstone et al. (2005) found frontal Go N1 and fronto-central No-Go N1 components in children, but not adults, which was hypothesized to signify different approaches to processing novel stimuli, such as that stimuli may be more attention-grabbing for children. Johnstone et al. (2007) found larger N1 components during the Stop stimulus of the Stop-signal task compared to the No-Go stimulus of the Go/No-Go task. Johnstone et al. (2005) found larger N1 components during No-Go stimuli as compared to the Go stimuli. In addition, as participant's age increased, N1 amplitude increased (Johnstone et al., 2005). With regard to latency, the N1 components occurred earlier for No-Go stimuli compared to Stop stimuli (Johnstone et al., 2007). Overall, these studies suggest that greater attentional engagement is needed during the No-Go rather than Go condition (Johnstone et al., 2005; Johnstone et al., 2007).

The P2 ERP component is less widely studied but has been found to relate to cognitive processes as well, specifically selective attention (Wongupparaj et al., 2018) and stimulus classification (García-Larrea et al., 1992). Previous research has shown that the fronto-central P2 occurs around 200 ms (Wongupparaj et al., 2018). P2 has been found to be elicited during oddball paradigms, which are similar to Go/No-Go tasks with the presence of a regular and irregular stimulus (García-Larrea et al., 1992).

N2 is an ERP component that has been found to reflect conflict monitoring between Go and No-Go responses (Donkers & van Boxtel, 2004; Piispala et al., 2016; Pliszka et al., 2000; Smith, 2011) and inhibitory control (Falkenstein et al., 1999; Johnstone et al., 2007; Piispala et al., 2016; Piispala et al., 2017; Pliszka et al., 2000; Vuillier et al., 2016). N2 typically occurs between 200-400 ms post-stimulus onset (Johnstone et al., 2007; Jonkman, 2006; Jonkman et al., 2003; Piispala et al., 2016; Piispala et al., 2017; Vuillier et al., 2016). Typically, N2 is enhanced (i.e., more negative) during the No-Go condition as compared to the Go condition (i.e., "the No-Go effect"; Donkers & van Boxtel, 2004; Falkenstein et al., 1999; Jonkman, 2006; Jonkman et al., 2003; Piispala et al., 2016; Piispala et al., 2017; Vuillier et al., 2016). Johnstone et al. (2005) similarly found larger No-Go rather than Go N2 components, indicating successful task manipulation. Traditionally, No-Go N2 was related to the inhibition of motor responses (Kok, 1986). More recently, researchers have proposed the link between No-Go N2 and conflict monitoring (Donkers & van Boxtel, 2004; Jonkman, 2006; Nieuwenhuis et al., 2003). According to Jonkman (2006), conflict monitoring “is activated whenever there is conflict between the prepotent response and the currently required response” (p.182).

According to Johnstone et al. (2005) and Vuillier et al. (2016), reduced N2 amplitude and latency may signify reduced cognitive demand. Latency refers to the time interval between the presentation of a stimulus and an ERP component, typically measured at a component’s largest point, or peak (Luck, 2014). Amplitude refers to the maximal negativity or positivity of an ERP component peak (Luck, 2014). Larger N2 amplitudes and shorter N2 latencies were found during better inhibition compared to weaker inhibition (Falkenstein et al., 1999; Johnstone et al., 2005). Jonkman (2006) noticed a linear decrease in No-Go N2 effects with increasing age. Similarly, Vuillier et al., (2016) found that N2 peaked later in children than in adults. Increases in amplitude are often associated with higher focus on certain processes (Jonkman, 2006). Therefore, the N2 amplitude reduction from childhood to adulthood supports the theory that the level of conflict experienced reduces with age (Jonkman, 2006). Results from Johnstone et al. (2005) further support this because the amplitude of N2 and P3 reduced with increasing age, in combination with improved overall task performance. Vuillier et al. (2016) noted that children have more negative (e.g., larger) N2 amplitudes than adults. All of this further supports the connection between reduced amplitude and shorter latency N2 and improved inhibitory control.

P3 is a separate ERP component that typically occurs between 250-650 milliseconds (ms) post-stimulus onset (Johnstone et al., 2007; Jonkman, 2006; Jonkman et al., 2003; Piispala et al., 2016). Similar to N2, P3 is typically enhanced during the No-Go condition (Johnstone et al., 2005; Jonkman, 2006; Jonkman et al., 2003; Piispala et al., 2016). It has been suggested by numerous studies that the No-Go P3 represents a specific marker of response inhibition (Donkers & Van Boxtel, 2004; Piispala et al., 2016; Piispala et al., 2017). Specifically, the No-Go P3 may signify the outcome or overall success of inhibition in children (Johnstone et al., 2007). In a study by Bruin et al. (2001), larger amplitudes were present for strongly primed responses, which indicates increased inhibitory control was required. Johnstone et al., (2005) found a linear increase in P3 amplitude with age. Jonkman (2006) further supported this by specifying that the increase begins around age 9 to 10 and reaches maturity in young adulthood. Therefore, in contrast with reduced N2 amplitudes with age, P3 amplitudes increase with age, reflecting stronger inhibition skills in older children. P3 latency is typically longer in response to No-Go compared to Go stimuli (Eimer, 1993). Similar to N2 latencies, P3 latencies decrease with age (Johnstone et al., 2007).

EEG simultaneously collects electrical signals distributed across the brain, making it difficult to determine the specific location in the brain where a cognitive process occurs. Due to the electrode placement along the scalp, conclusions can be made about the general region displaying the most electrical activity. During inhibitory tasks (e.g., Go/No-Go), the N2 peak was maximal over fronto-central electrodes, near the anterior cingulate cortex (ACC) (i.e., frontal brain region; Bruin & Wijers, 2002; Eimer, 1993; Falkenstein et al., 1995; Falkenstein et al., 1999; Johnstone et al., 2005; Johnstone et al., 2007; Jonkman, 2006; Jonkman et al., 2007; Nieuwenhuis et al., 2003; Piispala et al., 2016; Piispala et al., 2017; van Veen & Carter, 2002). The anterior cingulate cortex (ACC) has been linked to various processes of self-regulation, including response selection, conflict monitoring, and outcome evaluation (Piispala et al., 2016; van Veen & Carter, 2002).

In children, the Go P3 is maximal over centroparietal brain regions (Bruin & Wijers, 2002; Falkenstein et al., 1995; Johnstone et al., 2005; Kok, 1986; Piispala et al., 2016; Piispala et al., 2017; Tekok-Kilic et al., 2001), while the No-Go P3 is maximal over fronto-central brain regions (Bokura et al., 2001; Bruin & Wijers, 2002; Falkenstein et al., 1995; Falkenstein et al., 2002;

Johnstone et al., 2005; Johnstone et al., 2007; Jonkman, 2006; Kok, 1986; Piispala et al., 2016; Piispala et al., 2017; Smith, 2011; Tekok-Klic et al., 2001). The topography differences between Go P3 and No-Go P3 may signify separate neural generators (Bokura et al., 2001; Piispala et al., 2017; Tekok-Kilic et al., 2001).

Inhibitory control processes are believed to be largely regulated by activity in the prefrontal cortex (Johnstone et al., 2007; Rubia et al., 2001). Decreased inhibitory abilities seen in younger compared to older children align with the development and maturation of the frontal brain area continues through puberty (Johnstone et al., 2005; Jonkman et al., 2003). Inhibitory control abilities continue to improve throughout childhood, aligned with increases in white matter connectivity in frontal brain regions (i.e., refinement through myelination and synaptic pruning; Jonkman, 2006; Sowell et al., 1999).

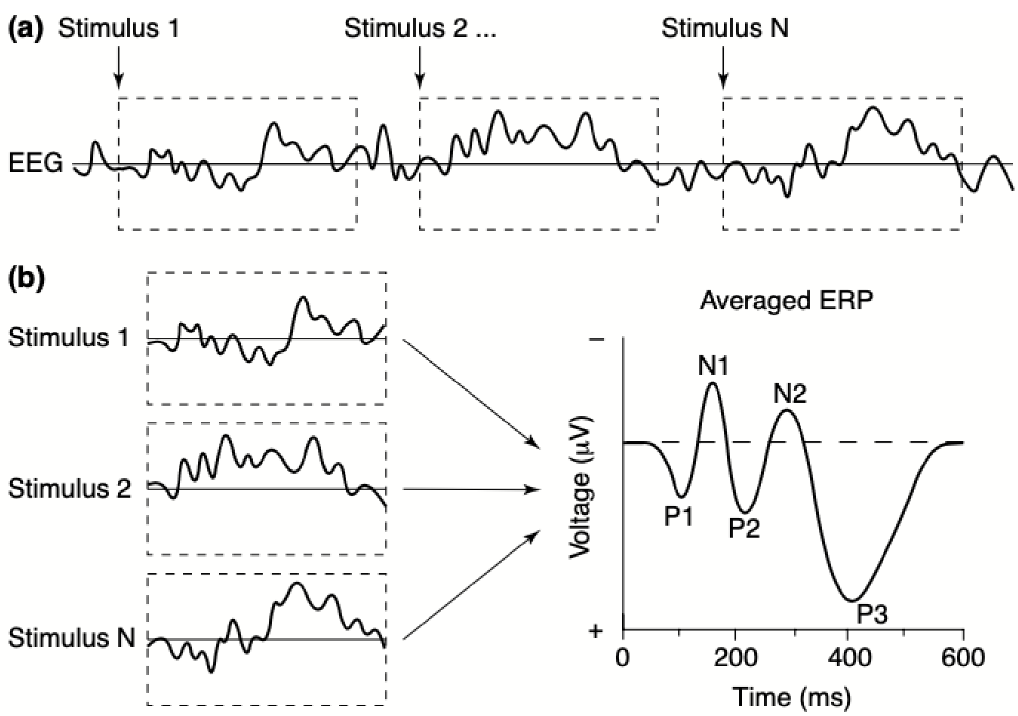

Figure 1 ERP Waveforms

Illustration of ERP waveforms, P1, N1, P2, N2, and P3 extracted from EEG data (Luck et al., 2000).

1.3 Inhibition in Children Who Stutter (CWS)

1.3.1 Parent Report Measures of Inhibition in CWS

Parent report measures are a valuable method for gathering behavioral information about CWS relating to inhibition skills in the real world. Ofoe et al. (2018) reviewed five parent report studies that included 136 CWS and 146 CWNS. Results indicated that parents of CWS provided weaker ratings of inhibitory control and attention than parents of CWNS. Specifically, their ratings were approximately half a standard deviation below the mean of CWNS (Ofoe et al., 2018). Previous studies found that parental ratings of effortful control (i.e., self-regulation) predicted the severity of stuttering, with lower rating of effortful control associated with higher severity levels (Kraft et al., 2014; Kraft et al., 2019). Together, these studies suggest that there may be a relationship between inhibitory control measured by tasks and observed stuttering behaviors, or stuttering severity.

