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Identifying Brain Stimulation Targets for Improving Automaticity in Reading

by

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Under the Direction of Robin D. Morris, PhD

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ABSTRACT

Adults with persistent reading disabilities (RD) continue to struggle with slow and dysfluent reading throughout their life, even following years of behavioral interventions. Research suggests that persistent fluency deficits result from an inability to develop automaticity in word recognition skills due to a hypothesized instability in activation or efficient connectivity within the brain's reading network. Transcranial magnetic stimulation (TMS) is known to affect cortical excitability and activation levels, and therefore may be capable of modulating variable activity in the brain's reading network and enhancing automaticity in word recognition. This may ultimately translate to new approaches for remediation of fluency deficits.

In this study, a mixed reading ability group of adults with impaired to above average reading skills received TMS to the supramarginal gyrus (SMG) and middle temporal gyrus (MTG), two key nodes within the brain's reading network. Measures of word reading speed and sentence reading speed, as well as measures of underlying component skills supporting automaticity in word recognition (Rapid Automatized Naming (RAN) and orthographic awareness (OA) took place prior to and following TMS. It was hypothesized that, based on the hypothesized role of SMG and MTG in automatic word recognition, TMS to SMG and/or MTG would result in improved automaticity in word recognition, and therefore faster word and sentence reading speed. We found that TBS to the SMG resulted in improved RAN, OA, and speeded word recognition, especially in individuals with weak initial reading skills. Based on our results, TMS may have potential as a future tool to facilitate improvement in reading fluency in conjunction with behavioral reading interventions.

INDEX WORDS: Reading disabilities, TMS, Reading fluency

Identifying Ideal Brain Stimulation Targets for Improving Automaticity in Reading

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DEDICATION

"If I have seen further it is by standing on the shoulders of giants".

It is only right that this capstone of my education be dedicated to the memory of those who built the foundation that I stand on. This work and the education behind it would not be possible without the sacrifices and hard-won achievements of my grandparents, Bernat Ackerman and Priscilla Cynthia Ackerman (née Steinman) and Edward Janous Ossowski and Anna Christine Ossowski (née Rotondo). Their values of hard-work, intellectual exploration, curiosity, empathy, and family loyalty have carried me to this point.

My grandfather Bernat Ackerman embodied the values of diligence, compassion, resilience and love in both his words and actions towards me, sculpting from nothing the life that I lead today. From an early age, my grandmother Priscilla Cynthia Ackerman brought to life my love of learning, my inner curiosity and thoughtfulness, and my sense of self. She illuminated an early path for the women in our family, including me, to think deeply and critically in our pursuits of higher education.

My grandfather Edward Janous Ossowski demonstrated unfailing self-sacrifice, hard work, loyalty to family, and courage of conviction. He never failed to instill a deep sense of self in his grandchildren, emphasizing the prowess of our lineage and our ability to accomplish all that we set our minds to. My grandmother Anna Christine Ossowski has been a guardian angel whom I hope to someday meet, passing on her intelligence, resilience, and bravery and paving the way for her female progeny to seek knowledge and education.

This is for you.

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1 INTRODUCTION

1.1 Overview

This study explores a novel use of transcranial magnetic stimulation (TMS) to address the challenge of persistent reading fluency deficits in adults with reading disabilities (RD). To date, few traditional educational interventions have been able to successfully remediate slow and inefficient reading in adults with RD (e.g., Mathes et al., 2005; Roembke et al., 2019). Persistently slow and inefficient reading skills in adults with RD are thought to be the result of an inability to develop automaticity in word recognition skills due to excessive noise and/or reduced activation/arousal within the brain's reading network. Ineffective levels of variability in the reading network may prevent adults with RD from automatizing reading skills taught during intervention. If TMS is able to modulate variability in this network, it may allow for automatization of learned reading skills via stabilization of excessive noise or enhancement of neural activation. This could therefore allow for remediation of automaticity deficits and improvement in persistent reading fluency deficits. In the following sections, we review 1) characteristics and consequences of lack of automaticity and consequent reading fluency deficits 2) cognitive and neural mechanisms supporting automaticity in reading and 3) how TMS may be capable of remediating these mechanisms.

1.2 Persistent Reading Disabilities in Adults

It is well established that many adults continue to struggle with reading throughout their lifespan. It is estimated that one in five adults in the United States today have difficulty reading at a proficient level, even if they are native English speakers who have received adequate reading instruction (National Center for Education Statistics, 2007; 2019). Such impairments in reading

are a massive public health problem known to lead to poorer health outcomes, lack of employment and community engagement, higher risk of incarceration, and higher risk of poverty (Kirsch et al., 1993; Kutner et al., 20007; McNamara et al., 2011; Weiss et al., 1992). Aside from the personal cost to individuals, the national prevalence of reading impairments in adults has a significant economic burden and increases the cost burden on healthcare systems as well as public safety infrastructure (Kozol, 1985). Recent estimates suggest that illiteracy currently costs the global economy over 800 billion dollars per year (Word Literacy Summit, 2018), and the United States economy over 225 billion dollars per year (Rothwell, 2020; Truman Center for National Policy, 2021).

In all aspects of life, from functioning effectively in the workforce to maintaining one's health and personal responsibilities, adults encounter complex texts which must be read both accurately and efficiently. Typically developing (TD) adult readers are able to accurately identify the sounds and meanings of words and phrases automatically without conscious effort. In fact, most expert readers find it difficult to *not* read text when it is presented to them. Kuhn et al. (2004) offer the example of how most fluent readers will find themselves reading subtitles appearing along the bottom of a TV screen, even if they do not intend to. Likewise, consider how it is almost impossible as a proficient adult reader to look directly at a word without reading it. This ability to recognize words without conscious effort, intention, or awareness is therefore considered to be an *automatic* process (Logan, 1998; Moors & DeHouwer, 2006).

Because the process of word recognition is, for typical adult readers, automatic, their cognitive resources can then be fully devoted to those higher-level linguistic and cognitive processes required for comprehending and reasoning about complex texts (Kuhn et al., 2004; 2006; Schwanenfluegel & Ruston, 2008; Schwanenfluegel et al., 2009). In order to successfully

and efficiently read at a level that allows for independent living, personal health, and professional success, multiple types of information must be integrated. These types of information include semantic knowledge and previously acquired background knowledge, syntactical structures, and the integration of these various components to draw conclusions about the meaning of the text. Typical adult readers are able to fully devote their cognitive resources to these processes without needing to allot additional resources for the identification of individual words. For example, imagine what takes place when a typical adult reader encounters the following passage:

Rent payments are due on the first of the month, and no later than the third. The full amount owed must be submitted at the time of payment. Failure to comply will result in an added late fee.

When a TD adult reader encounters this passage, resources are focused on deciphering the overall meaning of the passage (comprehending when the rent payments must be made), and reasoning/drawing conclusions about what this passage means in order to begin preliminary decision-making strategies (e.g., considering ways to have funds available by the payment date in order to avoid a late fee). However, cognitive resources are not typically devoted to deciphering the sounds and meaning of frequently encountered words such as *payment*, or even to deciphering less frequently encountered words with regular patterns such as *comply.* This is because such basic word recognition takes place *automatically.* The automaticity of this word recognition allows for a critical shortcut, allowing typical readers to focus on processing and reasoning about texts essential for daily life.

For adults with reading disabilities (RD) this level of automaticity often fails to develop, even following extensive interventions. This deficit in automaticity is frequently persistent

throughout the lifespan (e.g., Fernandes et al., 2017; Lovett et al., 2000; Swanson & Hsieh, 2009; Tighe & Schatschneider, 2016; Wexler et al., 2008) and occurs in those with RD across multiple languages and orthographies (Araujo & Faisca, 2019; Landerl et al, 2018; Shany & Share, 2011; Ziegler et al., 2003). This lack of automaticity in word recognition skills means that basic reading frequently requires the laborious decoding of individual words and remains an effortful task requiring conscious cognitive control. In turn, this lack of automaticity in word identification has a significant impact on one's ability to efficiently comprehend the complex texts encountered in daily life, as effortful decoding of words detracts cognitive resources from those higher-level processes (e.g., text comprehension and reasoning) needed for efficient reading. When accurate word recognition is not automatic and effortless, cognitive resources 1) cannot be entirely devoted to these higher-level processes and/or 2) can be allocated to these higher-level processes only after the words have been identified. This means that reading will either 1) take place quickly but inaccurately and with poor comprehension or 2) will occasionally occur accurately while taking a hindering amount of time. It is therefore not surprising that this lack of automatic word recognition has been shown to hinder the ability to comprehend complex texts both quickly and effectively (e.g., Araujo & Faisca, 2015; Li et al., 2009), leading to impaired ability to functionally use written material.

Although the process of reading remains effortful in adults with RD, these individuals are often able to develop strategies for identifying the meaning of words and phrases through cognitive and educational interventions. Coaching in strategies designed to improve phonological processing (i.e., increase sensitivity and ability to recognize sounds in words) often allows those with RD to develop skills and strategies for accurately decoding and then deciphering the meaning of words. For example, adults may be coached to "sound out" words in

order to be able to decipher their meaning. However, although adults with RD tend to improve their reading accuracy and develop adequate phonological skills following such coaching (e.g., Reis et al., 2020; Torgesen, Rashotte, & Wagner, 2001; Vanderberg et al., 2011; Wexler et al., 2008), these individuals are often persistently unable to develop the ability to automatically read without conscious effort, as TD readers can do. In other words, although those with RD often develop strategies for reading accurately after extensive training in phonological processing and decoding skills, this accuracy often occurs in the context of persistently slow and dysfluent reading due to a persistent lack of automaticity in word recognition (Curtis et al., 1997; 1990; Jenkins et al., 2003; Katzir et al., 2006; Levy et al., 2001; Mathes et al., 2005; Roembke et al., 2019). As a result, many adults with RD continue to struggle with slow and inefficient reading throughout their lifespan (e.g., Roberts et al, 2008; Shaywitz et al., 2003; Torgesen et al., 2006).

A few interventions have attempted to directly address dysfluent and non-automatic reading rather than focusing solely on decoding strategies. The most commonly attempted method for improving automaticity in word recognition across readers of all age groups is repeated reading (e.g., Meyer & Felton, 1999). This method typically involves students repeatedly reading the same text or the same set of words until a targeted speed is achieved. These interventions have shown mixed results on improving reading fluency, with some successes in improving reading fluency in young elementary school level struggling readers (e.g., Ring et al, 2011). In contrast, adults with persistent RD often show persistently slow reading rates even following interventions that incorporate repeated reading (e.g., Greenberg et al., 2011; Vanderberg et al, 2011), even when the intervention results in improved reading accuracy (e.g., Vanderberg et al, 2011). It is also important to note that while the target of a repeated reading intervention may be faster automatic word recognition, the intervention will be

most helpful in improving functional reading abilities if the post-intervention increase in reading rate for individual words persists at the level of more complex passages. Unfortunately, many studies indicate that repeated reading interventions improve reading rate for the learned study materials without generalization that improves students' ability to efficiently read and comprehend more complex text that was not studied (e.g., Hintikka et al., 2008; Kuhn & Stahl, 2003; Paris et al., 2005). A review of twelve repeated reading studies across age groups by Wexler et al (2008) found that while repeated reading often can improve speed on the practiced text, this improvement does not generalize well to novel passages (Thaler et al., 2004; Wexler et al, 2008). These findings beg the question of whether students are actually increasing their reading efficiency in a way that translates to real-world reading demands, or whether repeated reading interventions lead them to adopt strategies to increase their rate at the expense of their understanding. Overall, repeated reading interventions show some promise, but currently have several critical gaps in their effectiveness.

In summary, adults with persistent impairments in automatic word recognition often suffer from lifelong deficits in fluent reading, deficits which are often not remediated by existing reading interventions. In the next section, we review research on the neuroanatomic, neurocognitive, and neurophysiologic bases of automaticity in word recognition, and how these processes are believed to be different in those with persistent RD compared to TD readers.

1.3 Neurocognitive Basis of Automatic Word Recognition Deficits

1.3.1 Cognitive Processes Underlying Automatic Word Recognition

It is clear that many individuals with RD have a persistent deficit in automatic and efficient word recognition, which results in persistently dysfluent and slow reading even following intervention (Curtis et al., 1997; 1990; Katzir et al., 2006; Levy et al., 2001; Jenkins et

al., 2003; Mathes et al., 2005; Roembke et al., 2019). The inability to automatize word recognition has severe consequences for those with RD, as this deficit interferes with effective processing and comprehension of complex texts encountered in daily life. This leads us to two important questions: 1) which neurocognitive processes support the development of this automaticity in word recognition and 2) how are these processes aberrant in those with RD?

As previously described, most interventions for RD target phonological awareness (PA), a skill that is critical for accurate word identification and decoding. However, although improving PA in those with RD leads to increased accuracy in word identification, this process does not inadvertently raise the *speed* of word identification in those with RD to that of typical readers. For reading to be fluent and efficient, this accurate word identification must occur quickly and automatically, without conscious cognitive effort. An additional set of foundational cognitive skills, separable from phonological awareness, support automatization of word identification. One of the most important of these skills is rapid automatized naming (RAN), which refers to the automatic mapping of visual symbols to their corresponding word sounds. In other words, RAN is an index of how quickly and automatically visual symbols can be translated into their corresponding sound units (for a review, see Araujo et al, 2015; Norton & Wolf, 2012).

A related skill that contributes to this automaticity in naming and word reading is orthographic awareness (OA). This refers to an individual's sensitivity to common letter patterns that make up valid words in their written language, and the ability to learn and automatically recognize these patterns so that a word can be quickly recognized and linked to its corresponding phonology and semantics. (e.g., O'Brien et al, 2011; Rakhlin et al, 2019). If the processes of recognizing common orthographic patterns (OA) and rapidly translating visual patterns to their corresponding sounds (RAN) are automatic, words with familiar patterns can be automatically

read without conscious processing, contributing to fluent and efficient reading. It is therefore not surprising that both of these cognitive skills (RAN and OA) are strongly and uniquely predictive of the speed of individual word recognition (Georgiou et al., 2015, 2021; Rahklin et al., 2019; Reis et al., 2020; Verhagen et al., 2009; Xue et al., 2013) and of reading rate and fluency for both word lists and passages (Araujo & Faisca, 2019; Georgiou et al, 2016; Kim et al, 2015; Rakhlin et al, 2019; Song et al, 2016). These skills contribute significant additional variance to reading rate even when accounting for phonological awareness (e.g., Bowey et al, 2005; Georgiou, Parrila, & Kirby, 2009; Lam et al, 2017). In addition, it is well-established that many individuals with RD have specific deficits in RAN and OA (e.g., Norton & Wolf, 2012; Tong et al., 2019) and that these deficits are most strongly predictive of problems specific to reading rate and fluency (Araujo & Faisca, 2019; Georgiou et al., 2008; 2016; Kim et al., 2015; Negrete & Bear, 2019; Rakhlin et al., 2019; Song et al, 2016). The unique contributions of RAN and OA to reading fluency and speed have been confirmed by repeated factor analyses (Powell et al, 2007; Shany & Share, 2011; for a review see Norton & Wolf, 2012) and meta-analytic studies (i.e. Araujo et al, 2015; Song et al, 2016).

Given the contribution of OA and RAN to reading efficiency and automaticity, it seems logical that facilitation of these skills could improve reading automaticity. However, interventions designed to remediate these deficits have been inconsistent in their effectiveness. Some interventions aimed at increasing pattern recognition speed and letter-sound naming speed (e.g., Conrad & Levy, 2011; de Jong & Vrielink, 2004) showed no change in single word reading speed following intervention. In contrast, other studies (Pecini et al 2019; Vander Stappen, 2018; 2019) found that specific training in naming stimuli at increasing speeds can result in improved word identification speed, with one study (Pecini et al., 2019) finding improvements in both

single word reading speed and passage reading speed following intervention. Overall, research on remediation of OA and RAN is sparse and equivocal, making it unclear how best to remediate these processes and improve automaticity in word recognition. In addition, all of the described intervention studies occurred in children (typically grades 1-3). To our knowledge, no studies have reported the results of interventions for OA and RAN in adult struggling readers. Extensive further research, in both children and adults, is needed to determine if and how OA and RAN can be remediated to improve automatic word recognition speed and reading fluency.

In summary, it is well-established that OA and RAN are component reading skills that support reading automaticity, and that these skills are impaired in those with persistent reading automaticity deficits. In the next section, we review the literature on the neuroanatomic structures thought to underlie these skills, and how they differ in those with persistent reading automaticity deficits.