1.3.2 Behavioral Measures of Inhibition in CWS

A small number of experimental studies on inhibition in stuttering to date make it difficult to form strong conclusions about the relationship between cognitive functioning and stuttering in children (e.g., Anderson & Ofoe, 2019; Eggers et al., 2013; Ofoe et al., 2018). Several researchers have used inhibitory behavioral tasks to compare CWS and CWNS, but results were inconsistent across studies. For example, Anderson and Wagovich (2017) used grass-snow and baa-meow tasks, which are similar to HTKS, and found that CWS ages 3 to 6 had slower, less accurate responses than CWNS. They attributed this difference to less efficient and effective inhibitory control skills (Anderson & Wagovich, 2017). Eggers (2012) used a stop-signal task, which is similar to Go/No-Go, with CWS ages 7 to 11 and found no significant differences when compared to CWNS. Similarly, Anderson & Wagovich (2010) found no between-group differences on inhibitory control between CWS and CWNS. Additionally, Eggers et al. (2013) conducted a behavioral study assessing inhibitory control in CWS ages 4;10 to 9;11 on a Go/No-Go task. The most common error pattern found for both CWS and CWNS was false alarms, although CWS had a higher mean number of occurrences and faster response times (Eggers et al., 2013). This suggests that CWS had more difficulty inhibiting responses to No-Go signals (i.e., non-targets), which may have been impacted by the maintenance of quick responses (Eggers et al., 2013). CWS also exhibited significantly more premature responses than CWNS, which refers to non-stimulus related impulsivity (Eggers et al., 2013). In general, they found that as age increased, both groups had more response accuracy (Eggers et al., 2013). Behavioral data from Piispala et al. (2016) revealed longer reaction times for Go conditions in CWS during Go/No-Go tasks, but no significant differences in the number of false alarms or premature responses. These findings contradict findings from Eggers et al (2013). Piispala et al. (2016) found limited overall errors in both CWS and CWNS, in addition to no significant learning effects or fatigue between the first and last portions of the task. The accurate performance of both groups may reflect the relatively simplistic nature of Go/No-Go tasks for children.

There are several reasons that might explain the differences in results in the above studies. First, all of these studies had relatively small sample sizes. Second, each of the researchers used different methodologies, including the type of task used. While all of the tasks assess inhibitory control, they used different modalities and levels of difficulty. Third, each study included participants with a variety of ages. The purpose of the current study is to further address these limitations in the existing literature by analyzing behavioral data from a larger sample size of CWS within a specified age range on common inhibition tasks.

To my knowledge, there has been one published study examining performance on HTKS in CWS compared to CWNS. Ntourou et al. (2018) observed executive function skills in 75 CWS and 75 CWNS ages 3;0 to 5;11 through HTKS and parental report via the Behavioral Rating Inventory of Executive Function-Preschool Version (BRIEF-P; i.e., 63-item parent questionnaire). Data from parental reports revealed lower ratings of working memory, cognitive flexibility, and executive function skills for CWS (Ntourou et al., 2018). Data gathered from the HTKS task revealed decreased overall performance for only 3-year-old CWS compared to peers, but not the older CWS and CWNS (Ntourou et al., 2018). The researchers hypothesize that young CWS may have early executive function challenges that resolve with development (Ntourou et al., 2018). Previous research in general has found that children with lower levels of self-regulation have difficulty on HTKS; therefore, based on previous studies, including Ntourou et al. (2018), it can be hypothesized that CWS will have increased difficulty on HTKS as well (Gonzales et al., 2021).

1.3.3 Neural Measures of Inhibition in CWS

There is limited research investigating ERP components during Go/No-Go tasks in CWS. Piispala et al. (2016, 2017) published two monumental studies paving the way for future research. Both studies included participants that were between the ages of 6 and 10 (i.e., 11 CWS, 19 CWNS; Piispala et al., 2016, 2017). While the sample sizes are small and future research is still needed to confirm results, valuable information was obtained.

Piispala et al. (2016) concluded that CWS had atypical brain processing relating to stimulus evaluation and response selection. The majority of ERP differences found between CWS and

CWNS occurred during the Go conditions (Piispala et al., 2016). With regard to specific ERP components, CWS had significantly delayed (i.e., longer) N2 and P3 components in the Go conditions compared to CWNS (Piispala et al., 2016). This delay in Go N2 may relate to slower stimulus evaluation caused by attentional orientation difficulties, leading to slower stimulus evaluation and prolonged response selections (Piispala et al., 2016). Additionally, results from Piispala et al. (2016) revealed more negative N2 amplitudes in the No-Go versus Go condition in both CWS and CWNS. There were no significant effect differences in N2 or P3 amplitude between the groups, suggesting similar processing mechanisms (Piispala et al., 2016). Despite these findings, Piispala et al. (2016) could not definitively confirm inhibition differences between CWS and CWNS.

Piispala et al. (2017) found that the majority of ERP differences occurred during the No-Go conditions. They also reported atypical brain activation, specifically variable inter-regional differences for both CWS and CWNS, especially during No-Go stimuli (Piispala et al., 2017). The increased ERP components may suggest that CWS require additional resources to perform Go/No-Go tasks (Piispala et al., 2017). This excess, or widened, brain activity indicates abnormal stimulus processing mechanisms, which may reflect the use of compensatory mechanisms to achieve adequate performance (Piispala et al., 2017). Their results helped support their hypothesis regarding atypical distribution of EEG activity elicited by inhibition control in CWS (Piispala et al., 2017). Regarding specific ERP components, CWS had prolonged, widened, and asymmetrical N2 activity in comparison to CWNS, especially in right frontal areas (Piispala et al., 2017). This may explain the overarching differences between groups in the No-Go condition, in addition to the reduced P3 in CWS (Piispala et al., 2017). CWS were also found to have larger (i.e., more negative) N2 mean amplitudes for the Go condition, suggesting the need for CWS to allocate more cognitive resources toward stimulus classification and response (Piispala et al., 2017). Also, CWS were found to have larger (i.e., more negative) N2 mean amplitudes for the No-Go condition, suggesting the use of compensatory mechanisms to enable adequate performance despite possible abnormal stimulus processing (Piispala et al., 2017).

Both groups in Piispala et al. (2017) revealed significant differences in P3 mean amplitude, latency, and overall distribution of electrical activity. Specifically, CWS had diminished or indistinct P3 mean amplitude (Piispala et al., 2017). Interestingly, CWS had minimal (i.e., weaker) No-Go P3 activity compared to CWNS, which may reflect inhibition difficulties (Piispala et al., 2017). The authors hypothesize that this decrease may be due to inefficient motor area deactivation because No-Go P3 is typically diminished in non-motor inhibition tasks (Piispala et al., 2017). In Piispala et al. (2017), CWS had lower amplitudes in the right frontal areas compared to CWNS, CWS had less positive mean amplitudes (Piispala et al., 2017). This may signify reduced inhibitory control in CWS because several studies have found positive correlations between inhibition success with N2 amplitude (Falkenstein et al., 1999; Johnstone et al., 2007; Piispala et al., 2016; Pliszka et al., 2000). These findings suggest atypical brain activity lateralization patterns in CWS during inhibitory control tasks that involve visual and motor components (Piispala et al., 2017).

It is important to remember that all children, including CWNS and CWS, are continuously developing (i.e., inhibitory and attentional processes are not fully matured). Participant differences may be attributed to the nature of child development variability (Piispala et al., 2016). Group differences may indicate a “wider developmental spectrum in the CWS, even though the groups did not differ by chronological age” (Piispala et al., 2016, p.24). The question remains as to whether variability is due to permanent stuttering-related differences, developmental lags, or compensatory mechanisms (Piispala et al., 2016).

In conclusion, based on parent-report measures and results from behavioral tasks, Anderson & Ofoe (2019) stated, “CWS are more likely than CWNS to have difficulty suppressing inappropriate responses, regardless of whether the child is being evaluated in a laboratory-based setting or real-life activities” (p.309). Despite this broad conclusion, more research is needed to clarify the inconsistencies found in the literature. Based on ERP measurements from Go/No-Go tasks, CWS and CWNS “may allocate brain resources differently in the inhibitory task despite accurate performance in the behavioural task” (Piispala et al., 2017, p.196). Piispala et al. (2016) suggest that paradigms with increased complexity (e.g., higher time pressure with varying stimulus intervals) may provide more detailed information on inhibitory control impairments in CWS. The present study aims to address this recommendation in part by comparing Go/No-Go (i.e., simple inhibition task) to HTKS (i.e., complex inhibition task).

2.0 Present Study

2.1 Specific Aims

The current study aims to compare behavioral and neural inhibition processes in CWS and CWNS for several reasons. First, this project contributes additional information to the knowledge base while addressing current discrepancies within the limited available literature. Second, this study further increases our overall understanding of the development of inhibition in different populations, including CWS. This is important because inhibitory development could impact the onset, development, persistence, or recovery of stuttering (Ofoe et al., 2018). Third, this study will enhance our understanding of inhibitory neural processes in CWS.

2.2 Research Questions

1. Do CWS exhibit differences in behavioral and neural processes for inhibitory control compared to CWNS?
2. How are behavioral and neural processes for inhibitory control related in CWS?
3. Are relationships between behavioral and neural measures of inhibitory control similar in CWS and CWNS?

2.3 Hypotheses

Basic inhibition skills are considered a pre-requisite for successfully accomplishing complex types of inhibition. The current study aims to explore the differences in performance between CWS and CWNS when task complexity and demands increase (Go/No-Go versus HTKS). To address my first research question, I predict that CWS will exhibit differences in behavioral and neural processes for inhibitory control compared to CWNS. I predict that CWS will perform with reduced accuracy on HTKS and Go/No-Go compared to CWNS because previous studies suggest CWS have reduced inhibitory control compared to CWNS (Anderson & Wagovich, 2017; Eggers et al., 2013; Ntourou et al., 2018). Similarly, I predict that there will be differences between CWS and CWNS in the ERP components elicited by the Go/No-Go task, specifically with the N2 and P3, as suggested by previous studies (Piispala et al., 2016; Piispala et al., 2017). For example, I hypothesize that CWS will have smaller P3 mean amplitudes for the No-Go condition and larger N2 mean amplitudes for both conditions (Piispala et al., 2017). To address my second research question, I hypothesize that performance on Go/No-Go, especially ERP amplitudes for No-Go stimuli, will predict performance on HTKS for CWS. The meta-analysis study conducted by Ofoe et al. (2018) suggests differences in inhibitory control for CWS and CWNS, therefore, I predict there is a relationship between inhibitory tasks in CWS. To address my third research question, I have competing hypotheses due to the limited literature with inconsistent findings due to differences in methodologies. I hypothesize the relationships between behavioral and neural measures of inhibitory control will be stronger in CWS than CWNS. This is due to the belief that CWS have more difficulty with complex compared to simple inhibition tasks. Overall, CWNS may have stronger inhibition skills, leading to differences between CWS and CWNS becoming more apparent during difficult tasks. Given this, there may be a stronger relationship between simpler and complex inhibitory tasks in CWS than CWNS. Alternatively, the opposite can be predicted as well, being that performance on Go/No-Go and HTKS will be correlated more strongly in CWNS rather than CWS because their inhibitory control is more reliably regulated. As evidenced by previously mentioned studies, CWS have less consistent inhibition skills compared to CWNS (Anderson & Wagovich, 2017; Eggers et al., 2013).