1.3.2 Neuroanatomic Regions Supporting Automatic Word Recognition

In addition to knowledge of cognitive processes supporting automatic word recognition, neuroimaging research has offered clues into which particular brain networks may support these processes. Functional and anatomical differences in these networks in those with RD may contribute to deficits in the processes supporting automaticity, and to persistent fluency deficits in those with RD.

First, it is well established that in typical readers without RD, a set of well-integrated left-lateralized brain areas support fluent reading (Figure 2). The dorsal reading network includes the inferior parietal lobule (IPL) including the supramarginal gyrus (SMG), as well as the superior temporal gyrus (STG). This network supports identification and assembly of word sounds (“phonemes”) from print (Martin et al., 2015; Richlan et al., 2012). The ventral network includes

the left fusiform gyrus (FG), encompassing the identified visual word form area (VWFA) in the left FG as well as the middle temporal gyrus (MTG) and occipito-temporal area (OT). This network supports recognition of visual patterns corresponding to known words ("orthographic patterns") (Martin et al., 2015; Richlan et al., 2012). The anterior network, including left inferior frontal gyrus (IFG) and middle frontal gyrus (MFG) retrieves phonemes corresponding to print and translates this print into spoken word (e.g., Boets et al., 2013).

Dorsal Stream, *including* ***left supramarginal gyrus (SMG):*** *supports recognition and processing of word sounds*

Ventral Stream, *including* ***left middle temporal gyrus (MTG):*** *supports recognition of frequently encountered visual patterns used in words*

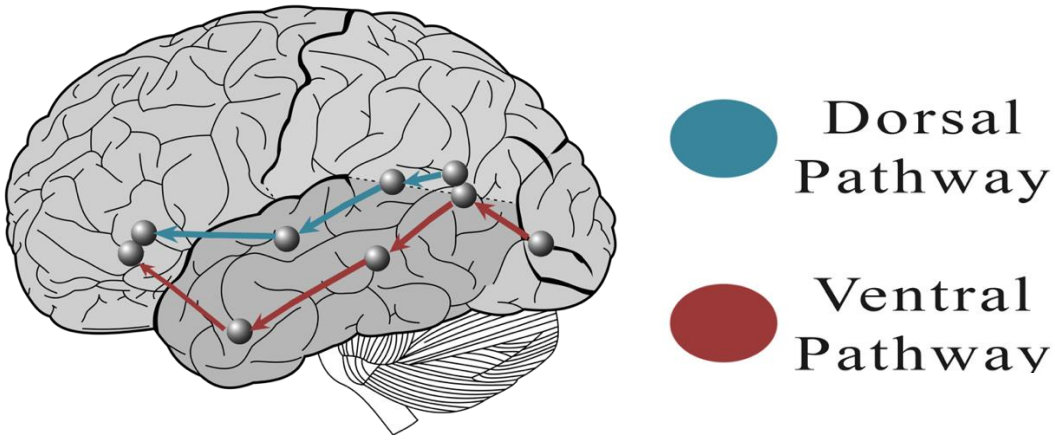


Figure 1. Diagram of the Reading Network

Efficient and fluent reading, including rapid recognition of orthographic patterns and mapping of these patterns to their corresponding sounds, requires effective communication between these regions. Dysfunction in activation of these regions, as well aberrant connectivity between these regions, is known to occur in adults with RD (e.g., Pugh et al., 2010; Richlan

2012; Rueckl et al, 2015; Rubenstein et al, 2014; Temple et al., 2003). In particular, dysfunctional activation and connectivity of these regions in those with RD has been shown to be associated with weaker component processes associated with reading automaticity, such as OA and RAN. For example, OA and RAN have been shown to be correlated with fMRI BOLD signal activation in dorsal and ventral reading network nodes (Al Dahhan et al., 2020; Gonzalez-Garrido et al., 2017; Hirshorn et al., 2016; Tian et al., 2020) including MTG and SMG. Differences in orthographic skill among individuals have been associated with differences in level of fMRI activation and N1 ERP signals over left ventral occipitotemporal area (vOT) in the ventral reading network (Pleisch et al., 2019). Resting state and task-based functional connectivity of dorsal and ventral reading network nodes, including left MTG, FG, and left IPL, has also been associated with both orthographic awareness skills and RAN performances (e.g., Qian et al., 2016; Schurz et al., 2015; van der Mark et al., 2011). Reduced activation in dorsal and ventral nodes, and reduced functional connectivity between these nodes, has been found in those with RD as compared to TD (Langer et al., 2015; Schurz et al., 2015; van der Mark et al., 2011). Those with RD also show different relationships between dorsal and ventral node functional activation/connectivity and RAN and OA skills as compared to TD readers (Langer et al., 2015; Schurz et al., 2015; van der Mark et al., 2011). In addition, structural connectivity from and within ventral nodes has been found to be weaker in those with RD as compared to TD readers (Deutsch et al., 2005; Su et al., 2018), leading to differences in their relationships with RAN.

Other studies have explored relationships between both functional activity and functional connectivity in dorsal and ventral reading network nodes and word reading speed and fluency. Both activation and connectivity of these reading network nodes has been associated with the

speed of both individual word recognition as well as more complex sentence recognition speed. fMRI studies have shown that increased functional activation in dorsal reading network regions, including the STG and SMG/IPL, is associated with individual word recognition speed, measured through lexical decision tasks and single word reading-aloud tasks (e.g., Arrington et al., 2019; Christodoulou et al., 2014; Lin et al., 2016). A recent meta-analytic study using an activation likelihood estimate approach confirmed the role of dorsal regions such as the STG and IPL in single word recognition tasks (Murphy & Talcott, 2019). One study evaluated speeded sentence reading, rather than the speed of individual word reading, in an attempt to examine the neural structures supporting fluent and automatic reading during reading tasks similar to those encountered during daily life (Christodolou et al., 2014). Similar to speeded word recognition tasks, activation in dorsal structures such as the STG and IPL showed increased activation to sentences presented at varying speeds as compared to rest. While this occurred in both TD adults and in those with RD, in TD adults, activation in STG and IPL increased correspondingly to faster rates of sentence presentation. In other words, TD adults showed appropriate increases in dorsal node activation as the required speed of sentence identification increased. However, those with RD did not show the same level of increasing activation levels to higher speeded word recognition demands, with less of a difference in activation in these regions between presented speeds (Christodolou et al., 2014). This finding may indicate that, in those with RD, there is a reduced ability to appropriately modulate activation in dorsal reading network nodes to increases in word identification speed demands. This lack of appropriate modulation to speeded word recognition demands may play a role in the reduced automatic processing of individual words and overall reduced reading fluency in those with RD. In addition to fMRI data, inhibition of the SMG and other dorsal network nodes through inhibitory transcranial magnetic stimulation

(TMS), has been found to slow word recognition speed in typically reading adults (Rochas et al., 2014; Sliwinska et al., 2012; Sliwinska et al., 2015). These findings suggest that precise activation of dorsal network regions is not only associated with, but necessary for, fast and efficient word recognition, as interference with activity in these nodes results in slower word recognition task performance.

fMRI studies also indicate that activity in ventral network nodes along the middle temporal gyrus (MTG) and ventral occipitotemporal regions (vOT) modulate speed and automaticity of word recognition. Activation in vOT has been associated with response times in single word recognition in both TD readers and those with RD (e.g., Langer et al., 2015; Kubota et al., 2019; Weiss & Booth, 2017), and reduced activation in ventral reading network nodes during speeded word recognition has been found in those with RD as compared to TD readers (e.g., Langer et al., 2015). A recent meta-analytic study of fMRI data using an activation likelihood estimate approach confirmed the role of ventral regions such as the MTG and vOT in single word recognition tasks (Murphy & Talcott, 2019). One of the few studies which studied speeded sentence reading rather than individual word recognition (mentioned above) also found that activation in ventral network structures was associated with speeded sentence recognition, and that reduced functional activation in these regions during speeded word recognition was found in adults with RD as compared to TD adults (Christodolou et al., 2014). Overall, findings suggest that ventral network nodes including MTG and vOT are important contributors to word recognition speed and fluency, and that differences in these regions' activity may play a role in overall reduced fluency in those with RD. In addition, inhibition of ventral network nodes including vOT through inhibitory transcranial magnetic stimulation (TMS) has been found to slow word recognition speed in typically reading adults (Duncan et al., 2010; Lavidor et al.,

2003; Lavidor & Walsh, 2003; Pattamadilok et al., 2010; 2015). These findings suggest that activation of ventral network regions is not only associated with, but also necessary for, fast and efficient word recognition, as suppression of these nodes results in slower word recognition task performance.

In addition to findings that activation in dorsal and ventral network nodes is associated with word recognition speed and fluency, the integrity and strength of the connections between dorsal and ventral network nodes has been shown to support word and sentence reading fluency. Functional connectivity as measured by fMRI and electrophysiological studies indicated that the strength of connections between dorsal and ventral nodes of the reading network is associated with the speed of word and sentence reading fluency (e.g., Schurz et al., 2014; Zaric et al., 2017; Zhou et al., 2015). The structural integrity of white matter tracts connecting dorsal and ventral reading network nodes to other brain regions, including the inferior longitudinal fasciculus (ILF) and uncinate fasciculus (UF), is associated with automaticity/speed of single word recognition (e.g., Arrington et al., 2017; Cummine et al., 2015) and speed of sentence recognition (e.g., Lebel et al., 2013). Reduced connectivity of these regions has also been found in those with RD as compared to TD readers and is suggested to play a role in reduced reading fluency in RD as compared to TD (e.g., Lebel et al., 2013).

1.3.3 Neural Mechanisms Supporting Automatic Word Recognition

Neuroimaging evidence indicates that functional activity of dorsal and ventral reading network nodes supports automatic word recognition in TD readers, and that alterations in the activity of these nodes contributes to impaired automaticity in those with RD. This begs the question of which neural mechanisms in these reading network nodes support the development of this automaticity, and how these mechanisms are aberrant in those with persistent RD.

What mechanistically is different in these nodes in those with RD, that contributes to this lack of automaticity? In order for frequently encountered words and orthographic patterns to be recognized effortlessly, automatic neural responses to these stimuli must occur. Neural responses within the brain regions supporting word recognition must learn and adopt a fixed response pattern to frequently encountered word stimuli, in order for this word recognition to become automatic and rapid. This process of learning, refining, and stabilizing a neural response to a repeated stimulus until it is automatized is called neural adaptation (Jaffe-Daxe, Frenkel, & Ahissar, 2017; Ulanovsky et al., 2004). Evidence suggests that a failure of neural adaptation occurs in regions supporting word recognition in those with RD, leading to a failure to automatize word recognition. For example, in TD readers, fMRI BOLD responses in dorsal and ventral reading network nodes are appropriately reduced and stabilized following repeated presentations of a word stimulus, reflecting refinement and automatization of the response to a known stimulus. However, in those with RD, less stable adaptation of these neural responses occurs to repeated stimuli, reflecting less consistent neural responses to word stimuli (Ahissar et al., 2006; Ahissar, 2007; Meghini et al., 2006; Perrachione et al., 2016; Pugh et al., 2008). Similarly, ERP studies of those with RD compared to TD readers have also found reduced neural response adaptation and less stability in the neural response to word stimuli in dorsal and ventral network nodes (Kimpa et al., 2018; Lam et al., 2017). The degree of this reduction in neural response adaptation and stabilization has been associated with weaker reading fluency (Kimpa et al., 2018; Lam et al., 2017), further confirming the relationship between precise adaptation of neural responses and automatic word reading.

Neural response adaptation in a given brain region is heavily influenced by levels of background neural noise. Neural noise refers to the level of random variability in neural

networks. A precise balance of excitatory and inhibitory signaling is required to produce a stable and consistent level of neural noise. This stable and consistent level of neural noise is required for effective learning of, and neural response adaptation to, familiar stimuli, as internal noise must be overcome in order to produce a repeated and stable neural response to a stimulus (Alain et al., 2007; Garrido et al., 2009; Sperling et al., 2005; 2006) thereby enabling automatic processing of the stimuli to develop. Hancock et al (2017) demonstrate the relationship between neural noise and neural response adaptation using the example that "a neuron that spikes at widely variable intervals in response to a repeated stimulus presentation is noisier than one that spikes at nearly the same time following each presentation". Therefore, inconsistent levels of neural noise in a given region will lead to less reliable learning of new stimuli and less reliable neuronal firing responses to a repeated stimulus, such as a regularly encountered word. Inconsistent levels of background neural noise (either hyperarousal or hypoarousal) have been theorized to occur in dorsal and ventral reading network regions in those with RD (Hancock et al., 2017) and to contribute to reduced neural adaptation to frequently encountered word stimuli (Hancock et al., 2017; Kimpa et al., 2018). This lack of neural adaptation in the presence of inconsistent background noise has also been tied to inefficiencies in word reading, such as reduced single word reading speed (e.g., Kimpa et al., 2018; Perrachione et al., 2016).

In summary, consistent levels of neural noise in dorsal and ventral reading network regions are needed for effective learning and neural adaptation to frequently encountered word stimuli to occur, thereby enabling automatic word recognition. Inconsistent levels of neural noise are found in reading network regions in those with RD, leading to reduced neural response adaptation and persistent inability to automatize word reading. Theoretically, if neural noise levels in those with RD could be modulated to a more consistent level, effective new learning

and neural adaptation to word stimuli might be able to take place, leading to more automatic word recognition and fluent reading. Transcranial magnetic stimulation (TMS), a neuromodulation technique capable of modulating cortical excitability, may be capable of modulating neural noise in dorsal and ventral network reading nodes, facilitating the development of automaticity in word recognition. In the following section, we briefly review evidence to suggest that TMS may be capable of modulating neural noise in reading network nodes in order to improve reading automaticity.

1.4 Transcranial Magnetic Stimulation (TMS) and Reading

1.4.1 Neural Effects of TMS

Transcranial magnetic stimulation (TMS) is a non-invasive neuromodulation technique during which an electric coil is held over a subject's head above a targeted cortical area (see Figure 3). Electric currents in the coil produce a short-lived magnetic field (sometimes referred to as a "magnetic pulse" or "pulse") which easily penetrates the skull and induces small electric currents in the underlying cortical area. These induced electric currents modulate the excitability of the underlying neural tissue (Hallett, 2007; Rossini et al., 2015; Walsh & Rushworth, 1999). Delivering repeated pulses in fixed temporal patterns (repetitive TMS or rTMS) can have long-lasting effects on increasing or suppressing cortical excitability, even after brief periods of stimulation (Huang et al., 2005; Klomjai, Katz, & Lackmy-Vallee, 2015). One of the most reliable and frequently applied protocols for rTMS is known as theta-burst stimulation, or TBS. In a TBS protocol, sets of 3 pulses given at 50 Hz (20 ms between pulses), are delivered in a set pattern (see Figure 4). Different patterns of TBS are known to have lasting effects on cortical excitability, both excitatory and inhibitory (for a review see Huang et al., 2005; Rossini et al., 2015).

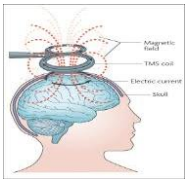


Figure 2. TMS Coil and Application

As previously described, the balance of excitation and inhibition in neural networks is related to level of neural noise in a given network. It is therefore unsurprising that, through adjusting the balance of neural excitation and inhibition, TBS has been shown to modulate levels of neural noise in cortical networks (Johnson, Hamidi, Postle, 2010; Ruzzoli, Marzi, Miniussi 2010; Schwarzkopf, Silvanto, Rees, 2011; Silvanto & Cattaneo, 2017; for a review see Miniussi & Ruzzoli, 2013). Through modulation of cortical excitability and levels of neural noise, application of TBS may also lead to more efficient neural learning and adaptation, and therefore more automaticity and consistency in neural responses to stimuli. The behavioral effects of theta-burst stimulation (TBS) are thought to occur via induction of long-term potentiation (LTP) or long-term depression (LTD), which over time may induce long-lasting changes in cortical excitability (for a review, see Suppa et al., 2016). These long-lasting changes in cortical excitability may therefore allow for modulation of neural noise and long-term stabilization of neural responses. The potential for such lasting effects makes TBS a promising interventional tool for facilitating long-term changes in brain function and cognitive skills such as reading.