2.4 Methods

2.4.1 Current Thesis Project and Study

The data for this study were previously collected as part of a larger project on attentional control in CWS. Data collection has already occurred for all participants described below. My thesis project involves design of this specific study, processing of all the data described below, and data analysis. All written aspects of this project have been completed by me as well.

2.4.2 Participants

Seventy-six participants between the ages of 3 and 8 years old were included in the current study, including 40 CWS and 36 CWNS. The mean age of CWS is 6.14 and the range is 3.89 to 8.84. Twenty CWS are males and 20 are females. The mean age of CWNS is 5.87 and the range is 3.11 to 8.57. 21 CWNS are males and 15 are females. Per parent report, all children were monolingual, native English speakers. Parents and caregivers of children reported 63 children as White, 2 as African American or Black, 8 as Multiple Races. The race of 3 children were unknown.

Parents and caregivers reported 61 children as Non-Hispanic/Latino and 8 as Hispanic/Latino. The ethnicity of 7 children were unknown. All participants had no history of developmental or acquired neurological, language, reading, hearing, or visual impairments, other than stuttering in CWS. Prior to participating in the study, all children passed a hearing screening at 500, 1000, 2000, 4000, 6000 and 8000 Hz at 20 dB SPL bilaterally. Children completed an abbreviated version of the Edinburgh Handedness Inventory (Oldfield, 1971), revealing 66 children were right-handed, 3 children were left-handed, and 4 children were ambidextrous. I did not have access to 3 children's handedness scores. Familial characteristics, including education, occupation, household income, and marital status, were collected to create a consensus measure of socioeconomic status (Pollak & Wolfe, 2020). Paternal and maternal occupation was converted to a job zone score using the Occupational Information Network (O*NET) database, which rates jobs in zones from 1-5 based on the knowledge, skills, and abilities needed to carry out a job (O*NET Resource Center, 2023). The means and standard deviations of this information can be found in Table 1. The Michigan State University Institutional Review Board approved this study.

Child participants included in this study were recruited from the local community, physician's offices, and speech-language clinics. Written consent for participation was provided by the participant's parents and caregivers. All children provided verbal consent. Children older than 7 years of age, also provided written consent. Children received compensation for their participation, including monetary payment and a small toy.

Several criteria were used to determine the presence of stuttering in children. The Stuttering Severity Instrument, Fourth Edition (SSI-4; Riley, 2009) was used to characterize stuttering severity. Children needed to score at least very mild to be included as children who stutter. Of the 40 CWS included in the present study, I had access to SSI-4 scores for 30 CWS. Average SSI-4 scores at the time of testing were 14.3, which corresponds with a “mild” severity. Speech and language samples were acquired by a speech-language pathologist in the laboratory in two ways. One sample was obtained during a spontaneous conversation and/or play and a second was obtained during the telling of a story using a wordless picture book as a guide (“Frog, Where Are You?”, Mayer, 1969; “Frog Goes to Dinner”, Mayer, 2003). Language samples were transcribed in CHAT and disfluencies were coded and analyzed using the FluCalc utility in the Child Language Analysis System (MacWhinney, 2000). The average number of stuttering-like disfluencies (SLDs) in words for the CWS was 5.19 and for the CWNS was 1.57. I had access to the total percent SLDs in words for all 40 CWS, but only 22 CWNS. An additional criterion was that all parents of CWS reported that their children were CWS.

All children included in the current study completed both behavioral and neurophysiological testing in the laboratory in separate sessions.

Table 1 Mean for Participant Characteristics

	Children who stutter (CWS)	Children who do not stutter (CWNS)
Age	6.14 years	5.87 years
Maternal Education	15.74	16.53
Paternal Education	14.79	16.12
Maternal Job Zone	3.65	4.25
Paternal Job Zone	3.16	3.79
% SLDs in Words	5.19%	1.57%
HTKS Total	91.90	87.61
HTKS Accuracy	78%	74%

Go Accuracy	92%	85%
No-Go Accuracy	64%	63%
Go Response Time	551.35 ms	532.17 ms

2.4.3 Behavioral Measures

2.4.3.1 Standardized Behavioral Measures

All children completed a battery of behavioral assessments (i.e., speech and language). The Core Language Index of the Clinical Evaluation of Language Fundamentals-Preschool, Second Edition (Wiig et al., 2004) or Clinical Evaluation of Language Fundamentals, Fifth Edition (CELF-5; Wiig et al., 2013), depending on the child's age, were administered to assess receptive and expressive language skills. Articulation and phonology skills were assessed using the Bankson Bernthal Test of Phonology, specifically the Word Inventory (WI), Consonant Inventory (CI), and Phonological Process Inventory (PPI) subtests (BBTOP; Bankson & Bernthal, 1990). The Primary Test of Nonverbal Intelligence (PTONI; Ehrler & McGhee, 2008) was administered to assess nonverbal reasoning abilities.

2.4.3.2 Head-Toes-Knees-Shoulders Task

The HTKS task was selected as a behavioral measure of inhibitory control. This task, which includes three test sections, was developed by McClelland et al. (2014) and revised by Gonzales et al. (2021). Prior to each test section, 3-4 practice items were presented to ensure understanding of instructions. In summary, this task requires participants to perform different actions than instructed and adapt to rule changes during the task.

Part 0 begins with an explanation to the participant: “When I say *head* you say *toes* and when I say *toes* you say *head*”. Four practice items are administered, followed by seven test items. With regard to scoring, 2 points are provided for each correct response/action, 1 point for self-corrections, and 0 points for incorrect responses. A child must earn a score greater than four in order to move on to Part 1. Part 1 begins with an explanation of the term “opposite” and instructions to perform the following actions: “When I say touch your *head,* you touch your *toes*” and “When I say touch your *toes,* you touch your *head.*” Clarification is obtained via three practice questions (e.g., “What do you do if I say: touch your *head*?”) and four practice trials (e.g., “Touch your *head*”), followed by 10 test stimuli. The participant continues to Part 2 if more than four points are scored. Part 2 introduces a novel command (e.g., “When I say touch your *knees,* you touch your *shoulders*” and vice versa). One clarification question and four practice trials are administered, followed by 10 test stimuli. Part 3 commences if the participant scores greater than four points. In Part 3, it is explained to the participant that the rules are switched (e.g., “When I say touch your *head*, you touch your *knees*”, “When I say touch your *shoulders*, you touch your *toes*”). Two practice questions, four practice trials, and 10 test stimuli are administered.

In total, there are 22 practice stimuli and 37 test stimuli, which equates to 59 items across Part 0 to Part 3. Scores range from 0 to 118 total points. This task does not require verbal responses from the participant, except for Part 0, which was excluded from analyses because not all participants completed this section. If this section was skipped due to meeting the passing criteria for Part 1, they were given full credit.

2.4.4 Electrophysiologic Measures

2.4.4.1 Go/No-Go Task

For the present study, a Go/No-Go task, called the Zoo Game, which was created by Grammer et al. (2014), was selected due to the child-friendly nature and relevance to inhibitory control. Children are told that in this game, they will be helping a zookeeper catch animals that escaped from the zoo and put them back in their cages. The participants are also told that there are three animals, orangutans, that are helping the zookeeper; therefore, they do not need to be captured. Children are instructed to press a button as quickly as possible each time an animal appears on the screen (Go Trial). They are also instructed to not press the button when an orangutan appears (No-Go Trial). This task involves one practice block and eight experiment blocks. The practice block has 12 trials, or pictures, including randomized zoo animals (9) and orangutans (3). After children are able to successfully complete the practice block, the subsequent eight blocks are completed. Each block contains 40 trials (30 novel zoo animals and 10 orangutans). All animal pictures were selected with consideration given to colors, size, and animal type. In total, each participant completes 320 trials. Each image was displayed on the screen for 750 ms. After each stimulus item, a black screen was presented for 500 ms. Before each image, a fixation cross appeared for a randomized period of time (between 200 and 300 ms, Figure 2. The participants could respond (i.e., press the button or inhibit action) at any point during image presentation or blank screen (total interval: 1250 ms). Figure 3 is an image of the “Zoo Map” slide that was shown following blocks 2, 4, 6, 7, and 8 to help participants monitor their progress on the task. This task requires only motoric finger press responses from the participant. No verbal responses are required.

Figure 2 Zoo Map

The zoo map displayed to participants following blocks 2, 4, 6, 7, and 8 for progress-monitoring purposes.

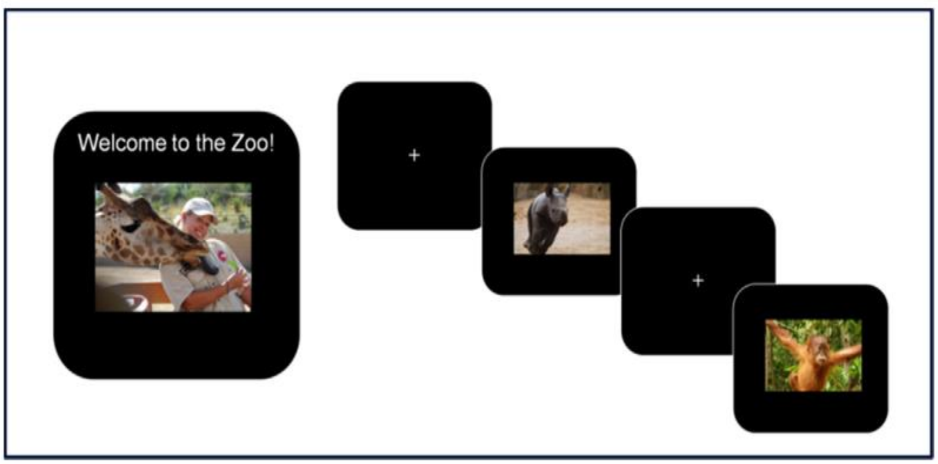

Figure 3 Go/No-Go Display

The Go/No-Go Zoo task, including the fixation cross, example animal images, and opening slide.

2.4.5 Procedures

Children visited the laboratory with their parents or caregivers on separate days for behavioral and neurophysiological testing. Each testing visit was approximately 1.5-2 hours in length. The purpose of the first session was to obtain consent and familiarize the participant with the laboratory setting. Throughout each visit, parents and caregivers could monitor their child through closed-circuit cameras placed in the testing room.

At the beginning of the EEG session, the participant's hearing was screened. Next, they were transitioned to the experiment room for electrode cap placement. Participants watched a movie or played a video game while this occurred. After, the child was transitioned to a comfortable chair in the sound-attenuating booth to complete the EEG tasks. A research assistant sat next to the child and provided all instructions and reinforcement throughout the session. Children were introduced to the Go/No-Go task and asked to remain very still throughout the task. Children were given breaks between each block to help reduce movement during the task and to encourage continued participation.