1.4.2 Behavioral Effects of TMS on Cognition, Language, and Reading

Through modulation of cortical excitability, rTMS protocols (and particularly TBS protocols) are capable of modulating several types of behavior. TBS has been used to induce

changes in motor responses (e.g., Rossini et al., 2015; Zhang et al. 2017) and has been successfully applied as a treatment for a number of neurological and psychiatric disorders (for a review, see Bozzay et al., 2020; Chen et al., 2019; Rachid, 2017). TBS has also been shown to successfully modulate cognitive task performance (e.g., Bolognini&Miniusi, 2018; Hoy et al., 2015; Veniero et al., 2019; for a review see Wischnewski & Schutter, 2015). In particular, theta-burst stimulation has been shown to modulate language related functions and improve automaticity and efficiency of language tasks (e.g., Acheson & Agorot, 2013; Andoh et al., 2008; Andoh & Zattore, 2012; Bruckner, Kiefer, & Kammer, 2013;Griffis et al., 2016; Kindler et al., 2020; Pestalozzi et al., 2020) For example, excitatory theta-burst stimulation has been shown to improve auditory comprehension (e.g., Acheson & Hagoort, 2013; Szaflarski et al., 2018; Versace et al., 2019), naming and speech accuracy and speed (Harvey et al., 2019; Restle, Murakami, & Ziemann, 2016), and speech fluency in those with aphasia (e.g., Griffis et al., 2016; Heiss, 2016).

Most relevant to the current project, rTMS and TBS in particular have been shown to facilitate the efficiency of cognitive processes necessary for successful reading. Stimulation to dorsal network regions such as SMG has been found to promote faster and more accurate performance on both semantic and phonological word recognition tasks. Sliwinska et al. (2015) found that rTMS to both the angular gyrus and the SMG modulated responses to word sounds and meaning. Consistent with these findings, Stoeckel et al. (2009) found that single pulse TMS applied to the SMG speeded response times on both phonological and semantic word discrimination tasks. In a few studies, dorsal node stimulation has also been shown to modulate speed and accuracy during speeded word and sentence reading (Costanzo et al., 2012, 2013; Nakamura et al., 2006). It is important to note that only two of these studies (Costanzo et al.,

2012; 2013) compared changes in word recognition speed following dorsal node rTMS stimulation to word recognition speed following non-active stimulation (TMS applied to the vertex of the skull, which is a validated control site that does not change excitability of cortical tissue). The inclusion of this control site in these studies increases confidence that the changes in word recognition speed following rTMS were directly related to applied stimulation. However, these studies also included relatively small sample sizes (N = 10), meaning that replication of these results is needed in order to draw further conclusions.

Stimulation to ventral reading network nodes, such as MTG and vOT, have been found to modulate visual word recognition speed in both paired pulse protocols (Duncan et al., 2010) and in rTMS protocols (Pattamadilok et al., 2010,2015; Lavidor & Walsh., 2003; Zhu et al., 2015). Each of these studies found that stimulation to ventral occipital regions showed greater modulation of word recognition speed relative to control sites, indicating that activity in these ventral node regions influences word recognition speed. rTMS to ventral regions, in particular the MTG, has also been shown to modulate speed of performance on word recognition tasks with high semantic processing demands. Hoffman et al (2012) found that rTMS to MTG as compared to a control site affected response times during a semantic association task, demonstrating how activity in MTG affects semantic response times. Pobric et al (2009) and Whitney et al (2011, 2012) also found that rTMS to MTG affected response times during a semantic lexical decision task, although these studies did not include comparisons to control sites. In summary, TMS to MTG and other ventral reading network regions has the potential to modulate word recognition speed.

Given that TBS is capable of modulating neural noise and facilitating neural adaptation, and that stimulation to dorsal and ventral reading network nodes has been shown to modulate the

efficiency of reading-related processes, TBS may also be capable of enhancing automatic word recognition. If TBS is capable of enhancing the speed of automatic processes underlying automatic word recognition in typical readers, this may also be the case in those with RD, leading to a potential tool for assisting in the remediation of persistent automaticity deficits. In addition, comparing the effects of TBS on reading performance between readers of varying skill levels may further inform understanding of how varying activity in reading network nodes contributes to variability in reading automaticity. To date, only one study using a TMS protocol (Costanzo et al., 2013) has included a sample of individuals with RD, so there is limited information regarding its influence across different reading levels. Additionally, no studies to date have examined the effects of TBS or any other TMS protocol on standardized measures of reading rate and fluency, and none have compared the effects of TMS across readers of varying skill levels**.**

1.5. The Current Study

In conclusion, TMS, especially TBS, is capable of inducing long-lasting changes in cortical excitability. This in turn may modulate neural noise and lead to stabilization of neural responses. TBS to nodes of the reading network (SMG and MTG) has been shown to modulate reading related skills. Therefore, it is possible that TBS to dorsal and ventral reading network nodes could improve the development of automaticity in word recognition, and thereby improve persistent automaticity deficits in those with RD. In this study, we investigate whether TBS to dorsal and/or ventral brain regions facilitates cognitive processes supporting automatic word recognition in adults with a range of reading fluency skills (above average to impaired). In addition, we investigate whether facilitation of automaticity in word recognition through TBS translates to improved performance on standardized measures of reading rate and fluency. If the

current study results suggest that TBS to specific reading network nodes can facilitate automaticity in reading, TBS may have promise as a future interventional tool to assist in remediation of impairments in those with RD. In addition, comparing the effects of TBS, an intervention aimed at modulating neural activity in certain regions, among individuals with both intact and impaired reading fluency skills allows for further understanding of how differential activity in these regions may contribute to differences in reading fluency. If TBS to reading network nodes has different effects on automatic reading processes in those with different reading skill levels, this may provide further information about how activity in these regions differs among those with different reading fluency skills.

1.5.1 Optimal Stimulation Node for Improving Reading Fluency (Dorsal vs. Ventral)

Despite a preponderance of evidence that TMS to both dorsal and ventral reading network nodes is capable of modulating reading-related processes, very little is known about *which* of these nodes may be more effective in modulating reading fluency and component skills such as OA and RAN, as no study to date has investigated these questions. However, we can hypothesize about how stimulation to each of these nodes may differentially impact reading fluency and its component skills. Whether dorsal or ventral node stimulation is more effective in modulating reading fluency will depend on which mechanisms within the reading network are most essential for improving reading fluency. Hypotheses supporting a more effective role for dorsal node stimulation or ventral node stimulation in improving reading fluency are discussed below.

Based on the neural noise hypothesis, inappropriate levels of neural noise in the network nodes may have a downstream effect of disrupting appropriate synchronization of the entire network. As discussed, this means that mapping of phonological sounds to visual symbols may

not be automatized, which could lead to dysfluent reading (Hancock et al., 2017). Both ERP studies and fMRI functional connectivity studies have shown that increased synchronization in activity across the reading network is associated with improved reading fluency (Breznitz et al., 2006; Hashimoto et al., 2020; Norton & Wolf, 2012; Zaric et al., 2017). It follows from this hypothesis that the optimal way to improve reading speed may be to facilitate better synchronization across the entire reading network. In this case, modulation of activity in earlier nodes in the circuitry, such as the dorsal network SMG, may be the most effective way to facilitate synchronization across the entire network. If excess neural noise in dorsal regions such as SPL and SMG impairs the ability of neurons in this region to maintain stable representations for phonemes (Durstewitz et al., 2006; Harm et al., 1999; Hullet et al., 2016), then the signals propagated throughout the rest of the network may be imprecise. This would lead to imprecision in the remainder of the processes facilitated throughout the rest of the network, including noisy grapheme to phoneme mapping in ventral regions. One of the few studies that examined TMS effects on whole word recognition and text-reading supports the hypothesis that TMS to dorsal network regions may have downstream effects and modulate neural activity throughout the entire reading network. These studies (Costanzo et al., 2012; 2013) found that rTMS to dorsal nodes (inferior parietal lobule) led to improvement in tasks requiring the function of the entire reading network, including reading aloud both words and non-words and reading of texts. In the absence of corresponding neuroimaging data, which was not collected in this study, we cannot unequivocally conclude that this stimulation truly led to downstream effects of increased synchronization across the entire network. However, downstream effects are likely based on the fact that stimulation to this region led to notable change in individual word reading, nonword reading, and text-reading, all tasks requiring integration and facilitation of reading-related

processes not directly mediated by SMG. Together, the neural noise hypothesis and limited available data supports the hypothesis that dorsal node stimulation may be optimal for facilitating better synchronization across the entire network. If this conceptualization is correct, we would expect to find greater improvement in reading fluency following SMG stimulation as compared to MTG stimulation.

It could also be argued, however, that the specific effects of TMS to dorsal node regions on reading fluency per se is not known, and that other sites may be more ideal for improving fluency. Current studies that examined reading following dorsal node stimulation (e.g., Costanzo et al., 2013; 2014) did not examine the effects of stimulation on standardized reading fluency measures. The text reading measure in Constanzo et al (2013) was not provided within a strict time limit, and rather was administered at the participant's own preferred pace. Single word identification RT did improve following IPL stimulation in those with RD, but only for nonwords, which have the most reliance on dorsal node regions due to the phonological decoding demands. In addition, stimulation to dorsal nodes (STG) was also effective in improving RT for words in those with RD. Theoretically, it could be argued that ventral nodes such as the STG would be ideal TMS targets for improving reading fluency. Ventral nodes of the reading network have traditionally been associated with processes including recognition of orthographic patterns (O'Brien et al, 2011; Rakhlin et al, 2019) which is a strong predictor of reading fluency. It has traditionally been theorized that ventral regions engage in the phase of reading development when readers transition to recognizing orthographic patterns automatically rather than relying on decoding through sounding out phonemes (Ben-Shachar et al., 2011; Das et al., 2011; Schlagger & McCandliss, 2007; Shaywitz et al., 2002; 2004; 2008; Younger et al., 2017). Furthermore, studies have shown inappropriate activation of ventral reading network

regions in those with RD compared to TD readers (Hoeft et al., 2007; Younger et al., 2017). There is also some evidence that this dysfunction in the ventral regions is primary and not simply the result of downstream effects of dysfunction in earlier reading network nodes, such as SMG. For example, multiple longitudinal studies have shown that structural and functional differences are found in ventral node regions prior to reading development in those who go on to have RD (Raschle et al., 2011; Yamada et al., 2011), and that activation in these ventral regions emerges as children develop reading skills. It is possible that aberrant neural noise in ventral reading network is primarily responsible for weakness in reading fluency. It could therefore be hypothesized that modulating excitability in ventral node regions specifically would lead to improved reading fluency by having a direct effect on the regions hypothesized to support orthographic pattern recognition and thereby reading fluency. If this conceptualization is correct, we would expect to find greater improvement in reading fluency following MTG stimulation as compared to SMG stimulation.

1.5.2 Results from Pilot Data

To date, preliminary pilot data from our lab has suggested that significant pre-post change in reading fluency at both the word level and the sentence level occurs following excitatory intermittent theta-burst stimulation (iTBS) to both SMG and MTG. Significant changes in fluency did not occur following an inhibitory continuous theta-burst stimulation (cTBS) paradigm; therefore, for this study, the decision was made to include only iTBS. While much of the literature suggested effects of cTBS on various reading related processes, unlike our pilot study, these studies were not specifically aimed at *improving* word reading reading speed. The few studies that did focus on improving reading (Costanzo et al., 2012; 2013) found excitatory TMS to be effective, which is consistent with the findings from our pilot data.

The collected pilot data also did not include a control site, limiting our ability to draw conclusions about the effects of TBS to specific reading network nodes. In this study, we have therefore included a third control site (vertex) not believed to contribute to reading skill (Vertex group), as well as a group of individuals who received all measures at two separate time points but received no stimulation (NS Control Group).

The sample for pilot data consisted mainly of individuals with baseline reading fluency skills in the average to above average range. In this proposed study, we have intentionally included individuals with below average reading fluency skills. We are interested in exploring whether the promising findings of faster word recognition speed and reading fluency in typical readers (from pilot data) extends to those with persistently below average reading fluency skills, as these individuals would be the targeted recipients of a future TMS-facilitated reading intervention.

1.5.3 Specific Aims

Aim 1: Investigate whether theta-burst stimulation (TBS) to dorsal (SMG) and/or ventral (MTG) reading network nodes leads to increased efficiency in component skills (OA and RAN) supporting automaticity in word recognition in readers of varying skill levels, and whether SMG or MTG stimulation is more effective in modulating OA and RAN.

Hypothesis 1a: Response times during RAN tasks will be significantly faster following application of TBS to both MTG and SMG (pre-TBS response time > post-TBS response time). Such changes will be greater in the groups receiving MTG and SMG stimulation as compared to 1) the group receiving vertex (Vertex site) stimulation, and 2) the group receiving no stimulation (No Stimulation Control group).

a. If SMG stimulation results in greater change in response time on RAN tasks, it would suggest that synchronization across the entire reading network has the strongest impact on reading fluency. If MTG stimulation results in greater change in response time on RAN tasks, it would indicate that cortical activity in ventral nodes specifically has strongest impact on reading fluency.

Hypothesis 1b: Response times during OA tasks will be significantly faster following application of TBS to both MTG and SMG (pre-TBS response time > post-TBS response time). Such changes will be greater in the groups receiving MTG and SMG stimulation as compared to 1) the group receiving vertex (Vertex site) stimulation, and 2) the group receiving no stimulation (No Stimulation Control group).

a. If SMG stimulation results in greater change in response time on OA tasks compared to MTG, it would suggest that synchronization across the entire reading network has the strongest impact on reading fluency. If MTG stimulation results in greater change in response time on OA tasks compared to SMG, it would indicate that cortical activity in ventral nodes specifically has strongest impact on reading fluency.

Aim 2: Investigate whether excitatory theta-burst stimulation (TBS) to dorsal (SMG) and/or ventral (MTG) reading network nodes leads to increased efficiency in single word recognition speed (TOWRE) in readers of varying skill levels.

Hypothesis 2a: TOWRE Sight Word Efficiency (TOWRE SWE) raw score (total number of words read correctly in 45 seconds) will significantly improve following application of TBS to dorsal (SMG) and/or ventral (MTG) reading network nodes (pre-TBS TOWRE SWE raw score < post-TBS TOWRE raw score) and will be greater in the MTG and SMG groups as

compared to the group receiving vertex stimulation (Vertex Group) or no stimulation (No Stimulation Control Group).

a. If SMG stimulation results in greater change in TOWRE SWE scores compared to MTG, it would suggest that synchronization across the entire reading network has the strongest impact on reading fluency. If MTG stimulation results in greater change in TOWRE SWE scores compared to SMG, it would indicate that cortical activity in ventral nodes specifically has the strongest impact on reading fluency.

Aim 3: Investigate whether excitatory theta-burst stimulation (TBS) to dorsal (SMG) and/or ventral (MTG) reading network nodes leads to increased reading speed at the sentence level in readers of varying skill levels.

Hypothesis 3a: WJ-3 Sentence Reading Fluency W scores (WJ3 RF) will significantly improve following application of TBS to dorsal and/or ventral reading network nodes (pre-TBS WJ3 RF W score < post-TBS WJ3 RF W score), and will show greater improvement in the MTG and SMG groups compared to the groups receiving vertex stimulation (Vertex Group) or no stimulation (No Stimulation Control Group).

a. If SMG stimulation results in greater change in WJ-3 standard scores compared to MTG, it would suggest that synchronization across the entire reading network has the strongest impact on reading fluency. If MTG stimulation results in greater change in WJ-3 standard scores compared to SMG, it would indicate that cortical activity in ventral nodes specifically has strongest impact on reading fluency.

2 METHODS

2.1 Study Protocol

All procedures for this study were approved by the GSU/Georgia Tech Center for Advanced Brain Imaging (CABI) Institutional Review Board, protocols H12871 and H16199. The data presented here were collected as a part of two larger studies approved with the above named protocols, both of which involved TMS, MRI, and behavioral data collection.

2.1.1 Recruitment

A total of 39 adults (N = 39) participated in this study. Adults were recruited from the Atlanta metro area through community message boards, flyer postings, and the research team recruitment website page. Adults were also recruited from the Georgia State University Regents Center for Learning Disorders and the Center for Adult Literacy Research.

2.1.2 Screening

Initially, individuals who expressed interest in the study were screened via phone to ensure that they met study criteria and that it was safe for them to participate in the TMS portion of the study (see exclusion/inclusion criteria below under Participants). If criteria were met, participants were scheduled for a screening session (Session 1). Participants had to meet both MRI and TMS criteria as they were recruited as part of two larger studies (see above).

2.1.3 Inclusion/Exclusion Criteria

Inclusion and exclusion criteria are outlined in Table 1. Rationale for each criterion follows below.

Inclusion Criteria:

1. **Participants must be between the ages of 18 and 50** to have been included.

2. **Participants must have a minimum of low average intellectual functioning,** as indicated by a full-scale IQ (FSQ) of at least 80 (SS >=80) on the Wechsler Abbreviated Scale of Intelligence-2 (WASI-2, Wechsler, 2011; see Measures). This served to exclude individuals who may show reading difficulties secondary to more general cognitive impairment, rather than those with specific reading disorders.

3. **Participants must be native speakers of English**. As reading is critically linked to language, this criterion served to exclude individuals who may show reading difficulties secondary to lack of English language proficiency, rather than a specific reading impairment.

4. **Participants must be right-handed**. While the reading network is typically localized to the left side of the brain, in rare cases, left-handed individuals may show different brain lateralization for language and reading. Therefore, the effects of TMS to the reading network could differ between right and left-handed individuals due to a higher potential for atypical lateralization in left-handed individuals. This could therefore introduce a confound when examining the effects of TMS to different reading network nodes on reading automaticity. For this reason, **all study participants were required to be right-handed.**

Exclusion Criteria:

1. To ensure that participants' reading performance was not confounded by impaired hearing or vision**, participants with reported hearing or vision problems** (as reported on CABI Health Screening Questionnaire, Appendix A) were excluded from participation.

2. To ensure that participants' reading performance was not confounded by other unrelated neurologic or psychiatric problems, **participants with currently reported severe psychiatric or neurologic conditions (as reported on CABI Health Screening Questionnaire, Appendix A) were excluded from participation.**

3. Although TMS is generally well-tolerated, rare side effects have been reported, the most serious of which is seizure. This risk is elevated in those with a history of seizure disorders and with certain medical conditions that lower seizure threshold. **For this reason, individuals at elevated risk for complications such as seizure following TMS were excluded from the study.** Participants underwent screening via CABI TMS Screening Form (Appendix B), which was then reviewed by the principal investigator, to ensure that they were free from conditions that increase their risk of TMS adverse effects.

4. MRI is unsafe for individuals with certain metals in their bodies or with certain health conditions. These parameters are outlined in the CABI Health Screening Questionnaire (Appendix A), the CABI MRI Contraindications Form (Appendix C), and the CABI MRI Screening Form (Appendix D). All participants filled out these forms both at screening and immediately before their MRI scan, with both forms reviewed by the CABI MRI technologist and the principal investigator. **Participants who could not safely undergo MRI were excluded from the study,** as lack of anatomical MRI data would have precluded us from accurately identifying TMS stimulation sites.

Table 1. *Participant Inclusion and Exclusion Criteria*

Participant Inclusion Criteria:	**Participant Exclusion Criteria:**
1. Between ages 18-50	1. Vision or hearing impairments
2. Minimum FSIQ =>80	2. Neurologic or psychiatric conditions
3. Native speaker of English	3. Increased risk of seizure due to medical conditions/medications (TMS Screening Form, Appendix B)
4. Right-handed	4. Unable to undergo MRI

2.2 Sample

2.2.1 Sample Demographics

Data was collected from a sample of thirty-three (N = 33) neurologically healthy adults, a sample size that is commensurate with the majority of the literature on neuromodulation and reading. Not all participants completed each measure, either due to attrition or technical malfunctions during the MRI or TMS session. Therefore, sample sizes for each measure are outlined. All adults who received TMS to active sites (SMG or MTG) and to control sites (vertex) were between 18 and 50 years old (M = 25.66 (8.28)) and free of vision, hearing, or learning disorders other than reading disabilities or ADHD. Participants with a history of ADHD were not excluded due to the high comorbidity of ADHD with RD (for a review, see Lonergan et al., 2019; Germano et al., 2010). All participants denied neurological or severe psychiatric disorders. In addition, six (N = 6) neurologically healthy adults served as an additional No-

Stimulation (NS) control sample. These individuals underwent the relevant behavioral measures at two separate time points (with 1-2 weeks between measures) but did not receive TMS stimulation. This sample was comparable in age to the group receiving TMS to the active and control sites (*M* = 22.09 (4.44)). Demographics for each sample are included below (Table 2a-2b). Demographics by stimulation site are listed in Appendix A.

Tables 2a-2b. *Participant Demographics*

Table 2a. TMS Participant Demographics

Gender	73% Female (*N* = 24) 27% Male (*N* = 9)
Ethnicity	42 % Caucasian (*N* = 14) 48% Black/African American (*N* = 16) 3% Hispanic/Latino (*N* = 1) 6% Not Reported (*N* = 2)
Education	*M* = 15.75 years (2.65), all >12 years

Table 2b. NS Control Sample Demographics

Gender	67% Female (*N* = 4) 33% Male (*N* = 2)
Ethnicity	33% Caucasian (*N* = 2) 67% Black/African American (*N* = 4)
Education	NR, all > 12 years
Age	*M* = 23.35 (3.47)

For all participants, initial measures of reading fluency skills ranged from impaired to above average relative to same-aged peers. Initial standard scores on a measure of single word reading fluency for real words (TOWRE-2 Sight Word Efficiency (SWE)) ranged from 75-115. Initial standard scores on a measure of sentence reading fluency (WJ-3 Reading Fluency) ranged from 75-115.

In the current sample, 8 participants show reading fluency scores (TOWRE and/or WJ-3 Reading Fluency) at least 0.67 SDs below their normative age-based average (SS < 90). 17 participants had fluency scores (TOWRE and/or WJ-3 Reading Fluency) within 0.3 SDs of their normative age-based average (95< SS < 105), and 8 had at least one reading fluency score (TOWRE SWE or WJ-3 Reading Fluency) at least 0.67 SDs above their normative age-based average (SS > 110). This represents a relatively balanced sample of individuals with varying levels of baseline reading fluency.

The counts of participants with baseline reading fluency in these different ranges is represented below in Tables 3a-3e.

Tables 3a-3e. *Baseline Reading Fluency Standard Scores*

Table 3a. Baseline Reading Fluency Standard Scores for All Participants

Baseline Standard Score	**WJ-3 Reading Fluency**	**TOWRE Sight Word Efficiency**
SS < 90	*N* = 8	*N* = 8
92 < SS < 110	*N* = 14	*N* = 16
SS > 110	*N* = 10	*N* = 8

**TOWRE SWE data and/or WJ-3 data were not collected for certain participants, either due to experimenter error or delays during the experimental session necessitating these measures to be skipped.*

Table 3b. Baseline Reading Fluency Standard Scores for Participants Receiving SMG Stimulation

Baseline Standard Score	**WJ-3 Reading Fluency**	**TOWRE Sight Word Efficiency**
SS < 90	*N* = 2	*N* = 3
92 < SS < 110	*N* = 6	*N* = 6
SS > 110	*N* = 5	*N* = 4

Table 3c. Baseline Reading Fluency Standard Scores for Participants Receiving MTG Stimulation

Baseline Standard Score	**WJ-3 Reading Fluency**	**TOWRE Sight Word Efficiency**
SS < 90	*N* = 4	*N* = 3
92 < SS < 110	*N* = 5	*N* = 7
SS > 110	*N* = 3	*N* = 2

Table 3d. Baseline Reading Fluency Standard Scores for Participants Receiving Vertex Stimulation

Baseline Standard Score	**WJ-3 Reading Fluency**	**TOWRE Sight Word Efficiency**
SS < 90	*N* = 2	*N* = 2
92 < SS < 110	*N* = 3	*N* = 3
SS > 110	*N* = 2	*N* = 2

Table 3e. Baseline Reading Fluency Standard Scores for No-Stimulation Control Group

Baseline Standard Score	**WJ-3 Reading Fluency**	**TOWRE Sight Word Efficiency**
SS < 90	N/A	*N* = 1
92 < SS < 110	*N* = 4	*N* = 5
SS > 110	*N* = 2	N/A

2.3 Overview of Study Procedures

An overview of study procedures is illustrated in Figures 3a-3b.

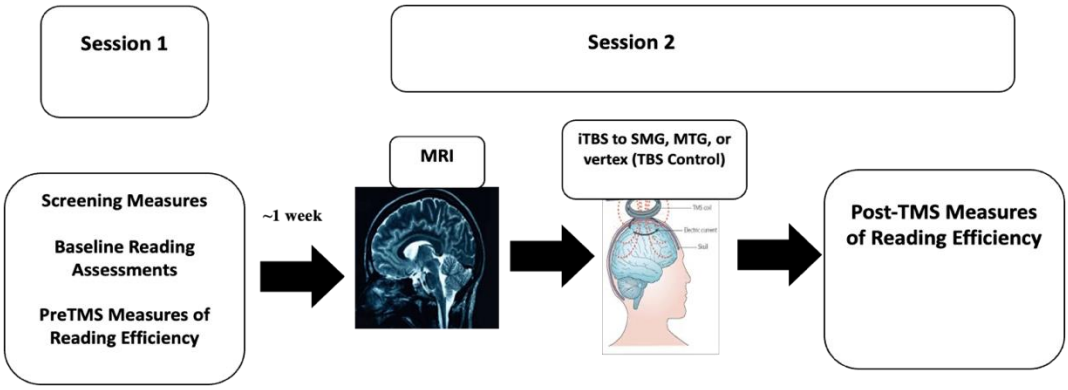


Figure 3a. Study Procedures for Stimulation Groups (SMG, MTG, Vertex)

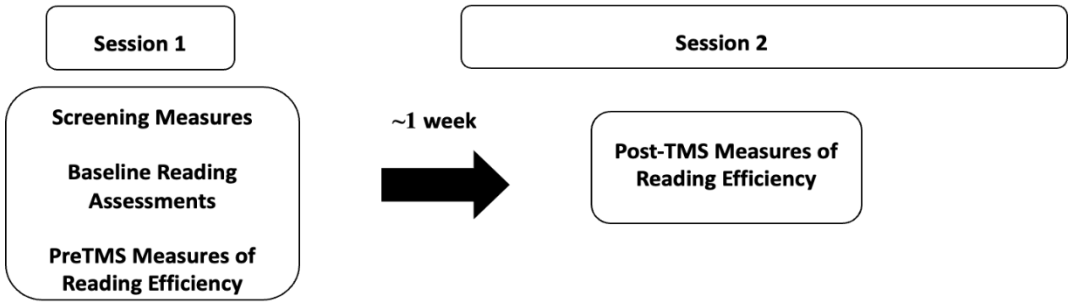


Figure 3b. Study Procedures for NS Control Group

Figure 3a-3b. Overview of study procedures

2.3.1 Session 1 Screening

Session 1 was initially conducted in person (N = 16) but then transitioned to being conducted via videoconferencing software due to the ongoing COVID-19 pandemic. Prior to beginning Session 1, formal consent was obtained for study participation. Following consent, participants were formally screened for health-related contraindications to study procedures (see Exclusion Criteria). Participants then underwent standardized assessments of overall reading skill (see Measures). For participants who enrolled prior to the onset of the COVID-19 pandemic, Session 1 included assessments of baseline reading skills and intellectual functioning and pre-TBS measures of sentence reading fluency (pre-TBS WJ-3 RF) and RAN (pre-TBS RAN). For participants who enrolled after the onset of the COVID-19 pandemic, Session 1 included assessments of baseline reading skills and intellectual functioning, with pre-TBS outcome measures taking place at Session 2 prior to TMS and MRI. All measures were intended to provided baseline estimates of participants' reading automaticity.

Participants were compensated with $10.00 for their participation in Session 1.

2.3.2 Session 2: MRI & TBS

Session 2 took place on average 2-4 weeks following Session 1. At this session, re-screening for any health-related contraindications to study procedures took place, followed by assessments of single word recognition (pre-TBS TOWRE-2 SWE). For participants who enrolled after the onset of the COVID-19 pandemic, Session 2 also included initial assessments of sentence reading fluency (pre-TBS WJ-3 RF) and RAN (pre-TBS RAN), as these measures were not administered when Session 1 took place virtually. Participants also spent about 1 hour in the MRI prior to receiving TBS during Session 2. Part of this time was devoted to structural scans used to localize TBS stimulation regions, with additional MRI sequences performed as part

of a larger ongoing study (CABI Institutional Review Board, protocols H12871 and H16199). During the MRI session, participants also completed the pre-TBS Orthographic Awareness Task (pre-TBS OA; see Measures). For the MTG, SMG, and Vertex groups, these assessments were followed by a 90 second session of TBS to either SMG (dorsal reading network node) MTG (ventral reading network node) or a control stimulation site (vertex). Following stimulation, participants underwent measures of the same sentence reading fluency (post-TBS WJ-3 RF), RAN (post-TBS RAN), and single word recognition tasks (post-TBS TOWRE-2 SWE) that they took part in prior to stimulation (Post-TBS Assessments, see Measures). They also underwent a post-TBS MRI scan lasting about 30 minutes, during which time they also repeated the OA task (post-TBS OA). This procedure was identical for the NS Control group except for the fact that no stimulation was performed prior to the second administration of the TOWRE-2 and the OA task. The amount of change in these measures was then calculated for each group (pre-TBS – post-TBS for SMG, MTG, and Vertex Group; Time Point 1 – Time Point 2 for NS Control Group).

Of note, pre-TBS WJ-3 Reading Fluency and TOWRE took place 2-4 weeks prior to the post-TBS measures for 16 participants (N = 16). However, due to concerns about lack of reliability and/or inability to administer these measures virtually, these measures were administered ~1 hour prior to TBS for participants enrolled after the onset of the COVID-19 pandemic (N = 22). In addition, baseline RAN was administered ~1 hour prior to TBS. There was some concern about practice effects given the brief interval (~1 hour) between pre-TMS and post-TMS administration of these measures. However, given the high test-retest reliability of these measures and similarity for means calculated across time points in the standardization sample (Woodcock, McGrew, & Mather, 2001; Torgesen, Wagner, & Rashotte, 2011; Wolf &

Denckla, 2005), such practice effects are likely to be minimal. In addition, two separate versions of the TOWRE were administered between the pre-and post-TBS time points (TOWRE-A administered pre-TBS, and TOWRE-B administered post-TBS) in order to further minimize practice effects.

Participants were compensated $65.00 for their participation in Session 2.

2.4 Measures

2.4.1 Baseline Measures

The following measures were administered at Session 1 (pre-TBS) to ensure that participants met inclusion criteria. These measures provided a baseline estimate of participants' intellectual functioning and reading ability.

1. Wechsler Abbreviated Scale of Intelligence, 2nd Edition (WASI-II). The WASI-II was used to determine a two-subtest measured full scale IQ (FSIQ) for all participants. The two subtests used were Vocabulary and Matrix Reasoning, with resulting age-based normative scores combined to provide a FSIQ estimate. The Vocabulary subtest is untimed, and requires the examinee to provide the meanings of different words when prompted. The words are ordered from easiest to most difficult, and administration is stopped when the examinee defines 3 consecutive words incorrectly. The Vocabulary subtest shows good internal consistency, with a Cronbach's alpha of 0.91. The Matrix Reasoning subtest of the WASI-II requires the examinee to examine visual patterns consisting of 4-6 images, and to choose from a selection which image best completes the pattern. Administration is stopped when the examinee answers 3 consecutive test items incorrectly. The Matrix Reasoning subtest shows good internal consistency, with a Cronbach's alpha of 0.89.

2. Woodcock-Johnson Test of Achievement – 3 (WJ-3) Measures of Untimed Reading: Subtests of the Woodcock-Johnson III Tests of Achievement (WJ-III; Woodcock et al. 2001) that provide indices of component reading skills other than fluency were administered at baseline. These included WJ-3 Letter-Word Identification, WJ-3 Word Attack, and WJ-3 Passage Comprehension. Each of these subscales has been shown to have high reliability/validity. The Letter-Word Identification subtest is used to test an examinee's ability to decode real words and is untimed. The Word Attack subtest is a measure of phonological ability and requires the examinee to decode pseudowords. This subtest is untimed. The Passage Comprehension subtest measures the examinee's ability to understand written material and is untimed. This subtest requires the examinee to read sentences that are missing one key word and to supply the missing word that completes the sentence based on context clues from the passage.

2.4.2 Pre-Post TMS Measures of Reading Efficiency

The following measurements of reading fluency, OA, and RAN were administered prior to TMS administration (pre-TBS) and following TMS administration (post-TBS).