2.4.6 EEG Collection

Due to high levels of artifact, 7 participants were excluded, forming a finalized group of 20 CWS and 16 CWNS with usable EEG data. EEG data were collected via an elastic cap placed on the scalp and embedded with 32 Ag-Ag/Cl electrodes (Biosemi Active 2, Amsterdam, Netherlands). The location and position of electrodes was consistent with the international 10-20 system (American Electroencephalographic Society, 1994). Electrode channels were placed at the midline (Fz, FCz, Cz, CPz, Pz), laterally (F7/F8, FT7/FT8, T7/8, TP7/TP8, P7/P8), and mid-laterally (F3/F4, FC3/FC4, C3/4, CP3/CP4, P3/P4). In addition, horizontal and vertical eye movements were tracked by electrodes located below the left orbital ridge (vertical electrooculogram [VEOG]) and the right and left outer canthi (horizontal electrooculogram [HEOG]). The purpose of these channels was to monitor eye movement and to help eliminate EEG artifacts during data processing stages. Figure 4 provides an illustration of electrode locations on the scalp. EEG signals were recorded relative to the Common Mode Sense (CMS) electrode at 512 Hz. Electrical signals were down-sampled offline to 256 Hz.

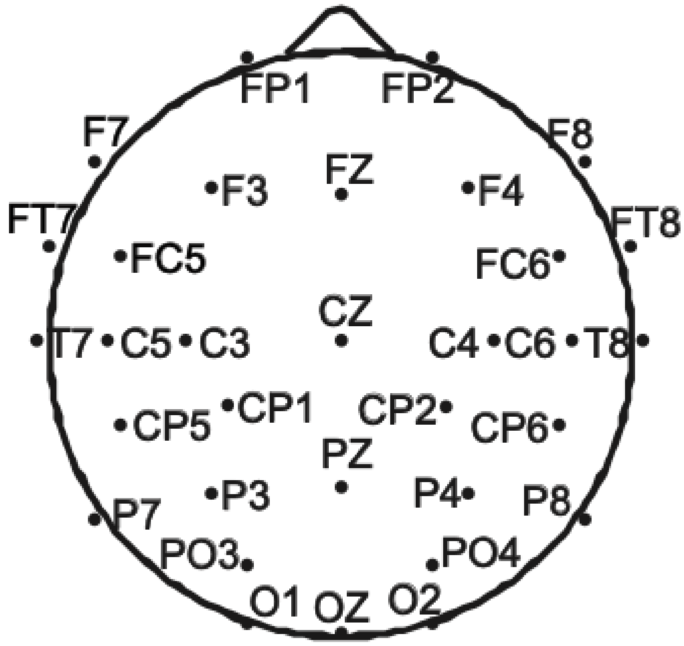

Figure 4 Electrode Cap

Location of electrodes placed on the scalp via an elastic cap.

2.4.7 EEG Data Processing

Analysis of EEG data were completed using MATLAB (Math-Works), EEGLAB (Delorme & Makeig, 2004), and ERPLAB (Lopez-Calderon & Luck, 2014). MATLAB scripts developed and generously provided by Dr. Elif Isbell from the University of California Merced and edited by Dr. Mandy Hampton Wray were used to process the data.

Eye movements, such as blinking, and other artifact were removed from continuous EEG data via independent component analysis (ICA). The purpose of ICA is to separate information into individual components, or sources, therefore unwanted movements (e.g., blinks) can be removed to create cleaner, usable data. ICA components that contained primarily eye artifact, that being greater than 80 percent eye artifact, were automatically identified and removed from the data. This resulted in subtraction of the eye movements, in addition to other artifact from existing EEG data.

After ICA artifact component removal, continuous EEG data were epoched from 100 ms before to 1000 ms after stimulus onset. The 100 ms prior to stimulus onset represents the baseline period. The baseline period is the time period immediately prior to the presentation of a new stimulus. Data from 100 ms before the stimulus onset, which was presented at time 0 ms, represented baseline activity. Each EEG epoch was baseline corrected prior to averaging for the purpose of normalizing the amplitude at stimulus onset. Each epoch underwent automatic artifact rejection using a 50 ms moving window voltage dependent artifact detection algorithm. Artifacts were marked if the change in EEG amplitude in an epoch was greater than 100 μV within a 200 ms window in eye channels or greater than or equal to 200 μV in all other channels. These signals were low-pass filtered at 40 Hz to reduce high frequency noise (with a 12 dB roll off).

After the data were cleaned through the removal of artifacts, ERP averages for each channel were generated by separately averaging Go and No-Go trials for each participant. Grand averages were created for each group by averaged ERP waveforms for each condition, Go and No-Go, across each participant within a group, CWS and CWNS. Averages included all responses, both correct and incorrect, for each Go and No-Go condition.

For each ERP component of interest, mean amplitudes, which represent the average voltage, or the area under the curve, were extracted within specific time windows based on previous studies (Johnstone et al., 2007; Jonkman, 2006; Jonkman et al., 2003; Lewin et al., 2023; Piispala et al., 2016; Piispala et al., 2017; Vuillier et al., 2016) and visual inspection of the current dataset. Time windows centered around the peak of each ERP component in grand averaged waveforms and were as follows: N1: 180-220 ms, P2: 250-350 ms, N2: 350-450 ms, and P3: 600-850 ms.

2.4.8 Statistical Analyses

I used the Statistical Package for the Social Sciences (SPSS) data software program to perform quantitative analysis on both behavioral and ERP data to address my research questions. Specifically, t-tests, repeated-measures ANOVAs, and linear regressions were used.

Do children who stutter (CWS) exhibit differences in behavioral and neural processes for inhibitory control compared to children who do not stutter (CWNS)?

Group differences in demographic information (age, material/paternal education, maternal/paternal job zone) and behavioral testing (PTONI Nonverbal Index, CELF Core Language Standard Score, HTKS Total Score, HTKS Percent Correct, Go Response Time, Go Accuracy, and No-Go Accuracy) were analyzed using two-tailed t-tests. In order to determine whether there were group differences in accuracy for the different conditions of HTKS, the practice and test trials for each HTKS condition were averaged and the average accuracy per condition was analyzed using a repeated-measures ANOVA with a between-groups factor (CWS, CWNS) and a within-groups factor of condition (trial set 1, 2, 3).

How are behavioral and neural processes for inhibitory control related in children who stutter (CWS)? Are relationships between behavioral and neural measures of inhibitory control similar in children who stutter (CWS) and children who do not stutter (CWNS)?

ERPs were analyzed using repeated-measures ANOVAs as well. Composite Regions of Interest (ROI) were determined based on previous studies (Johnstone et al., 2007; Jonkman, 2006; Jonkman et al., 2003; Lewin et al., 2023; Piispala et al., 2016; Piispala et al., 2017; Vuillier et al.,

2016) and visual inspection, determining the electrode sites over which the ERP responses were most prominent. For N1, P2, and N2, the electrode sites averaged together to create the ROI were F3, F4, FC5, FC6, C5, C6, C3, C4, P3, and P4. For P3, the electrode sites averaged together to create the ROI had a more centroparietal distribution, consistent with P3 distribution in previous studies (e.g., Johnstone et al., 2007; Jonkman, 2006; Jonkman et al., 2003). ROI electrodes were C3, C4, CP5, CP6, P3, P4, P7, P8, PO3, and PO4. Separate repeated-measures ANOVAs were used for each ERP component (N1, P2, N2, P3) with a between-groups factor of group (CWS, CWNS) and a within-groups factor of condition (Go all trials, No-Go all trials).

Linear regressions were performed to evaluate the relationship between HTKS accuracy (overall percent correct) and individual ERP components elicited by the Go and No-Go conditions (N1, P2, N2, P3) for each group (all participants, CWNS, CWS). HTKS accuracy was regressed on ROI mean amplitudes for each component and condition (i.e., N1 No-Go all trials, P2 No-Go all trials, N2 No-Go all trials, P3 No-Go all trials). If a significant correlation was found between HTKS accuracy and a specific ERP component, then additional linear regressions were performed between HTKS Part 1, 2, and 3 accuracy and that ERP component to determine whether the overall correlation was driven by one specific part of the HTKS task.

3.0 Results

3.1 Demographic Information

There were no statistically significant differences between groups for participant age, maternal education, PTONI nonverbal index, or CELF core language standard scores (all $t(71)<1.77$, all $p>0.081$). There were significant differences between groups for paternal education ($t(70)=2.58$, $p=0.012$), maternal job zone score ($t(61)=2.52$, $p=0.014$), and paternal job zone score ($t(68)=2.48$, $p=0.016$), with CWNS having higher scores in each category than CWS.

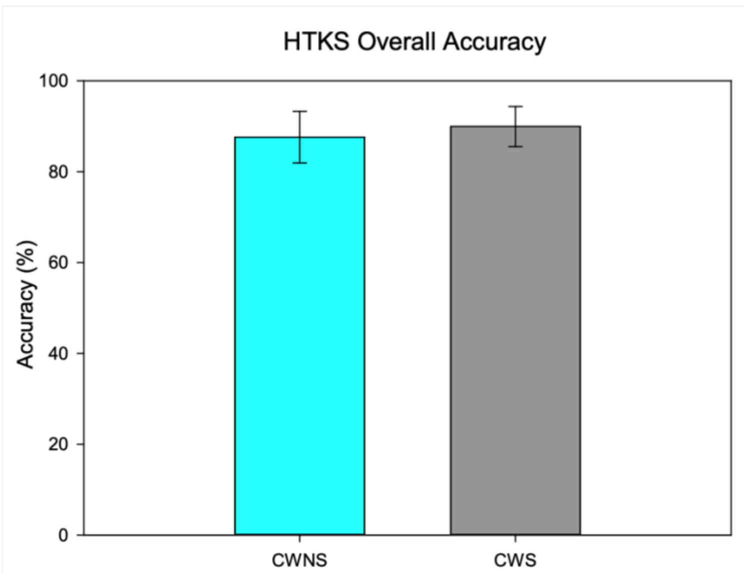

Figure 5 HTKS Bar Graph

Bar graph showing HTKS overall accuracy in percept for CWS (gray) and CWNS (blue).

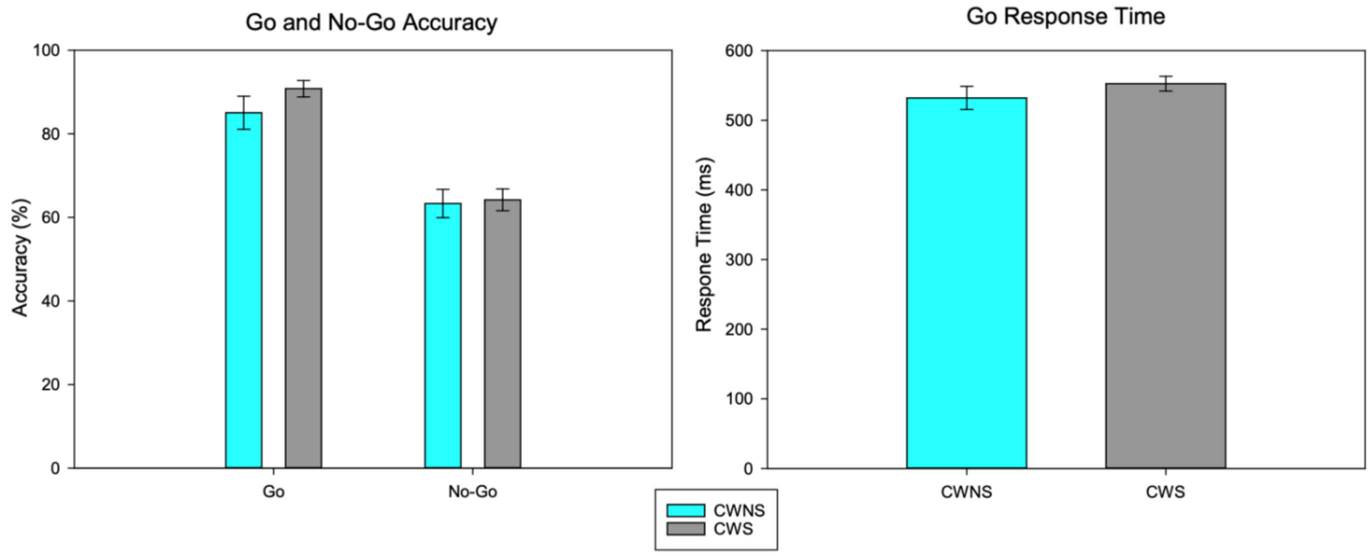

Figure 6 Go/No-Go Bar Graphs

Left bar graph showing Go and No-Go accuracy in percept for CWS (gray) and CWNS (blue). Right bar graph showing the response time for the Go condition in ms for CWS (gray) and CWNS (blue).