1. Experimental Orthographic awareness (OA) task: this assessment measures how quickly and automatically participants can identify valid orthographic patterns. In this well-validated and well-replicated experimental task (Olson, 1994), we measured the speed at which participants could identify whether or not letter strings represent a correctly spelled real word. During their MRI scans, participants saw a letter string on the screen that either represented a correctly spelled real word (e.g., "flute") or an incorrectly spelled word (e.g., "roze"). They were asked to judge with a button press whether the letter string was a "real word" or "not a real word". Correctly and incorrectly spelled words were intermixed pseudo-randomly and response times

were recorded for a total of 32 trials. The median response time across correct trials was calculated for each participant.

2. Rapid Automatized Naming Test (RAN; Wolf & Denckla, 2005): this assessment measures how quickly and automatically participants can match letter and number symbols to their corresponding sounds**.** In this test, participants were asked to rapidly name visual symbols presented on three separate cards, one containing colors, one containing numbers, and one containing letters. This test typically took up to 3 minutes for administration, with a separate score calculated for each card (RAN Colors, RAN Numbers, RAN Letters). For each participant, we recorded the number of correctly named items and the total time required name all items on each card. We then calculated the mean response time per item (in seconds) based on recorded accuracy and total response time. We chose to use a measure of response time as the RAN outcome measure in order to maximize sensitivity to changes in RAN following TBS, as the use of traditional standard scores may fail to capture change in RAN due to the wide intervals of raw scores per standard score for adults over 18. The use of response time measures for RAN is also consistent with several studies measuring RAN throughout the literature (for a review, see Araujo & Faisca, 2019). We transformed the total response time for each card to the mean response time per item in an attempt to reduce skewness in the distribution of RAN outcomes (e.g., Tabachnick & Fiddell, 2007).

Meta analytic studies (e.g., Araujo & Faisca, 2019) suggest that performance on individual RAN tasks using either colors, numbers, or letters are all strongly predictive of reading skill. Unsurprisingly, pre-and post-TBS scores on each RAN task were highly correlated in our sample ($r > 0.5$, $p < .05$). Therefore, we conducted analyses that created a composite score of seconds per item (SPI) on each measure of RAN, referred to as RAN SPI. This

composite RAN score was calculated by dividing the total time to name colors, numbers, and letters across all three tasks by the total number of items named correctly across all three tasks (Vander Stappen & Reybroeck, 2018).

3. Test of Word Reading Efficiency – Second Edition (TOWRE-2; Torgesen et al., 2011): this assessment measures how quickly and automatically participants can read aloud individual real words (Sight Word Efficiency, SWE). The items are ordered from easiest to most difficult, and the examinee reads as many items as possible in 45 seconds. Number of items read accurately and response times to read the items (words/sec) are recorded. We chose to use raw scores as the outcome measure in order to maximize sensitivity to change following TBS, as the use of traditional standard scores may fail to capture change in TOWRE-2 scores due to the wide intervals of raw scores per standard score for adults over 18. Participants in the SMG, MTG, and Vertex group completed two different versions of the TOWRE-2 at the pre and post stimulation time points (TOWRE-2 A pre-TBS and TOWRE-2 B post-TBS) in order to reduce the impact of practice effects. The NS Control Group completed the TOWRE-2 A at both time points.

4. Measure of sentence-level reading fluency (Woodcock-Johnson Test of Achievement – 3 Reading Fluency (WJ-3 RF): this assessment measures how quickly and automatically participants can read information at the level of simple sentences. The subtest requires the examinee to read simple sentences and correctly answer yes/no questions about them within a 3-minute time limit. We chose to use W scores as the outcome measure in order to maximize our ability to detect change following TBS, as the use of traditional standard scores may fail to capture change in WJ-3 scores due to the wide intervals of raw scores per standard score for adults over 18. The W score is essentially a raw score that accounts for 1) the number of items that an individual answers correctly and 2) the relative difficulty of the items that the

individual answers correctly, creating a general index of ability (for a review, see Benson et al., 2018). Increases in W scores are therefore considered to measure increases in proficiency of a given skill; as such, an increase reflects increased ability to accurately answer more difficult items.

2.5 Pre-TMS MRI

A 3T Siemens TIM MR system at the joint Georgia State University and Georgia Institute of Technology Center for Advanced Brain Imaging (CABI) in Atlanta was used to collect T1-weighted images that provide anatomic landmarks for TMS sessions.

2.6 Stimulation

2.6.1 TMS Equipment

The TMS equipment consists of an electric stimulator (MagVenture MagPro X1000 Stimulator) with a figure-of-eight wire coil (MagVenture CB60 static cooled coil). Turning the stimulator on and off produces brief electrical currents in the coil, and these currents create a short-lived magnetic field around that coil (also called a magnetic pulse). When the coil is held close to the head, and it generates a magnetic pulse, the pulse can induce very small electric currents in the underlying cortical tissue.

2.6.2 Determination of Motor Threshold

Prior to each iTBS session, participants underwent a practice session in order to establish their individual active motor threshold (MT). MT is an index of the excitability of the motor cortex and is standard in the TMS literature for determining the appropriate intensity of stimulation for a given individual, a level that will both be effective and fall within established safety guidelines. MT is defined as the minimum magnetic intensity needed to elicit a visual hand twitch (in the contralateral first dorsal interosseus muscle). This procedure usually took

about 15 minutes and also served the purpose of acquainting subjects to TMS stimulation prior to the TMS session.

2.6.3 Theta-Burst Stimulation

Participants were randomly assigned to receive iTBS to either left MTG, left SMG, or a control site (vertex). All other procedures were kept constant between each participant group. Via the Localite Neuronavigation System, each participant's structural MRI scan was used to identify anatomical landmarks defining stimulation sites (MTG, SMG, and vertex).

Theta-burst stimulation (iTBS) was delivered at 80% of a participant's MT, as is recommended by current safety and effectiveness guidelines (Rossi et al., 2021). To block out the clicking noise of TMS, participants were provided with earplugs. Participants typically heard a clicking sound and felt a tapping sensation at their scalp, but rarely reported discomfort. Stimulation took 90 seconds.

During stimulation, participants were provided with a list of words and instructed to read the words silently to themselves. This was done to raise the level of neuronal activation in the targeted reading areas which has been shown to enhance the effectiveness of TMS (for a review, see Miniussi & Ruzzoli, 2013).

2.6.3.1 Stimulation Protocol

iTBS consists of a set of theta burst stimulation (TBS) units delivered every 10 seconds, with 8 second breaks in between. Each TBS unit consists of 3 pulses of stimulation given at 50 Hz (Huang et al., 2005; see Figures 5a-5b). 20 sets of 10 TBS units (2 second duration) are repeated every 10 seconds for a total of 190 seconds. One session of excitatory stimulation delivers a total of 600 pulses. Diagram illustrates excitatory intermittent TMS session lasting 190 seconds.

1

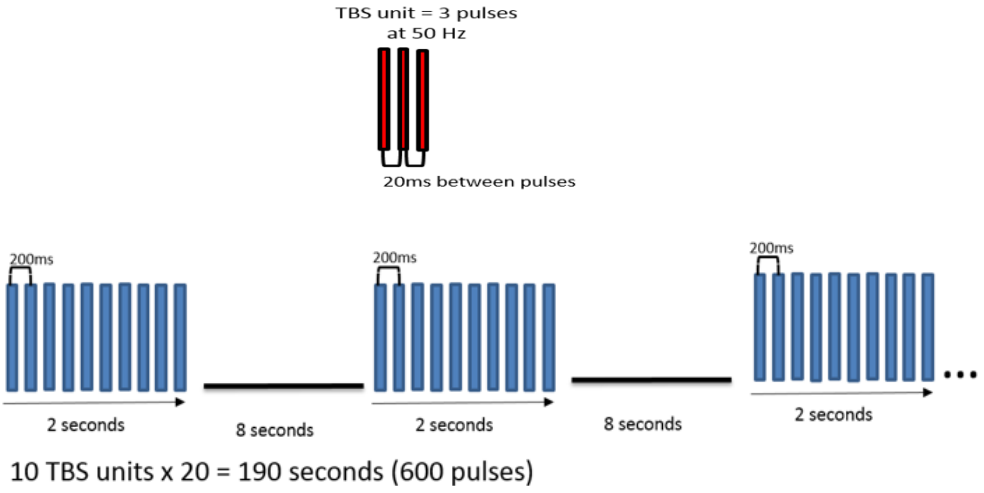


Figure 4. TBS Unit and Diagram of iTBS Procedure[1]

2.7 Data Analysis

2.7.1 Measures of Change

We calculated the amount of change (Δ) for each participant for all measures of reading and component reading skills (ΔMeasure = Pre-TBS score – Post-TBS score for SMG, MTG, and Vertex groups; ΔMeasure = Time Point 1 – Time Point 2 for NS Control group).

2.7.2 Overview of Analyses

For each measure, we:

1) Identified whether significant change occurred in the measure pre-post TBS

2) Compared differences in pre-post TBS scores on each measure between the 4 groups: those who received SMG stimulation (SMG), those who received MTG

[1] Figures used with permission of C. Nikki Arrington, Ph.D

stimulation (MTG), those who received vertex stimulation (Vertex), and those who received behavioral measures at two time points (1-2 weeks in between [2]measures) without any TBS stimulation (NS Control). The NS Control group did not undergo measures of RAN or WJ-3 Reading Fluency. Therefore, pre-post TBS RCIs for RAN and WJ-3 Reading Fluency were compared only among the SMG group, MTG group, and Vertex group.

2.7.3 Addressing Potential Sources of Bias

2.7.3.1 Comparable Baseline Reading Fluency in Each Group

We compared baseline scores (pre-TBS for SMG, MTG, and Vertex and Time Point 1 for NS Control Group) on each outcome measure. This was done to ensure that each group was comparable in terms of their initial scores, so that differences in initial scores would not confound analyses of ΔMeasures between groups. There was no significant difference in Pre-TBS RAN SPI between participant groups, ($F(2, 11) = 0.83$, $p = .46$), and no significant difference in Pre-TBS OA median RTs ($F(3, 31) = 0.12$, $p = .95$) or in Pre-TBS OA accuracy ($F(3, 31) = 0.96$, $p = .42$) between participant groups. In addition, there was no significant difference in pre-TBS TOWRE SWE raw scores between participant groups ($F(3, 30) = 1.06$, $p = .38$), and no significant difference in pre-TBS WJ-3 RF W scores between participant groups ($F(2, 24) = 0.04$, $p = .97$). This suggests that the SMG, MTG, Vertex, and NS Control group were well-equated in terms of baseline RAN, orthographic awareness, word recognition, and sentence reading fluency skills. Therefore, differences in ΔMeasures between groups are unlikely to be due to baseline differences.

2.7.3.2 Normality of Population Distributions

Given the small sample sizes within each group, distributions that are non-normal cannot be readily assumed to follow a normal distribution at the population level. We examined the sampling distributions for each measure for non-normality. Estimates of skewness and kurtosis, tests of normality, and descriptive statistics and histograms for each group are shown in Appendix C (Tables 4-8c, Figures 6a-9c). Given that the distributions for orthographic awareness (OA) and RAN deviated significantly from normal, we used bootstrapped confidence intervals for significance tests (Efron, 1981; Efron & Tibshirani, 1986), to avoid over-estimation of parameter standard errors in parametric tests. In addition, we ran non-parametric tests in addition to parametric tests for all analyses using RAN and OA.

2.7.3.3 Homogeneity of Variances

Levene's test did not suggest significant heterogeneity in variances of pre-post TBS difference scores for OA median RT ($F(3, 31) = 0.71$, $p = .55$) or OA accuracy ($F(3, 31) = 0.98$, $p = .41$) between participant groups. There was also no significant heterogeneity in the variances of pre-post TBS differences in RAN scores between participant groups (RAN Colors: $F(2, 11) = 0.70$, $p = .52$; RAN Numbers: $F(2, 11) = 1.83$, $p = .21$; RAN Letters: $F(2, 11) = 2.2$, $p = .16$; RAN Composite: $F(2, 11) = 0.54$, $p = .60$). There was no significant heterogeneity in variances of pre-post TBS TOWRE-2 scores ($F(2, 22) = 2.00$, $p < .16$), and no significant heterogeneity in variances of pre-post WJ-3 scores ($F(2, 21) = 0.71$, $p < .51$.

3 RESULTS

3.1 Results for Specific Aim 1

3.1.1 Hypotheses for Aim 1a: The Effects of TBS on RAN SPI

We hypothesized that the composite mean response time per item on RAN subtests (including colors, numbers, and letters) would be significantly faster following application of TBS to dorsal and/or ventral reading network nodes (pre-TBS RAN SPI > post-TBS RAN SPI). In addition, we hypothesized that change in RAN task performance would be greater in the groups receiving SMG and/or MTG stimulation as compared to the group receiving Vertex stimulation. Increasingly positive ΔRAN SPI (faster naming) indicates improved performance (ΔRAN SPI = Pre-TBS RAN SPI– Post-TBS RAN SPI).

3.1.2 Analyses for Aim 1a: The Effects of TBS on RAN SPI

The first hypothesis for Aim 1 was that mean response time per item (seconds/item or SPI) to name letters, colors, and digits on RAN/RAS test would be significantly faster following application of TBS to dorsal and/or ventral reading network nodes (pre-TBS RAN SPI > post-TBS RAN SPI). We conducted paired-samples *t*-tests using pre and post RAN composite SPI scores for the SMG, MTG, and Vertex Stimulation Groups, with results displayed in Table 4 and Figure 5. RAN data was not available for the No-Stimulation Control Group. The distributions of RAN data indicated significant deviation from normality, which is especially concerning given the very small sample size for each group (see Appendix D: Tables D.6-D.8, Appendix G.9.a-G.10.c). We therefore used bootstrapped confidence intervals and performed Wilcoxon Signed Rank Tests in addition to traditional parametric tests. Given the small sample size for each group, we also present each individual participant's pre-TBS and post-TBS RAN SPI in each stimulation group (Appendix C: Table C.1). These are meant to provide a visual aid for

qualitative interpretations of these results, given the inherent limitations of quantitative analyses with such small sample sizes.

Table 4. *Paired T-Test Results for Pre-TBS and Post-TBS TBS RAN SPI*

Stimulation Group	*N*	Mean Change (SD)*	*T*	*P*	Cohen's *D*	Bootstrapped CI	Wilcoxon *Z*	Wilcoxon *p*
SMG	4	0.05 (0.01)	17.50	.001	8.75	[0.05, 0.06]	-1.83	.07
MTG	4	-0.04 (0.14)	-0.63	.56	0.14	[-0.18, 0.03]	-0.37	.72
Vertex	5	0.03 (0.02)	4.78	< .01	0.02	[0.51, 3.34]	-2.20	.03

*(Pre-TBS SPI – Post-TBS SPI)

As shown in the above table, participants receiving SMG stimulation showed borderline significantly faster RAN (smaller SPI) following TBS, whereas participants receiving MTG stimulation did not show significant change in RAN following TBS. Contrary to our hypothesis, participants receiving Vertex stimulation showed significantly faster RAN (smaller SPI) following TBS.

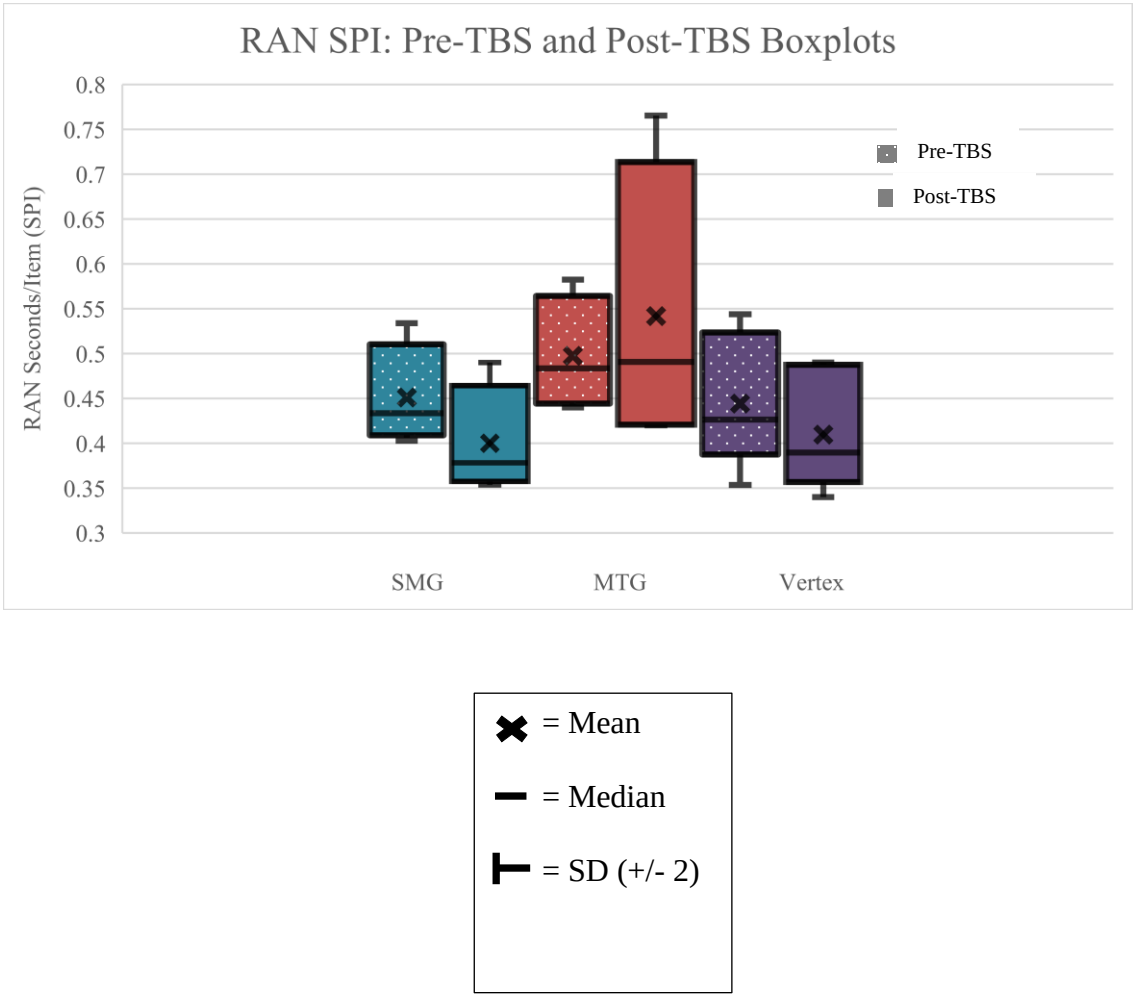


Figure 5. Pre and Post TBS RAN SPI: Boxplots for Each Group

A one-way ANOVA comparing ΔRAN SPI between stimulation groups fell below significance, $F(2, 11) = 1.95$, $p = .19$, $\eta_p^2 = .26$. Planned contrasts showed greater, though non-significant, ΔRAN SPI in the SMG stimulation group compared to the MTG stimulation group, $t(12) = -1.79$, $p = .09$, and slightly greater change, although again non-significant, in RAN in the Vertex stimulation group compared to the MTG stimulation group, $t(12) = -1.31$, $p = .13$. Contrary to our hypotheses, there was no significant difference in ΔRAN SPI in the SMG

stimulation group as compared to the Vertex stimulation group, $t(12) = -1.65$, $p = .74$. The ΔRAN SPI for each stimulation group is displayed in Figure 6.

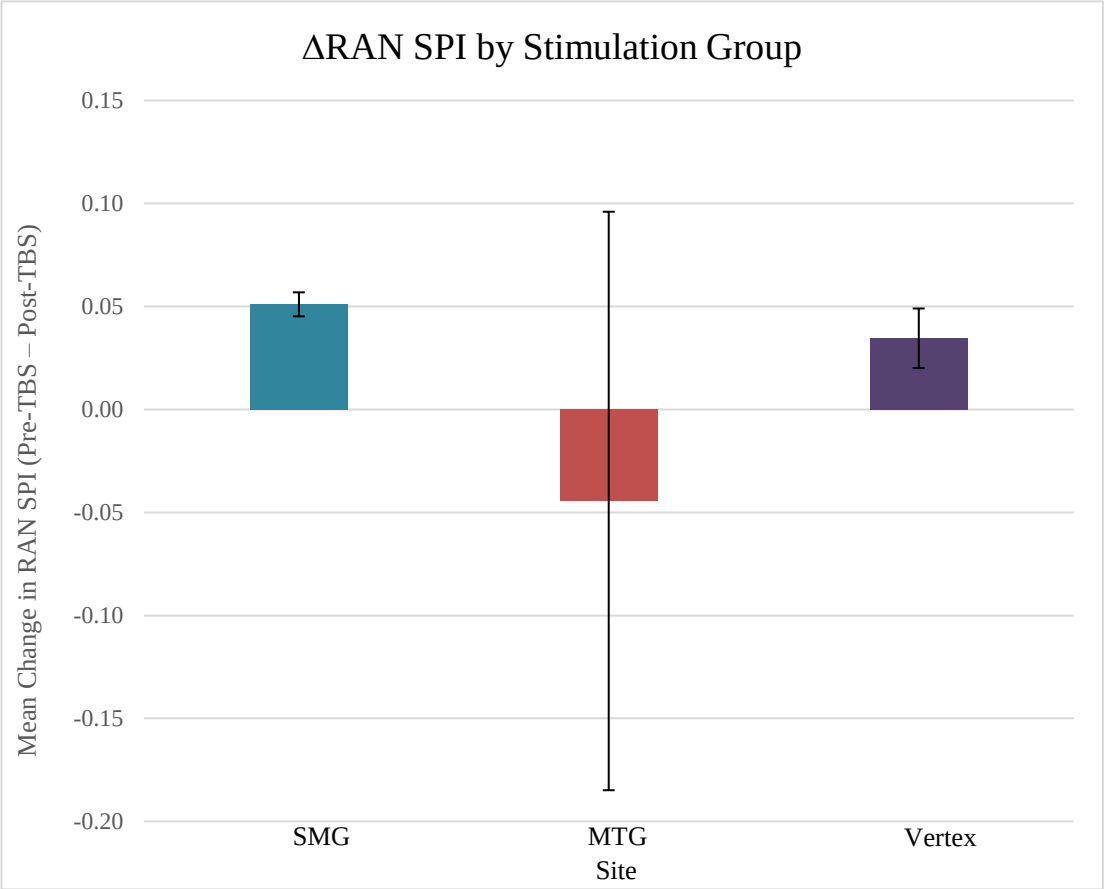


Figure 6. Change in RAN SPI by Stimulation Group

3.1.3 Hypotheses for Aim 1b: The Effects of TBS on OA RT

We hypothesized that response times (RT) during OA tasks would be significantly faster following application of TBS to dorsal and/or ventral reading network nodes (pre-TBS RT > post-TBS RT). We also hypothesized that change in OA task RT (ΔOA RT) would be greater in the groups receiving SMG and/or MTG stimulation as compared to the group receiving vertex (Vertex Group) stimulation or the group receiving no stimulation (NS Control Group). Increasingly positive ΔOA RT indicates improved performance (ΔOA RT = Pre-TBS OA RT

(ms) – Post-TBS OA RT (ms) for SMG, MTG, and Vertex Groups; ΔOA RT = Time Point 1 OA RT (ms) – Time Point 2 OA RT (ms) for NS Control Group).

3.1.4 Analyses for Aim 1b: The Effects of TBS on OA RT

The second hypothesis for Aim 1 was that mean response time (RT) on the orthographic awareness (OA) task would be significantly faster following application of TBS in participants receiving MTG and SMG stimulation (pre-TBS OA RT > post-TBS OA RT). In contrast, we hypothesized little to no change in RT following TBS in participants receiving Vertex Stimulation, and little to no change in RT between time points in the NS Control Group. Each individual participant's pre-TBS and post-TBS OA RT are shown in Appendix E: Table E.1 .

We conducted paired-samples *t*-tests using pre and post OA RT for the SMG, MTG, Vertex, and NS Control groups, with results displayed in Table 5 and Figure 7. The distributions of OA data indicated significant deviation from normality (see Appendix D: Tables D.1-D.4, Appendix G.1.a-G.8.c). We therefore used bootstrapped confidence intervals and performed Wilcoxon Signed Rank Tests in addition to traditional parametric tests. Accuracy was very high (>85%) at both time points for each stimulation group, but no significant change in accuracy between time points was found in any of the stimulation groups likely due to ceiling effects (Appendix F: Table F.1). We therefore focused on RT for the following analyses.

Table 5. *Paired T-Test Results for Pre and Post** Orthographic Awareness (OA) RT*

Stimulation Group	*N*	Mean (SD)*	*T*	*P*	Cohen's *D*	Bootstrapped CI	Wilcoxon *Z*	Wilcoxon *p*
SMG	13	85.00 (104.36)	2.94	< .01	104.36	[-33.00, 150.81]	-2.48	.01

MTG	11	64.77 (156.98)	1.37	.20	0.41	[-30.40, 145.72]	-1.25	.21
Vertex	5	108.30 (103.20)	2.35	.08	1.05	[13.4, 164.07]	-1.75	.08
NS Control	6	23.25 (191.34)	0.29	.78	0.12	[-177.55, 224.05]	-0.94	.35

**(SMG, MTG, and Vertex : Pre-TBS OA RT– Post-TBS OA RT; NS Control: OA RT A Time Point 1 – OA RT Time Point 2)

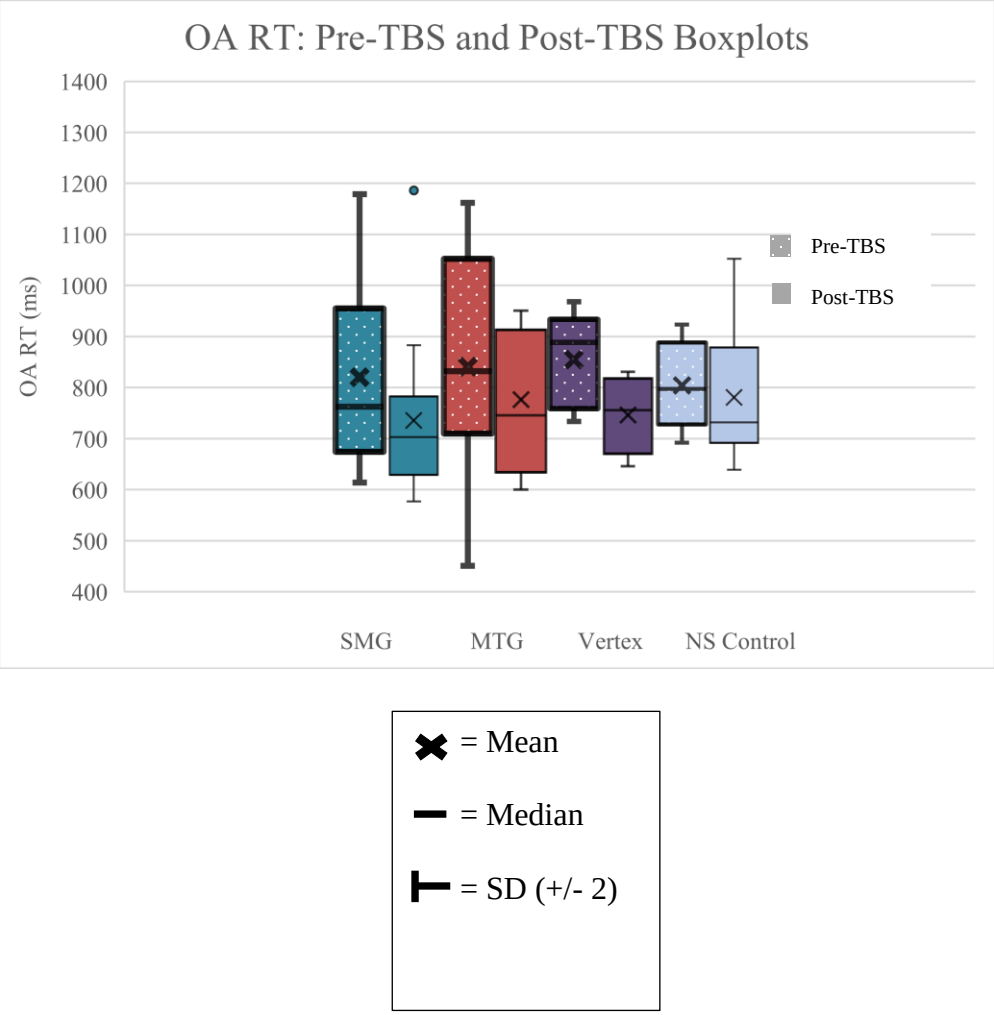


Figure 7. Pre and Post TBS OA RT: Boxplots for Each Group

As displayed above (Table 5, Figures 7), participants receiving SMG stimulation showed significantly faster OA RT (fewer median RT in milliseconds) following TBS, whereas participants receiving MTG stimulation did not show significant change in OA RT following TBS. Contrary to our hypothesis, participants receiving Vertex stimulation also showed borderline significantly faster OA RT following TBS. However, no significant change in OA RT was noted in the NS Control group between time points.

A one-way ANOVA comparing ΔOA RT between stimulation groups was non-significant, $F(3, 31) = 0.41$, $p = .74$, $\eta_p^2 = .04$. Contrary to our hypotheses, planned contrasts did not show any significant difference in ΔOA RT between the SMG and MTG groups and the Vertex and NS Control groups. The ΔOA RT for each stimulation group is displayed in Figure 8.

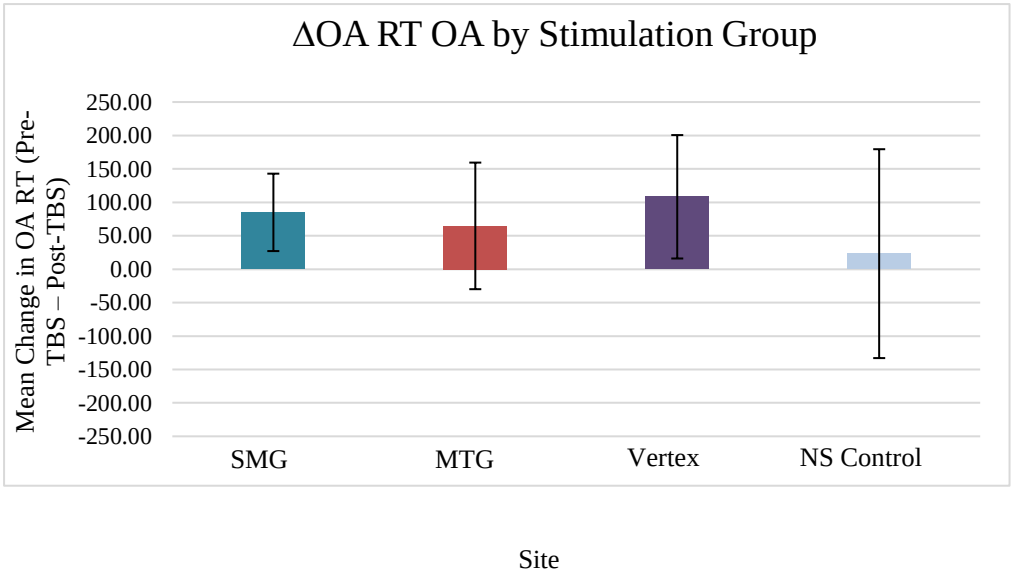


Figure 8. Change in OA Response Time by Stimulation Group

3.2 Results for Specific Aim 2

3.2.1 Hypotheses for Aim 2: The Effects of TBS on TOWRE SWE

We hypothesized that TOWRE-2 Sight Word Efficiency (TOWRE SWE) raw scores would significantly improve following application of TBS to dorsal and/or ventral reading network nodes (pre-TBS TOWRE SWE < post-TBS TOWRE SWE). We also hypothesized that change in TOWRE SWE scores (ΔTOWRE SWE) would be greater in the groups receiving SMG and/or MTG stimulation as compared to the group receiving vertex stimulation (Vertex) stimulation or the group receiving no stimulation (NS Control). Increasingly negative ΔTOWRE SWE indicates improved performance (ΔTOWRE SWE Score = Pre-TBS TOWRE SWE Score – Post-TBS TOWRE SWE Score for SMG, MTG, and Vertex Groups; ΔTOWRE SWE Score = Time Point 1 TOWRE SWE Score – Time Point 2 TOWRE SWE Score for NS Control Group).