3.2 Behavioral Findings

The mean percent correct for HTKS was 74% for CWNS and 78% for CWS (Figure 5). The mean response time for Go trials was 532.17 ms for CWNS and 551.35 ms for CWS (Figure 6). The percent accuracy for Go trials was 85% for CWNS and 92% for CWS (Figure 6). The percent accuracy for No-Go trials was 63% for CWNS and 64% for CWS. There were no statistically significant differences between groups on HTKS or Go or No-Go behavioral accuracy or Go response time (all $t(74)<1.6$, all $p>0.106$).

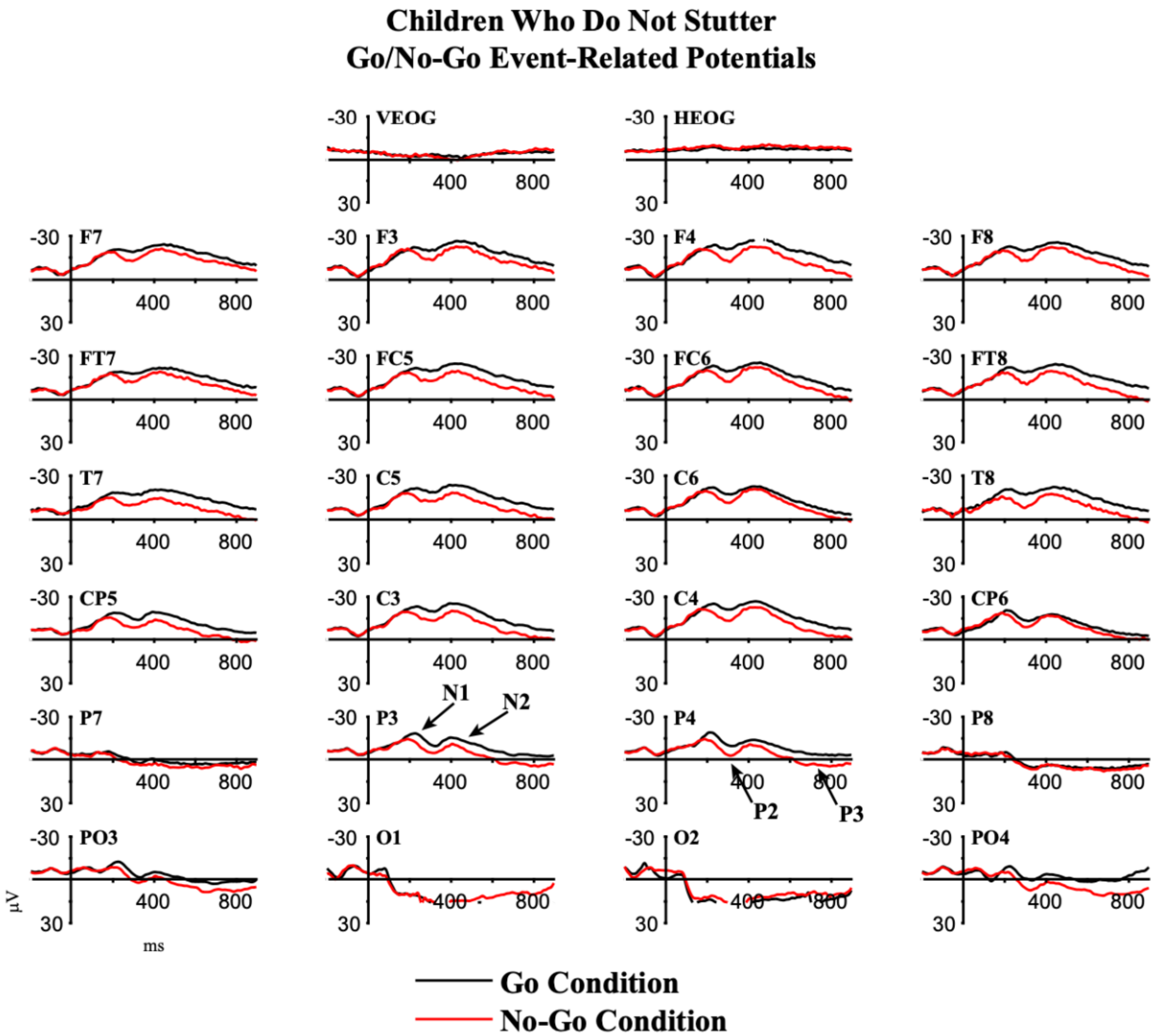

Figure 7 CWNS ERPs

Electrophysiological responses elicited by Go (black) and No-Go (red) trials in CWNS. This figure shows ERPs over all of the electrode locations included in the analyses. Each component is marked with an arrow (N1, P2, N2, P3).

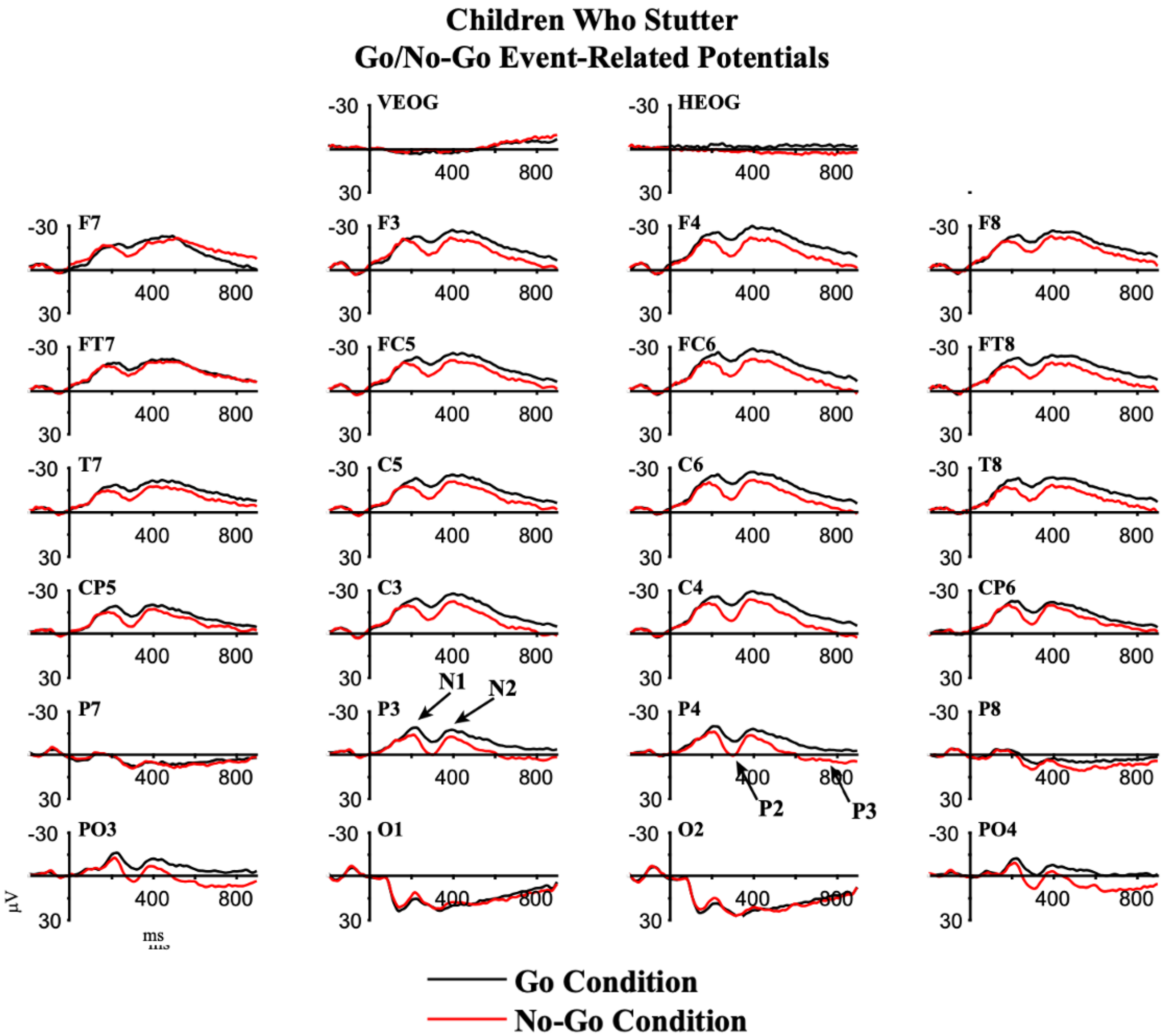

Figure 8 CWS ERPs

Electrophysiological repsonses elicited by Go (black) and No-Go (red) trials in CWS. This figure shows ERPs over all of the electrode locations included in the analyses. Each component is marked with an arrow (N1, P2, N2, P3).

3.3 N1

ERPs elicited by the Go and No-Go conditions for the CWNS and CWS are illustrated in Figure 7 and Figure 8 respectively. For the N1 ERP component, there was a condition effect between Go and No-Go mean amplitudes ($F(1,34)<1=20.49$, $p<0.001$, $n_p^2=0.376$), with larger amplitudes elicited by the Go condition (i.e., more negative). There was no interaction between group and condition ($F(1,34)<1$, $p=0.583$), and no overall group effect ($F(1,34)<1$, $p=0.748$).

There were no statistically significant correlations between overall HTKS accuracy and the N1 ERP component for Go or No-Go mean amplitude for CWNS, CWS, or across both groups (all $r<-0.441$, all $p>0.057$).

3.4 P2

For the P2 ERP component, there was a condition effect between Go and No-Go mean amplitudes ($F(1,34)=65.17$, $p<0.001$, $n_p^2=0.657$), with larger amplitudes elicited by the No-Go condition (i.e., more positive). There was no interaction between group and condition ($F(1,34)=0.103$, $p=0.751$) and no overall group effect ($F(1,34)=0.103$, $p=0.751$).

When CWS were looked at independently, there was a statistically significant correlation between overall HTKS accuracy and the P2 mean amplitude elicited by the No-Go condition ($r=0.378$, $p=0.05$). Also, for CWS, there was a statistically significant correlation between HTKS Part 3, which is the final, most complex section of the task involving two rule changes that are different from previous parts (e.g., “When I say touch your head, you touch your knees” and vice versa; "When I say touch your shoulders, you touch your toes” and vice versa), and the P2 mean amplitude for No-Go trials (r=0.413, p=0.035). For CWS, there were no statistically significant correlations between Part 1 or Part 2 accuracy and No-Go P2 mean amplitude (all r<0.328, all p>0.079). There were no statistically significant correlations for CWS between HTKS accuracy and P2 Go mean amplitude (r=0.067, p=0.390).

There were no other statistically significant correlations between overall HTKS accuracy and P2 Go or No-Go mean amplitude for CWNS or across both groups (all r<-0.336, all p>0.101).

3.5 N2

For the N2 ERP component, there was a condition effect between Go and No-Go mean amplitudes (F(1,34)=24.297, p<0.001, n_p^2=0.419), with larger amplitudes elicited by the Go condition (i.e., more negative). There was no interaction between group and condition (F(1,34)=0.123, p=0.728) and no overall group effect (F(1,34)=0.123, p=0.728).

There were no statistically significant correlations between overall HTKS accuracy and N2 Go or No-Go mean amplitude for CWNS, CWS, or across both groups (all r<0.339, all p>0.072).

3.6 P3

For the P3 ERP component, there was a condition effect between Go and No-Go mean amplitudes (F(1,34)=21.982, p<0.001, n_p^2=0.393), with larger amplitudes elicited by the No-Go condition (i.e., more positive). There was no interaction between group and condition (F(1,34)=0.173, p=0.680) and no overall group effect (F(1,34)=3.161, p=0.84).

Across all participants, there was a statistically significant correlation between overall HTKS accuracy and the P3 mean amplitudes elicited by the Go condition (r=-0.330, p=0.025). Looking specifically at individual HTKS tasks across all participants, there was a statistically significant correlation between HTKS Part 1, which is the first, most simple section of the task involving one rule (i.e., “When I say touch your head, you touch your toes" and vice versa), and the P3 Go mean amplitude (r=-0.333, p=0.024). The correlation between HTKS Part 2, which is the second section of the task that introduces a new rule to follow in addition to the first rule (i.e., “When I say touch your knees, you touch your shoulders” and vice versa), and the P3 Go mean amplitude was also significant (r=-0.288, p=0.044). HTKS Part 3, which is the final, most complex section of the task involving two rule changes that are different from previous parts (e.g., “When I say touch your head, you touch your knees” and vice versa, "When I say touch your shoulders, you touch your toes” and vice versa), and the P3 Go mean amplitudes were also correlated (r=-0.284, p=0.047). These results reveal that P3 mean amplitudes elicited by the Go condition were correlated with overall HTKS performance as well as performance on each subsection of the task (Parts 1, 2, and 3). There were no statistically significant correlations between HTKS accuracy and P3 No-Go mean amplitude for all participants (r=-0.120, p=0.243).

For CWNS, there was a statistically significant correlation between overall HTKS accuracy and the P3 mean amplitude elicited by the Go condition (r=-0.428, p=0.049). There were no statistically significant correlations between HTKS Parts 1, 2, or 3 and the P3 Go mean amplitude (all r<-0.390, all p>0.68). Also, there were no statistically significant correlations between overall HTKS accuracy and the P3 No-Go mean amplitude (r=-0.221, p=0.206).

For CWS, there were no statistically significant correlations between overall HTKS accuracy and the P3 Go or No-Go mean amplitudes (all r<0.282, all p>0.114).

4.0 Discussion

The purpose of the present study was to compare behavioral and neural processes of inhibition in children who stutter (CWS) and children who do not stutter (CWNS). My research questions included: 1) Do CWS exhibit differences in behavioral and neural processes for inhibitory control compared to CWNS? 2) How are behavioral and neural processes for inhibitory control related in CWS? 3) Are relationships between behavioral and neural measures of inhibitory control similar in CWS and CWNS?

4.1 Behavioral Findings

I found that were no statistically significant differences between groups (CWS and CWNS) for accuracy on the behavioral tasks included in this study (HTKS, Go/No-Go). This suggests that CWS and CWNS perform these inhibitory control tasks comparably. I am unaware of studies to date comparing these two specific behavioral tasks, but when CWS and CWNS were compared by Eggers et al. (2013) on a behavioral No-Go task, inhibitory control differences were found between CWS and CWNS, including more premature responses and false alarms and slower reaction times on independent inhibitory tasks. The participants in this study ranged from age 4 to 10 years (Eggers et al., 2013). Ntourou et al. (2018) examined executive function abilities in CWS and CWNS, including inhibition, through HTKS and found that the 3-year-old CWS performed worse than the same-aged CWNS, but there were no differences for the 4- and 5-year-olds. The present study included participants ranging from 3 to 8, which may contribute to the difference in findings.

4.2 Neural Findings

As expected, there were differences between Go and No-Go mean amplitudes for all ERP components (N1, N2, P2, P3), meaning the ERP components are sensitive to cognitive-related processes. These results are consistent with previously published studies (Donkers & van Boxtel, 2004; Falkenstein et al., 1999; Johnstone et al., 2005; Jonkman, 2006; Jonkman et al., 2003; Piispala et al., 2016; Piispala et al., 2017; Vuillier et al., 2016).

In previous literature, the N1 has been found to reflect attention and discrimination abilities (Luck, 2014). Johnstone et al. (2005) found the N1 to be more negative during the No-Go compared to the Go condition. This is not consistent with the current findings because N1 was more negative during the Go condition. Although there is limited information about the P2, it has been found to relate to selective attention (Wongupparaj et al., 2018) and stimulus classification (García-Larrea et al., 1992). N2 has been found to reflect conflict monitoring and inhibitory control (Donkers & van Boxtel, 2004; Falkenstein et al., 1999; Johnstone et al., 2007; Piispala et al., 2016; Piispala et al., 2017; Pliszka et al., 2000; Smith, 2011; Vuillier et al., 2016). Per the "No-Go effect", the N2 is typically more enhanced (i.e., more negative) during the No-Go condition (Donkers & van Boxtel, 2004; Falkenstein et al.,1999; Jonkman, 2006; Jonkman et al., 2003; Piispala et al., 2016; Piispala et al., 2017; Vuillier et al., 2016). Interestingly, the present study found that the N2 was more negative during the Go condition. Previous studies have suggested that P3, specifically related to the No-Go mean amplitude, represents a marker of response inhibition (Donkers & Van Boxtel, 2004; Piispala et al., 2016; Piispala et al., 2017). The P3 is most commonly enhanced (i.e., more positive) during the No-Go condition (Johnstone et al., 2005; Jonkman, 2006; Jonkman et al., 2003; Piispala et al., 2016), which was seen in the present study as well.

The differences between the present study compared to previous studies, specifically relating to N1 and N2 results, may be attributed to the images used for Go in the Zoo game Go/No-Go task (Lewin et al., 2023). The Go stimuli in the Zoo game include different pictures of animals, while the Go stimuli in other Go/No-Go tasks are usually identical images.

Importantly, in the current study, no statistically significant differences were found in ERP mean amplitudes for the Go or No-Go conditions between CWS and CWNS. This may suggest that the neural processes necessary to complete this inhibitory task are comparable between groups, which aligns with the behavioral results. If there are underlying differences, they are not evident on the specific tasks used in this study. Perhaps other more challenging inhibitory control tasks would elicit group differences. It is important to note the Go/No-Go task used in this study, the Zoo task, uses Go stimuli consisting of different images of animals. The Zoo task may require additional cognitive processing to remain engaged with the stimuli. This could be considered a limitation of the present study because the P3 ERP response, which has been found to represents working memory (Luck, 2014), cannot become as habituated to the Go stimuli as may be possible in other Go/No-Go tasks. While Piispala et al. (2016) reported differences in the P3 peak latency for the Go condition between groups, our data did not reveal a reliable P3 peak to measure peak latency, therefore, we are unable to make a direct comparison to these findings. However, in the current study, our ERP results suggest that behavioral and neural processes for inhibitory control are similar in CWS and CWNS.

4.3 Relationship Between Behavioral and Neural Findings

The current study is the first to my knowledge to compare the HTKS behavioral task with ERP components elicited by a Go/No-Go task. Despite there being no statistically significant differences in behavioral or neural patterns between CWS and CWNS, there were a few meaningful correlations between behavior and ERP components.

There were no statistically significant differences for CWS, CWNS, or across both groups between HTKS accuracy and the N1 or N2 ERP components for Go or No-Go mean amplitudes, suggesting that CWS and CWNS have similar discrimination abilities for processing stimuli (Johnstone et al., 2005; Luck, 2014) and similar inhibitory control mechanisms (Falkenstein et al., 1999; Johnstone et al., 2007; Piispala et al., 2016; Piispala et al., 2017; Pliszka et al., 2000; Vuillier et al., 2016), respectively.

There was a positive correlation between HTKS accuracy and the P2 mean amplitude for the No-Go condition for CWS only, with more accurate HTKS performance associated with larger P2 mean amplitudes. No relationships were observed for CWNS or across both groups. Further analyses revealed a relationship specifically between HTKS Part 3 and No-Go P2 mean amplitudes for CWS. The P2 has been suggested to be an index of attention modulation (Wongupparaj et al., 2018). In other words, P2 reflects the processing of stimuli, both familiar and novel. These results may suggest that CWS who perform better on the HTKS task have increased attentional engagement for the No-Go condition, indicated by a larger P2 response. Part 3 of HTKS is the most complex section because children are required to disregard the previous two rules they learned and adopt two novel rules. CWS may require more allocation of attention to complete the task accurately. Thus, the statistically significant relationship seen may suggest that CWS who have more robust attentional engagement during the No-Go condition, which requires withholding a behavioral response, also perform better on this complex rule-changing task, which requires active inhibition of previous rules to learn and use a new set of rules. CWNS may not need to recruit the same number of attentional resources to support their inhibition during the Zoo or HTKS task. With this being said, it is important to note that replication of this study with a larger sample size is needed to further evaluate this suggestion.

There were also statistically significant relationships across all participants between HTKS accuracy and P3 mean amplitude for the Go condition. These relationships across participants were observed between accuracy on HTKS Parts 1, 2, and 3 and Go P3 mean amplitudes. Significant correlations between HTKS accuracy and Go P3 mean amplitudes in CWNS, but not CWS, suggest that the significant correlation across participants is largely influenced by the CWNS group. Previous literature has shown that P3 reflects the detection of change and requires working memory to update and reallocate attention (Luck, 2014). This negative correlation may suggest an inverse relationship between HTKS accuracy and Go P3 mean amplitudes. When Go P3 mean amplitudes are smaller, HTKS accuracy is larger because less attention is needed to update working memory responses because the Go stimuli are consistent over time (i.e., there are more Go stimuli than No-Go during the Zoo task). Increased efficiency on the Go/No-Go task appears to be associated with increased accuracy on the HTKS task, particularly in CWNS. Interestingly, this pattern is seen for all HTKS parts (Part 1, 2, and 3) across participants. A potential explanation may be that children who are better able to complete the HTKS task may also be able to more efficiently use their attention when a task becomes more familiar, as with the Go condition. Another potential explanation for this relationship may be that in the Zoo task, the P3 occurs very late in time, between 600-900 ms after the stimulus. The timing of the P3 overlaps with the timing of when the participants are providing a motor response to the stimuli, typically between 400-600 ms after the stimulus. Therefore, the motor response to the Go stimulus may be influencing the P3 mean amplitudes, influencing the relationships between Go P3 mean amplitude and HTKS accuracy. Additional studies are necessary to more completely understand this relationship and confirm if motor responses are influencing the P3 for the Go condition. While this hypothesis cannot be definitely concluded from our data, it is a caveat to consider in the correlation between HTKS accuracy the Go P3 mean amplitude.