3.2.2 Analyses for Aim 2: The Effects of TBS on TOWRE SWE

The hypothesis for Aim 2 was that raw score on the TOWRE-2 Sight Word Efficiency subtest (reflecting the number of words correctly read in 45 seconds) would significantly improve following application of TBS to dorsal and/or ventral reading network nodes (pre-TBS TOWRE SWE Raw Score < post-TBS TOWRE SWE Raw Score), reflecting improved efficiency in single word recognition. Each participant's pre-TBS and post-TBS TOWRE-2 in each stimulation group are shown in Appendix E: Table E.1. We conducted paired-samples *t*-tests using pre and post TOWRE SWE Raw Score for the SMG, MTG, and Vertex Stimulation Groups as well as for the No Stimulation Control Group. Results are displayed in Table 6 and Figure 9. As previously described, the TOWRE-2 Version A was administered pre-TBS whereas the TOWRE-2 Version B was administered post-TBS in the SMG, MTG, and Vertex Stimulation Groups in order to correct for potential practice effects. However, for the No-Stimulation Control Group, TOWRE-2 A was administered at both time points. As with previous analyses, we used bootstrapped confidence intervals and performed Wilcoxon Signed Rank Tests in addition to

traditional parametric tests as distributions of TOWRE-2 A and TOWRE-2 B raw scores indicated significant deviation from normality (Appendix D: Tables D.8-D.11, Appendix G: G.11.a-G.14.c).

Table 6. *Paired T-Test Results for Pre and Post ** TOWRE-2 Raw Score*

Stimulation Group	*N*	Mean (SD)*	*t*	*p*	Cohen's *D*	Bootstrapped CI	Wilcoxon *Z*	Wilcoxon *p*
SMG	9	-3 (6.46)	-1.39	.10	-0.46	[-6.89, 1.00]	-1.26	.21
MTG	9	-1.78 (2.82)	-1.89	.10	-0.63	[-3.44, 0.00]	-1.85	.06
Vertex	7	-3.43 (4.54)	-1.99	.09	-0.76	[-6.87, -.43]	-1.70	.09
NS Control	5	-3.00 (6.44)	-1.04	.36	-0.47	[-8.2, 1.81]	-1.10	.27

*(SMG, MTG, and Vertex : Pre-TBS TOWRE-2 A Raw Score – Post-TBS TOWRE-2 B Raw Score; NS Control: TOWRE-2 A Time Point 1 – TOWRE-2 A Time Point 2)

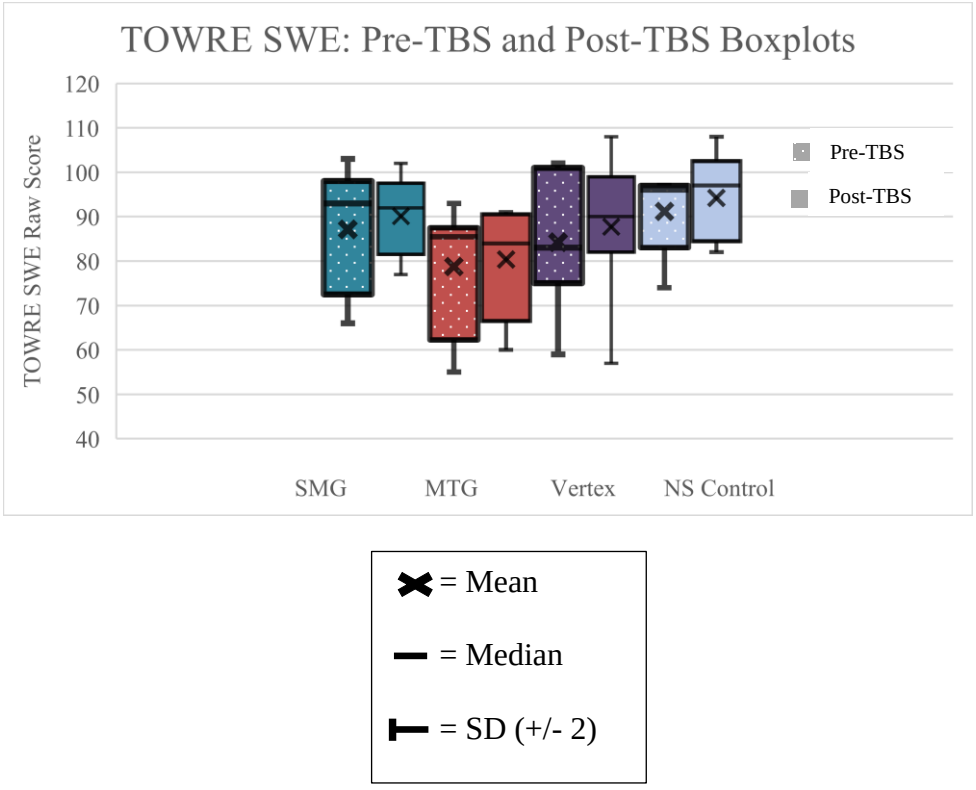


Figure 9. Pre and Post TOWRE SWE: Boxplots for Each Group*

Contrary to our hypotheses, we found pre-post TBS change in TOWRE-2 scores that trended toward statistical significance in the SMG, MTG, and Vertex group. However, the amount of change in TOWRE-2 scores in the NS Control group was non-significant. For both the SMG group and MTG group, 67% (6/9) participants showed an increase in their TOWRE-2 score post-TBS. In the Vertex group, 71% (5/7) participants showed an increase in TOWRE-2 score post-TBS. In the NS Control group, 60% (3/5) participants showed an increase in TOWRE-2 score post-TBS.

Although pre-post change in the NS Control group was non-significant, it should be noted that the average amount of change in this group was similar in magnitude to the amount of change in the SMG and Vertex groups, and the analyses with this group may have been under-powered due to having the smallest sample size (N = 5). The fact that change of equal magnitude was found in the NS Control group and the stimulation groups could be interpreted to mean that change across stimulation groups is likely a result of practice effects rather than TBS-induced change. However, it is important to remember that the NS Control group received the same version of the TOWRE at both time points, whereas all other stimulation groups received different versions of the TOWRE pre and post TBS. If practice effects were solely responsible for the observed TOWRE-2 change, we would expect to see much larger and more consistent change in TOWRE-2 scores in the NS Control group as compared to stimulation groups, as this group received the same version of the TOWRE-2 at comparable time intervals to the stimulation group. As the NS Control group did not show substantially larger amounts of change as compared to other stimulation groups, it is likely that the pre-post changes were at least partially due to the effects of stimulation rather than solely due to practice effects.

A one-way ANOVA comparing the ΔTOWRE SWE between stimulation groups was non-significant, $F(3, 30) = 0.16$, $p = .92$, $\eta_p^2 = .02$. Contrary to our hypotheses, planned contrasts did not show any significant difference in the amount of change in TOWRE-2 scores between the SMG and MTG groups and the Vertex and NS Control groups. The amount of change in TOWRE-2 for each stimulation group is displayed in Figure 10.

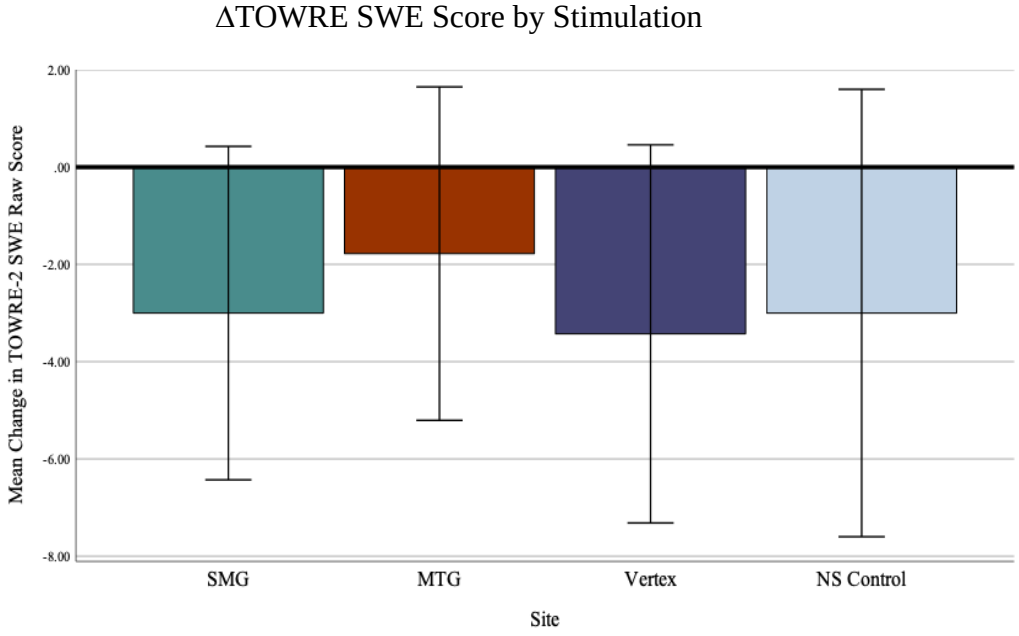


Figure 10. ΔTOWRE SWE Score in Each Stimulation Group

3.3 Results for Specific Aim 3

3.3.1 Hypotheses for Aim 3: The Effects of TBS on WJ-3 RF

Hypothesis 3a: We hypothesized that WJ-3 Sentence Reading Fluency (WJ-3 RF) W score would significantly improve following application of TBS to dorsal and/or ventral reading network nodes (pre-TBS WJ-3 RF W score < post-TBS WJ-3 RF W score). We also hypothesized that the amount of change in WJ-3 RF task performance (ΔWJ-3 RF) would be greater in the groups receiving SMG and/or MTG stimulation as compared to the group receiving

vertex (Vertex) stimulation or the group receiving no stimulation (NS Control). Increasingly negative ΔWJ-3 RF indicates improved performance (ΔWJ-3 RF W Score = Pre-TBS WJ-3 RF W Score – Post-TBS WJ-3 RF W Score).

3.3.2 Analyses for Aim 3: The Effects of TBS on The Effects of TBS on WJ-3 RF

The hypothesis for Aim 3 was that W scores on the WJ-3 Sentence Reading Fluency subtest (reflecting the number of simple sentences read and understood correctly in three minutes) would significantly improve following application of TBS to dorsal and/or ventral reading network nodes (pre-TBS WJ-3 RF W Score < post-TBS WJ-3 RF W Score), reflecting improved efficiency in reading at the sentence level. Each participant's pre-TBS and post-TBS WJ-3 RF W score in each stimulation group are shown in Appendix E: Table E.1. We conducted paired-samples *t*-tests using pre and post WJ-3 RF W Scores for the SMG, MTG, and Vertex Stimulation groups. No WJ-3 data was available for the NS Control group. Results are displayed in Table 7 and Figure 11. Although the distributions for WJ-3 data appeared to be normally distributed (see Appendix D: D.12-D.14), we reported bootstrapped confidence intervals and performed Wilcoxon Signed Rank Tests in addition to parametric tests in order to maintain consistency across analyses.

Table 7. *Paired T-Test Results for Pre-TBS and Post-TBS TBS WJ-3 Reading Fluency W Score*

Stimulation Group	*N*	Mean (SD)*	*t*	*P*	Cohen's *D*	Bootstrapped CI	Wilcoxon *Z*	Wilcoxon *p*
SMG	8	-9.63 (8.86)	-3.07	.02	-1.09	[-15.13, -3.75]	-2.11	.04
MTG	10	-6.10 (10.00)	-1.93	.09	-0.61	[-12.20, 0.00]	-1.74	.08
Vertex	6	-12.83 (12.91)	-2.44	.06	-1.00	[-22.83, -4.01]	-2.02	.04

*(Pre-TBS WJ-3 RF W Score– Post-TBS WJ-3 RF W Score)

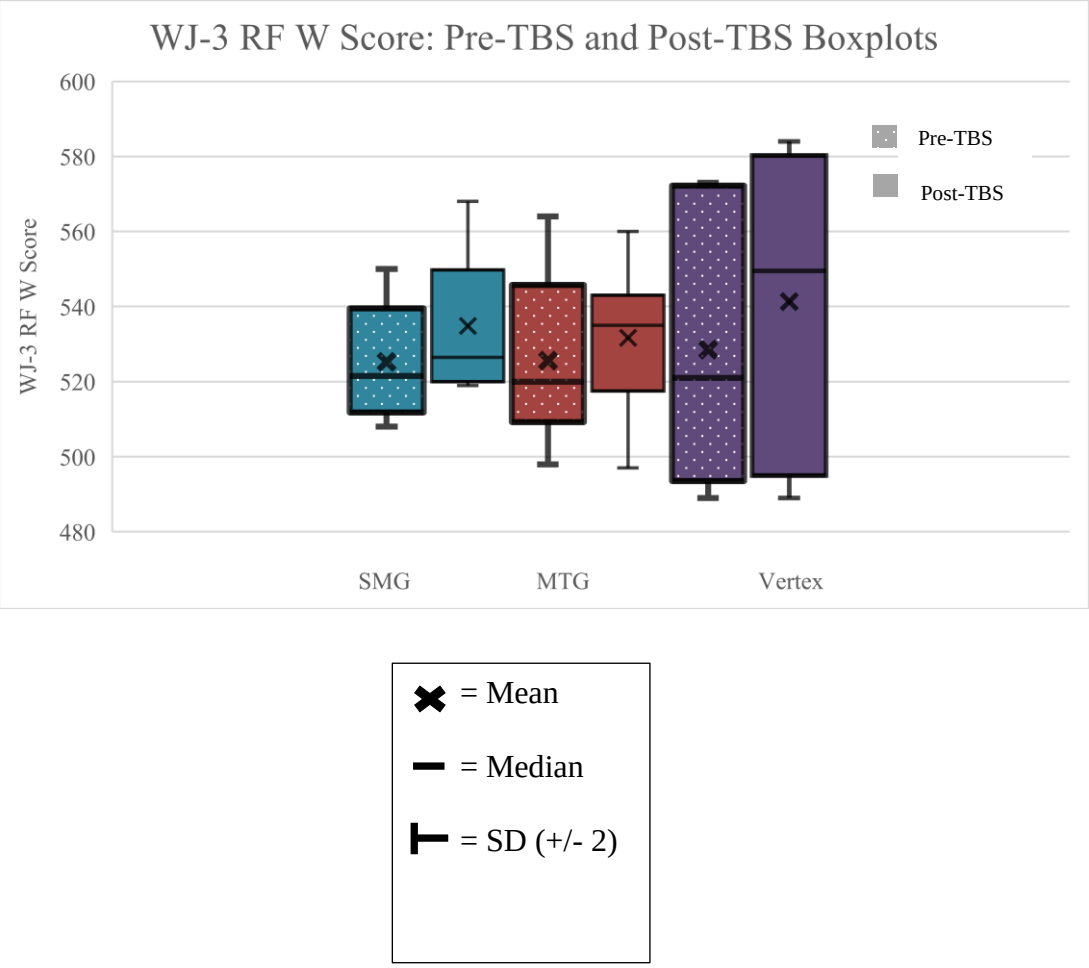


Figure 11. Pre and Post TBS WJ-3 RF W Scores: Boxplots for Each Group

As shown in the above table and figure, participants receiving SMG stimulation showed a significant increase in WJ-3 RF W scores, whereas stimulation to the MTG showed a borderline significant increase in W scores following TBS. Contrary to our hypothesis, participants receiving Vertex stimulation also showed significant increases in WJ-3 RF W scores following TBS. Due to the fact that no WJ-3 data was available for the NS Control group, the Vertex group was intended as a control; however, change was found post-TBS in this group as well as in the SMG group. In addition, the same version of the WJ-3 was administered at both time points, as no alternate version was available. It is therefore difficult to determine whether or not the

observed changes in WJ-3 scores in each group are the result of TBS-induced change or the result of practice effects.

A one-way ANOVA comparing ΔWJ-3 RF W Score (Pre-TBS – Post-TBS) between stimulation groups was non-significant, $F(2, 21) = 0.81$, $p = .46$, $\eta_p^2 = .07$. Contrary to our hypotheses, planned contrasts did not show any significant difference in the amount of change in WJ-3 RF scores between the SMG and MTG groups and the Vertex group. The amount of change in WJ-3 RF for each stimulation group is displayed in Figure 12.