4.4 Limitations

There are several limitations to the current study. First, although my total sample size included 76 participants, only 36 of these children had usable EEG data. Therefore, I had more behavioral data to analyze and obtain valuable results from. Additionally, although there were a few statistically significant correlations found between HTKS and the P2 and P3 ERP components, these correlations have the potential to be strengthened or weakened with an increased sample size. Due to the small sample size, the results of the current study are not generalizable to the greater population. Second, this study included a wide age range of participants, 3 to 8 years of age, spanning approximately 5 years between the youngest and oldest participant. There are many significant developmental changes that occur between these years, including behavioral and neural advancements in inhibitory control. This may contribute to the limited differences found between CWS and CWNS. Third, interestingly, about 75% of CWS naturally recover between 2-4 years post-stuttering onset (Yairi & Seery, 2015). This is a limitation because it is possible that some of our participants who stutter may naturally recover over the next few years. This may have an impact on their current and future neural and behavioral processing, contributing to the pattern of differences found in the current study.

4.5 Future Research

It would be interesting to repeat the present study with a larger sample size for both behavioral and neural tasks with more specific age ranges to account for developmental differences across the lifespan (e.g., 3 to 5 years, 5 to 8 years). This would be beneficial for further pinpointing the specific behavioral or neural differences relating to cognitive processes (e.g., inhibition, working memory, attention). Also, it would be interesting to repeat this study with a different Go/No-Go task that uses a more consistent Go stimuli. In the Zoo task, the Go stimuli consist of different types of animals. This may have impacted the brain's neurological responses when processing the stimuli. Additionally, it would be beneficial to create a similar study using tasks with increased complexity. While HTKS is more complex than Go/No-Go, both are relatively straight-forward. Perhaps differences between groups would appear if the tasks were more cognitively demanding.

4.6 Conclusions

The findings of the current study suggest that CWS and CWNS perform similarly, both behaviorally and neurologically, on tasks involving inhibitory control, despite task complexity differences between HTKS and Go/No-Go. There were no significant differences found between

HTKS and Go/No-Go behavioral performance across both groups. Additionally, there were no significant differences between CWS and CWNS for ERP mean amplitude elicited by the Go-No/Go task. The analyses performed between HTKS and Go/No-Go ERP mean amplitudes yielded only few significant correlations. First, there was a relationship between HTKS accuracy and the P2 mean amplitude for the No-Go condition for CWS only, with more accurate HTKS performance associated with larger P2 mean amplitudes. Further analyses revealed a relationship specifically between HTKS Part 3 and No-Go P2 mean amplitudes for CWS. This finding suggests that in CWS, increased attentional engagement, which is needed to withhold a response during the No-Go condition of the Go/No-Go task, indicated by larger P2 responses, may support stronger performance on HTKS, especially on the complex rule-changing section. Second, there were also statistically significant relationships across all participants between HTKS accuracy and P3 mean amplitude for the Go condition, which was suspected to be heavily influenced by CWNS. These relationships across participants were observed between accuracy on HTKS Parts 1, 2, and 3 and Go P3 mean amplitudes. This suggests when children, across both groups, are able to use their attention more efficiently during tasks with more familiarity, as with the Go condition in the Go/No-Go task, they perform better on all parts of the inhibitory control task (HTKS). Together, these preliminary findings suggest that relationships between behavioral responses and neural processes that regulate inhibition may differ in subtle ways between CWS and CWNS. Replication of this study with a larger sample size is needed to confirm the findings of this study.

Bibliography

Anderson, & Ofoe, L. C. (2019). The role of executive function in developmental stuttering. *Seminars in Speech and Language, 40*(4), 305–319. https://doi.org/10.1055/s-0039-1692965

Anderson, & Wagovich, S. A. (2017). Explicit and implicit verbal response inhibition in preschool-age children who stutter. *Journal of Speech, Language, and Hearing Research, 60*(4), 836–852. https://doi.org/10.1044/2016_JSLHR-S-16-0135

Bankson, N. W., & Bernthal, J. E. (1990). *Bankson- Bernthal Test of Phonology (BBTOP).* Pro-Ed, Inc.

Barry, & De Blasio, F. M. (2013). Sequential processing in the equiprobable auditory Go/NoGo task: A temporal PCA study. *International Journal of Psychophysiology, 89*(1), 123–127. https://doi.org/10.1016/j.ijpsycho.2013.06.012

Beal, Gracco, V. L., Brettschneider, J., Kroll, R. M., & De Nil, L. F. (2013). A voxel-based morphometry (VBM) analysis of regional grey and white matter volume abnormalities within the speech production network of children who stutter. *Cortex, 49*(8), 2151–2161. https://doi.org/10.1016/j.cortex.2012.08.013

Bokura, Yamaguchi, S., & Kobayashi, S. (2001). Electrophysiological correlates for response inhibition in a Go/NoGo task. *Clinical Neurophysiology, 112*(12), 2224–2232. https://doi.org/10.1016/S1388-2457(01)00691-5

Bruin, Wijers, A., & van Staveren, A. S. (2001). Response priming in a go/nogo task: do we have to explain the go/nogo N2 effect in terms of response activation instead of inhibition? *Clinical Neurophysiology, 112*(9), 1660–1671. https://doi.org/10.1016/S1388-2457(01)00601-0

Bruin, & Wijers, A. (2002). Inhibition, response mode, and stimulus probability: a comparative event-related potential study. *Clinical Neurophysiology, 113*(7), 1172–1182. https://doi.org/10.1016/S1388-2457(02)00141-4

Cameron Ponitz, McClelland, M. M., Jewkes, A. M., Connor, C. M., Farris, C. L., & Morrison, F. J. (2008). Touch your toes! Developing a direct measure of behavioral regulation in early childhood. *Early Childhood Research Quarterly, 23*(2), 141–158. https://doi.org/10.1016/j.ecresq.2007.01.004

Carlson, S., & Wang, T. (2007). Inhibitory control and emotion regulation in preschool children. *Cognitive Development, 22*(4), 489–510. https://doi.org/10.1016/j.cogdev.2007.08.002

Chang, S. E., & Guenther, F. H. (2020). Involvement of the cortico-basal ganglia-thalamocortical loop in developmental stuttering. *Frontiers in Psychology, 10*, 3088. https://doi.org/10.3389/fpsyg.2019.03088

Chang. S. E., & Zhu, D. C. (2013). Neural network connectivity differences in children who stutter. *Brain, 136*, 3709-3726. https://doi.org/10.1093/brain/awt275

Chang, S. E., Zhu, D. C., Choo, A. L., & Angstadt, M. (2015) White matter neuroanatomical differences in young children who stutter. *Brain, 138*, 694-711. https://doi.org/10.1093/brain/awu400

Christ, White, D. A., Mandernach, T., & Keys, B. A. (2001). Inhibitory control across the life span. *Developmental Neuropsychology, 20*(3), 653–669. https://doi.org/10.1207/S15326942DN2003_7

Clark, J. (1996). Contributions of inhibitory mechanisms to unified theory in neuroscience and psychology. *Brain and Cognition, 30*(1), 127–152. https://doi.org/10.1006/brcg.1996.0008

Diamond A. (2013). Executive functions. *Annual Review of Psychology, 64*, 135–168. https://doi.org/10.1146/annurev-psych-113011-143750

Delorme, A., & Makeig, S. (2004). EEGLAB: An open source tool- box for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods, 134*(1), 9–21. https://doi.org/10.1016/j.jneumeth.2003.10.009

Dollaghan, C., & Campbell, T. F. (1998). Nonword repetition and child language impairment. *Journal of Speech, Language, and Hearing Research, 41*(5), 1136–1146. https://doi.org/10.1044/jslhr.4105.1136

Donkers, & van Boxtel, G. J. . (2004). The N2 in go/no-go tasks reflects conflict monitoring not response inhibition. *Brain and Cognition, 56*(2), 165–176. https://doi.org/10.1016/j.bandc.2004.04.005

Dustman, Emmerson, R. Y., & Shearer, D. E. (1996). Life span changes in electrophysiological measures of inhibition. *Brain and Cognition, 30*(1), 109–126. https://doi.org/10.1006/brcg.1996.0007

Eggers, K.(2012).*Temperament characteristics of children with developmental stuttering: From parent questionnaire to neuro-psychological paradigms* (Doctoral thesis, Katholieke Universiteit Leuven and Tilburg University). http://pure.uvt.nl/ws/files/1456864

Eggers, De Nil, L. F., & Van den Bergh, B. R. (2013). Inhibitory control in childhood stuttering. *Journal of Fluency Disorders, 38*(1), 1–13. https://doi.org/10.1016/j.jfludis.2012.10.001

Ehrler, D. J., & McGhee, R. L. (2008). *Primary Test of Nonverbal Intelligence (PTONI)*. Pro-Ed.

Eimer. (1993). Effects of attention and stimulus probability on ERPs in a Go/Nogo task. *Biological Psychology, 35*(2), 123–138. https://doi.org/10.1016/0301-0511(93)90009-W

Falkenstein, Hoormann, J., & Hohnsbein, J. (1999). ERP components in Go/Nogo tasks and their relation to inhibition. *Acta Psychologica, 101*(2), 267–291. https://doi.org/10.1016/S0001-6918(99)00008-6

Falkenstein, Hoormann, J., & Hohnsbein, J. (2002). Inhibition-related ERP components: Variation with modality, age, and time-on-task. *Journal of Psychophysiology, 16*(3), 167–175. https://doi.org/10.1027//0269-8803.16.3.167

Falkenstein, Koshlykova, N. ., Kiroj, V. ., Hoormann, J., & Hohnsbein, J. (1995). Late ERP components in visual and auditory Go/Nogo tasks. Electroencephalography and Clinical *Neurophysiology / Evoked Potentials Section, 96*(1), 36–43. https://doi.org/10.1016/0013-4694(94)00182-K

García-Larrea, Lukaszewicz, A.-C., & Mauguiére, F. (1992). Revisiting the oddball paradigm. Non-target vs neutral stimuli and the evaluation of ERP attentional effects. *Neuropsychologia, 30*(8), 723–741. https://doi.org/10.1016/0028-3932(92)90042-K

Garon, Bryson, S. E., & Smith, I. M. (2008). Executive function in preschoolers: A review using an integrative framework. *Psychological Bulletin, 134*(1), 31–60. https://doi.org/10.1037/0033-2909.134.1.31

Gonzales, Bowles, R., Geldhof, G. J., Cameron, C. E., Tracy, A., & McClelland, M. M. (2021). The Head-Toes-Knees-Shoulders Revised (HTKS-R): Development and psychometric properties of a revision to reduce floor effects. *Early Childhood Research Quarterly, 56*, 320–332. https://doi.org/10.1016/j.ecresq.2021.03.008

Grammer, Carrasco, M., Gehring, W. J., & Morrison, F. J. (2014). Age-related changes in error processing in young children: A school-based investigation. *Developmental Cognitive Neuroscience, 9(C)*, 93–105. https://doi.org/10.1016/j.dcn.2014.02.001

Hee, Xu, Y., & Krieg, A. (2018). Validation of the Head–Toes–Knees–Shoulders task in Native Hawaiian and non-Hawaiian children. *Early Childhood Research Quarterly, 44*, 192–205. https://doi.org/10.1016/j.ecresq.2017.12.007

Johnstone, Dimoska, A., Smith, J. L., Barry, R. J., Pleffer, C. B., Chiswick, D., & Clarke, A. R. (2007). The development of stop-signal and Go/Nogo response inhibition in children aged 7–12 years: Performance and event-related potential indices. *International Journal of Psychophysiology, 63*(1), 25–38. https://doi.org/10.1016/j.ijpsycho.2006.07.001

Johnstone, Pleffer, C. B., Barry, R. J., Clarke, A. R., & Smith, J. L. (2005). Development of inhibitory processing during the Go/NoGo task: A behavioral and event-related potential study of children and adults. *Journal of Psychophysiology, 19*(1), 11–23. https://doi.org/10.1027/0269-8803.19.1.11

Jonkman, L. M. (2006). The development of preparation, conflict monitoring and inhibition from early childhood to young adulthood; a Go/Nogo ERP study. *Brain Research, 1097*(1), 181–193. https://doi.org/10.1016/j.brainres.2006.04.064

Jonkman, L. M., Lansbergen, J. E., Stauder, A. (2003). Developmental differences in behavioral and event-related brain responses associated with response preparation and inhibition in a go/nogo task. *Psychophysiology, 40*(5), 752-761. https://doi.org/10.1111/1469-8986.00075.

Kok, A. (1986). Effects of degradation of visual stimuli on components of the event-related potential (ERP) in go/nogo reaction tasks. *Biological Psychology*, *23*(1), 21–38. https://doi.org/10.1016/0301-0511(86)90087-6

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), 080–094. https://doi.org/10.1055/s-0034-1371753

Kraft, S. J., Lowther, E., & Beilby, J. (2019). The role of effortful control in stuttering severity in children: Replication study. *American Journal of Speech-Language Pathology, 28*(1), 14–28. https://doi.org/10.1044/2018_AJSLP-17-0097

Toplak, West, R. F., & Stanovich, K. E. (2013). Practitioner Review: Do performance-based measures and ratings of executive function assess the same construct? *Journal of Child Psychology and Psychiatry, 54*(2), 131–143. https://doi.org/10.1111/jcpp.12001

Trommer, Hoeppner, J.-A. B., Lorber, R., & Armstrong, K. J. (1988). The Go-No-Go paradigm in attention deficit disorder. *Annals of Neurology*, *24*(5), 610–614. https://doi.org/10.1002/ana.410240504

Lopez-Calderon, J., & Luck, S. J. (2014). ERPLAB: An open- source toolbox for the analysis of event-related potentials. *Frontiers in Human Neuroscience, 8*, 213. https://doi.org/10.3389/fnhum.2014.00213

Luck, S. J. (2014). *An introduction to the event-related potential technique.* (2nd ed.). MIT Press.

Luck, S. J., Woodman, G. F., & Vogel, E. K. (2000). Event-related potential studies of attention. *Trends in Cognitive Sciences, 4*(11), 432-440. https://doi.org/10.1016/s1364-6613(00)01545-x

Lewin, K. M., Meshi, D., Alade, F., Lescht, E., Herring, C., Devaraju, D. S., & Hampton Wray, A. (2023). Children's screentime is associated with reduced brain activation during an inhibitory control task: A pilot EEG study. *Frontiers in Cognition*. *2.* https://doi.org/10.3389/fcogn.2023.1018096

MacWhinney, B. (2000). The CHILDES Project: Tools for Analyzing Talk. 3rd Edition. Mahwah, NJ: *Lawrence Erlbaum Associates.*

Mayer, M. (1969). *Frog, where are you?* New York, Dial Press.

Mayer, M. (2003). *Frog goes to dinner*. New York, Dial Press.

McClelland, Cameron, C. E., Connor, C. M., Farris, C. L., Jewkes, A. M., & Morrison, F. J. (2007). Links between behavioral regulation and preschoolers' literacy, vocabulary, and math skills. *Developmental Psychology, 43*(4), 947–959. https://doi.org/10.1037/0012-1649.43.4.947

McClelland, Cameron, C. E., Duncan, R., Bowles, R. P., Acock, A. C., Miao, A., & Pratt, M. E. (2014). Predictors of early growth in academic achievement: the head-toes-knees-shoulders task. *Frontiers in Psychology, 5*, 599–599. https://doi.org/10.3389/fpsyg.2014.00599

Nieuwenhuis, Yeung, N., van den Wildenberg, W., & Ridderinkhof, K. . (2003). Electrophysiological correlates of anterior cingulate function in a go/no-go task: Effects of response conflict and trial type frequency. *Cognitive, Affective, & Behavioral Neuroscience, 3*(1), 17–26. https://doi.org/10.3758/CABN.3.1.17

Ntourou, K., Anderson, J. D., & Wagovich, S. A. (2018). Executive function and childhood stuttering: Parent ratings and evidence from a behavioral task. *Journal of Fluency Disorders, 56*, 18–32. https://doi.org/10.1016/j.jfludis.2017.12.001

Ofoe, Anderson, J. D., & Ntourou, K. (2018). Short-term memory, inhibition, and attention in developmental stuttering: A meta-analysis. *Journal of Speech, Language, and Hearing Research, 61*(7), 1626–1648. https://doi.org/10.1044/2018_JSLHR-S-17-0372

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh Inventory. *Neuropsychologia*, 9(1), 97–113. https://doi.org/10.1016/ 0028-3932(71)90067-4

O*NET Resource Center. (2023). https://www.onetcenter.org/

Piispala, Kallio, M., Bloigu, R., & Jansson-Verkasalo, E. (2016). Delayed N2 response in Go condition in a visual Go/Nogo ERP study in children who stutter. *Journal of Fluency Disorders*, *48*, 16–26. https://doi.org/10.1016/j.jfludis.2016.02.001

Piispala, Määttä, S., Pääkkönen, A., Bloigu, R., Kallio, M., & Jansson-Verkasalo, E. (2017). Atypical brain activation in children who stutter in a visual Go/Nogo task: An ERP study. *Clinical Neurophysiology, 128*(1), 194–203. https://doi.org/10.1016/j.clinph.2016.11.006

Pliszka, Liotti, M., & Woldorff, M. G. (2000). Inhibitory control in children with attention-deficit/hyperactivity disorder: event-related potentials identify the processing component and timing of an impaired right-frontal response-inhibition mechanism. *Biological Psychiatry, 48*(3), 238–246. https://doi.org/10.1016/S0006-3223(00)00890-8

Pollak, S. D., & Wolfe, B. L. (2020). Maximizing research on the adverse effects of child poverty through consensus measures. *Developmental Science*, 23(6), e12946. https://doi.org/10.1111/desc.12946

Riley, G. (2009). *Stuttering Severity Instrument Fourth Edition (SSI-4)*. Pro-Ed.

Rubia, Russell, T., Overmeyer, S., Brammer, M. J., Bullmore, E. T., Sharma, T., Simmons, A., Williams, S. C., Giampietro, V., Andrew, C. M., & Taylor, E. (2001). Mapping motor inhibition: Conjunctive brain activations across different versions of Go/No-Go and stop tasks. *NeuroImage (Orlando, Fla.)*, *13*(2), 250–261. https://doi.org/10.1006/nimg.2000.0685

Smith. (2011). To Go or not to Go, that is the question: Do the N2 and P3 reflect stimulus- or response-related conflict? *International Journal of Psychophysiology, 82*(2), 143–152. https://doi.org/10.1016/j.ijpsycho.2011.07.019

Smith, A., & Weber, C. (2017). How stuttering develops: The multifactorial dynamic pathways theory. *Journal of Speech, Language, and Hearing Research: JSLHR*, *60*(9), 2483–2505. https://doi.org/10.1044/2017_JSLHR-S-16-0343

Sowell, Thompson, P. M., Holmes, C. J., Batth, R., Jernigan, T. L., & Toga, A. W. (1999). Localizing age-related changes in brain structure between childhood and adolescence using statistical parametric mapping. *NeuroImage (Orlando, Fla.), 9*(6), 587–597. https://doi.org/10.1006/nimg.1999.0436

Tekok-Kilic, A., Shucard, J.L., & Shucard, D.W. (2001). Stimulus modality and Go/NoGo effects on P3 during parallel visual and auditory continuous performance tasks. *Psychophysiology, 38*, 578–589. https://doi.org/10.1017/S0048577201991279

Toplak, West, R. F., & Stanovich, K. E. (2013). Practitioner review: Do performance-based measures and ratings of executive function assess the same construct? *Journal of Child Psychology and Psychiatry*, *54*(2), 131–143. https://doi.org/10.1111/jcpp.12001

Wagner Fuhs, & Day, J. D. (2011). Verbal ability and executive functioning development in preschoolers at Head Start. *Developmental Psychology, 47*(2), 404–416. https://doi.org/10.1037/a0021065

Wanless, McClelland, M. M., Lan, X., Son, S.-H., Cameron, C. E., Morrison, F. J., Chen, F.-M., Chen, J.-L., Li, S., Lee, K., & Sung, M. (2013). Gender differences in behavioral regulation in four societies: The United States, Taiwan, South Korea, and China. Early *Childhood Research Quarterly, 28*(3), 621–633. https://doi.org/10.1016/j.ecresq.2013.04.002

Wiig, E. H., Secord, W. A., & Semel, E. M. (2004). *Clinical Evaluation of Language Fundamentals Preschool-2 (CELF-Preschool 2).* Pearson.

Wiig, E. H., Semel, E. M., & Secord, W. A. (2013). *Clinical Evaluation of Language Fundamentals: Fifth edition (CELF-5).* Pearson.

Wongupparaj, Sumich, A., Wickens, M., Kumari, V., & Morris, R. G. (2018). Individual differences in working memory and general intelligence indexed by P200 and P300: A latent variable model. *Biological Psychology, 139*, 96–105. https://doi.org/10.1016/j.biopsycho.2018.10.009

Yairi, E. & Seery, C. (2015). *Stuttering: Foundations and Clinical Applications*. (2nd Edition). Pearson Education.

van Veen, & Carter, C. S. (2002). The anterior cingulate as a conflict monitor: fMRI and ERP studies. *Physiology & Behavior, 77*(4), 477–482. https://doi.org/10.1016/S0031-9384(02)00930-7

Vuillier, Bryce, D., Szücs, D., & Whitebread, D. (2016). The maturation of interference suppression and response inhibition: ERP analysis of a cued Go/Nogo task. *PloS One, 11*(11), e0165697–e0165697. https://doi.org/10.1371/journal.pone.0165697