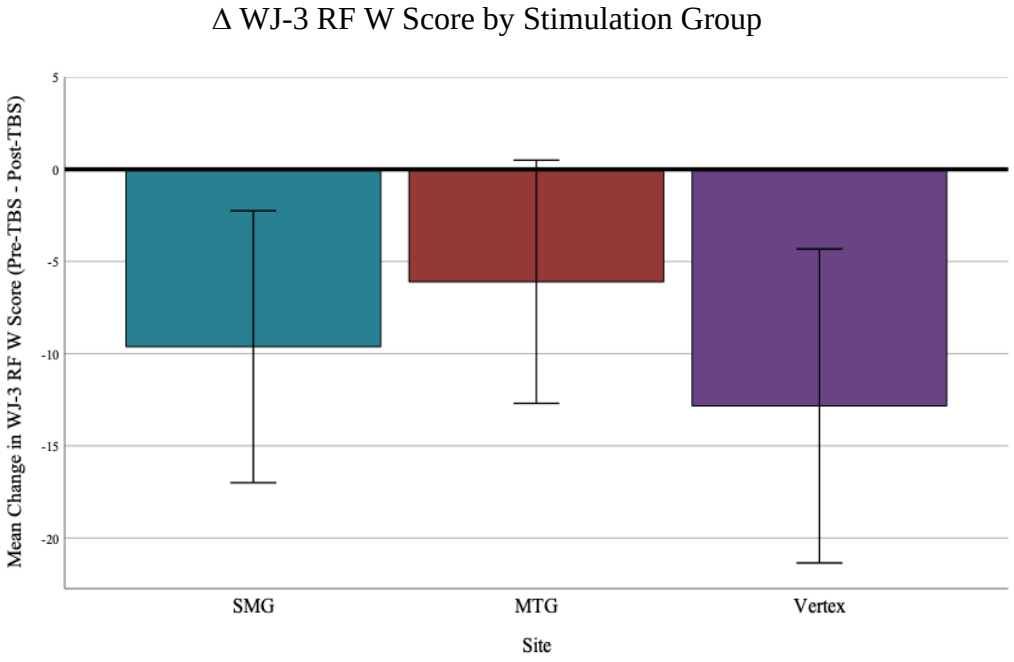


Figure 12. ΔWJ-3 RF W Score by Stimulation Group

3.3.3 Summary of Initial Results

Results are summarized in Tables 8a-8b. Across all measures, a pattern emerged in which the SMG and Vertex stimulation resulted in greater change between time points on all measures than MTG stimulation did, although a number of these results were borderline significant. In addition, the SMG group showed significant change between pre-TBS and post-TBS time points on RAN, OA, and WJ-3 RF W scores, with borderline significant change on TOWRE SWE. Similarly, the

Vertex group showed significant change between pre-TBS and post-TBS time points on RAN and WJ-3 RF W scores, with borderline significant change on TOWRE SWE and OA. In contrast, the MTG group did not show significant change between time points on RAN, OA, or TOWRE SWE, and showed only borderline significant change between time points in WJ-3 RF W scores. The NS Control group did not have data available for RAN or WJ-3 RF; however, the NS Control group showed no significant change between time points on OA or on TOWRE SWE. These results were contrary to our hypothesis that change on measures of reading automaticity would be greater following both SMG and MTG stimulation as compared to Vertex, which we theorized would serve as a control site. However, our hypothesis that the SMG group would show greater change compared to NS Control group was supported. Possible explanations for these findings are described in detail in the Discussion.

Table 8a-8b. *Summary of Initial Results*

Table 8a. Mean Change by Participant Group

	Mean ΔRAN SPI (Pre-TBS SPI - Post-TBS SPI)	**Mean Δ OA RT** (Pre-TBS RT - Post-TBS RT)	**Mean ΔTOWRE SWE** (Pre-TBS Raw Score - Post-TBS Raw Score)	**Mean ΔWJ-3 RF** (Pre-TBS W Score - Post-TBS W Score)
Stimulation Group				
SMG Group	0.05	85	-3	-9.63
MTG Group	-0.04	64.77	-1.78	-6.10
Vertex Group	0.03	108.3	-3.43	-12.83
NS Control Group	N.A.	23.25	-3	N.A.

Significant Improvement ($p < .1$)
No Significant Change
Significant Decline ($p < .10$
No Data

Table 8b. Pre and Post Means For Each Measure by Participant Group

Group	***Mean RAN SPI (SD)***		***Mean OA RT (ms) (SD)***		***Mean TOWRE SWE Raw Score (SD)***		***Mean WJ-3 RF W Score (SD)***	
	Pre*	***Post****	***Pre****	***Post****	***Pre****	***Post****	***Pre****	***Post****
SMG	0.45 (0.06)	0.40 (0.06)	820.35 (171.78)	735.35 (162.62)	87.11 (13.65)	90.11 (8.62)	525.25 (15.07)	534.88 (18.04)
MTG	0.50 (0.06)	0.54 (0.16)	841.00 (199.46)	776.23 (129.15)	78.78 (13.78)	80.56 (11.87)	525.60 (21.39)	531.70 (19.21)
Vertex	0.44 (0.07)	0.41 (0.06)	854.80 (94.50)	746.50 (76.48)	84.29 (14.94)	87.71 (16.10)	528.50 (36.52)	541.33 (40.25)
NS Control	---	----	804.17 (87.81)	780.92 (145.68)	91.20 (9.83)	94.20 (10.09)	---	

**Pre = Pre-TBS for SMG, MTG, and Vertex groups; Time Point 1 for NS Control Group*

***Post = Post-TBS for SMG, MTG, and Vertex groups; Time Point 2 for NS Control Group*

3.4 Post-Hoc Analyses

3.4.1 Relationships Between TBS-Induced Change on Measures of Reading Automaticity

We hypothesized that TBS to nodes of the reading network would improve component skills supporting word recognition automaticity, such as OA and RAN. TBS-induced improvement in these component skills should theoretically facilitate improved single word recognition (TOWRE-2) as well as reading efficiency at the sentence level (WJ-3). We were therefore interested in whether or not the amount of change in component reading skills (OA and RAN) was correlated with the amount of change in performance on the TOWRE-2 and the WJ-3.

First, we assessed the correlations between pre-TBS measures across all participants (as previously described, pre-TBS measures for RAN, OA, TOWRE-2, and WJ-3 were comparable across all participant groups). Theoretically, as all of the measures represent components of

reading fluency, all should show strong correlations with one another. As expected, moderate to large correlations were found between pre-TBS WJ-3 and TOWRE-2 scores ($r = .71$, $p < .001$), as well as between pre-TBS RAN and pre-TBS TOWRE-2 ($r = -.82$, $p < .01$), and between pre-TBS RAN and pre-TBS WJ-3 ($r = -0.6$, $p = .04$). Surprisingly, pre-TBS OA RT was not strongly correlated with other baseline measures. This measure showed no meaningful correlations with pre-TBS TOWRE ($r = -.16$, $p = .43$) or with pre-TBS RAN ($r = -.19$, $p = .55$), and showed only a slight non-significant relationship with pre-TBS WJ-3 ($r = -.33$, $p = .15$). Possible reasons for this unexpected finding are described in the discussion.

Having established strong correlations between pre-TBS RAN, TOWRE-2, and WJ-3, we then explored the extent to which change (pre-TBS – post-TBS) in each of these measures were correlated with one another. For each stimulation group, we found non-significant correlations between the changes on each measure. This may have been influenced by the very small sample sizes for each correlation analysis, making it difficult to determine if any significant relationships between change in different variables was present. Correlations between Pre-Post change measures on each variable are displayed in Tables 9a-9d.

Table 9a-9b. *Correlations Between Pre-Post Change Measures by Participant Group*

Table 9a. Correlations Between Change (Pre-TBS – Post-TBS) Measures for SMG Group

Measure	Δ OA RT (Pre-TBS – Post-TBS)	Δ RAN SPI (Pre-TBS – Post-TBS)	Δ TOWRE SWE (Pre-TBS – Post-TBS)	ΔWJ-3 RF W Score (Pre-TBS – Post-TBS)
ΔOA RT (Pre-TBS – Post-TBS)	----	r = .81, p =.19, N = 4	r = .41, p = .31, N = 8	*r = -.67, p = .07, N = 8
ΔRAN SPI (Pre-TBS – Post-TBS)	r = .81, p = .19, N = 4	----	r = -.56, p = .44, N = 4	r = -.16, p = .84, N = 4
Δ TOWRE SWE (Pre-TBS – Post-TBS)	r = .41, p = .31, N = 8	r = -.56, p = .44, N = 4	----	r = -.51, p = .20, N = 8
ΔWJ-3 RF W Score (Pre-TBS – Post-TBS)	*r =-.67, p = .07, N = 8	r = -.16, p = .84, N = 4	r = -.51, p = .20, N = 8	----

**significant at level of 0.1*

***significant at level of 0.05*

Table 9b. Correlations Between Change (Pre-TBS – Post-TBS) Measures for MTG Group

Measure	Δ OA RT (Pre-TBS – Post-TBS)	Δ RAN SPI (Pre-TBS – Post-TBS)	Δ TOWRE SWE (Pre-TBS – Post-TBS)	ΔWJ-3 RF W Score (Pre-TBS – Post-TBS)
Δ OA RT (Pre-TBS – Post-TBS)	----	r = .77, p = .23, N = 4	r = -.48, p = .23, N = 8	r = .57, p = .14, N = 8
Δ RAN SPI (Pre-TBS – Post-TBS)	r = .77, p = .23, N = 4	----	r = -.10, p = .90, N = 4	r = -.88, p = .12, N = 4
Δ TOWRE SWE (Pre-TBS – Post-TBS)	r = -.48, p = .23, N = 8	r = -.10, p = .90, N = 4	----	r = .01, p = .99, N = 8
ΔWJ-3 RF W Score (Pre-TBS – Post-TBS)	r = .57, p = .14, N = 8	r = -.88, p = .12, N = 4	r = .01, p = .99, N = 8	----

**significant at level of 0.1*

***significant at level of 0.05*

Table 9c. Correlations Between Change (Pre-TBS – Post-TBS) Measures for Vertex Group

Measure	Δ OA RT (Pre-TBS – Post-TBS)	Δ RAN SPI (Pre-TBS – Post-TBS)	Δ TOWRE SWE (Pre-TBS – Post-TBS)	ΔWJ-3 RF W Score (Pre-TBS – Post-TBS)
Δ OA RT (Pre-TBS – Post-TBS)	----	r = .92, p = .09, N = 4	r = -.62, p = .39, N = 4	r = -.52, p = .48, N = 4
Δ RAN SPI (Pre-TBS – Post-TBS)	r = .92, p = .09, N =4	----	r = .82, p = .18, N = 4	r = -.56, p = .45, N = 4
Δ TOWRE SWE (Pre-TBS – Post-TBS)	r = -.62, p = .39, N = 4	r = .82, p = .18, N = 4	----	r = .53, p = .47, N = 4
ΔWJ-3 RF W Score (Pre-TBS – Post-TBS)	r = -.52, p = .48, N = 4	r = -.56, p = .45, N = 4	r = .53, p = .47, N = 4	----

**significant at level of 0.1*

***significant at level of 0.05*

Table 9d. Correlations Between Change (Pre-TBS – Post-TBS) Measures for NS Control Group

Measure	Δ OA RT (Pre-TBS – Post-TBS)	Δ TOWRE SWE (Pre-TBS – Post-TBS)
Δ OA RT (Pre-TBS – Post-TBS)	----	r = -.74, p = .16, N = 5
Δ TOWRE SWE (Pre-TBS – Post-TBS)	r = -.74, p = .16, N = 5	----

**significant at level of 0.1*

***significant at level of 0.05*

We also examined the strength of the associations between pre-TBS and post-TBS scores on each measure and compared these associations between stimulation groups. We reasoned that if these relationships differed between groups, it would further support differential effects of stimulation to each site. These relationships are displayed in Table 10.

Table 10. *Correlations Between Pre* and Post** Time Point Measures by Stimulation Group*

Correlations: Pre* and Post** Time Points				
	Pre-TBS and Post-TBS RAN SPI	Pre-TBS and Post-TBS OA RT	Pre-TBS and Post-TBS TOWRE SWE	Pre-TBS and Post-TBS WJ-3 RF
SMG Group	r = 0.99, p = .02, N = 4	r = 0.81, p < .001, N = 13	r = 0.93, p < .001, N = 9	r = 0.87, p = .005, N = 8
MTG Group	r = 0.51, p = .48, N = 4	r = 0.62, p = .04, N = 11	r = 0.98, p < .001, N = 9	r = 0.88, p < .001, N = 10
Vertex Group	r = 0.97, p < .001, N = 6	r = 0.29, p = .64, N = 5	r = 0.96, p < .001, N = 7	r = 0.66, p = .22, N = 6
NS Control Group	---	r = -0.30, p = .22, N = 6	r = 0.66, p = .22, N = 5	---

**Pre = Pre-TBS for SMG, MTG, and Vertex groups; Time Point 1 for NS Control Group*

***Post = Post-TBS for SMG, MTG, and Vertex groups; Time Point 2 for NS Control Group*

3.4.2 Baseline characteristics predicting response to TBS

Although participants in the various stimulation groups, particularly SMG and Vertex, showed overall improvements in reading efficiency and related component skills, there was notable variability in the responses of individual participants to stimulation. Tables 11a-11d demonstrate the wide ranges and distributions of change for each measure in each stimulation group.

Table 11a-11d. *Change on Pre-Post TBS Measures by Stimulation Group*

Table 11a. Change on Pre-Post TBS Measures for Participants Receiving SMG Stimulation

	RAN Change (Pre-TBS SPI - Post-TBS SPI)	**OA Change** (Pre-TBS RT - Post-TBS RT)	**TOWRE-2 Change** (Pre-TBS Raw Score - Post-TBS Raw Score)	**WJ-3 RF Change** (Pre-TBS W Score - Post-TBS W Score)
SMG_1	N.A.	-81.50	-15	6
SMG_2	0.04	5.00	-7	-19
SMG_3	0.05	211.00	-2	-11
SMG_4	0.06	267.50	-2	-19
SMG_5	0.05	118.50	7	-18
SMG_6	N.A.	19.00	-5	N.A.
SMG_7	N.A.	230.00	N.A.	N.A.
SMG_8	N.A.	63.00	N.A.	N.A.
SMG_9	N.A.	158.00	N.A.	N.A.
SMG_10	N.A.	-7.00	3	-6
SMG_11	N.A.	53.00	N.A.	
SMG_12	N.A.	19.50	1	-4
SMG_13	N.A.	49.00	-7	-6
Mean	0.05	85.00	-3.00	-9.63
SD	0.01	104.36	6.46	8.86
Median	0.05	53.00	-2.00	-8.50
Min	0.04	-81.50	-15.00	-19.00
Max	0.06	267.50	7.00	6.00

**Direction of Change represents change from baseline, not statistical evaluations of significance*

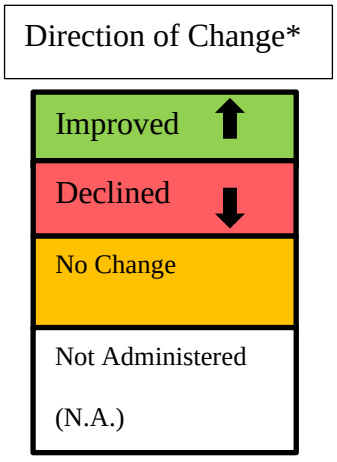


Table 11b. Change on Pre-Post TBS Measures for Participants Receiving MTG Stimulation

	RAN Change (Pre-TBS SPI - Post-TBS SPI)	**OA Change** (Pre-TBS RT - Post-TBS RT)	**TOWRE-2 Change** (Pre-TBS Raw Score - Post-TBS Raw Score)	**WJ-3 RF Change** (Pre-TBS W Score - Post-TBS W Score)
MTG_1	N.A.	-254.50	2	-25
MTG_2	N.A.	N.A.	-3	-3
MTG_3	-0.25	249	-4	1
MTG_4	0.03	89	-3	-7
MTG_5	0.02	205	-2	-14
MTG_6	0.02	124	-6	-12
MTG_7	N.A.	122	2	9
MTG_8	N.A.	65.5	N.A	N.A.
MTG_9	N.A.	-149	-3	-9
MTG_10	N.A.	-63	1	-7
MTG_11	N.A.	127	N.A	6
MTG_12	N.A.	197.5	N.A	N.A.
Mean	-0.04	64.77	-1.78	-6.10
SD	0.14	156.98	2.82	9.99
Median	0.02	122.00	-3.00	-7.00
Min	-0.25	-254.50	-6.00	-25.00
Max	0.03	249.00	2.00	9.00

**Direction of Change represents change from baseline, not statistical evaluations of significance*

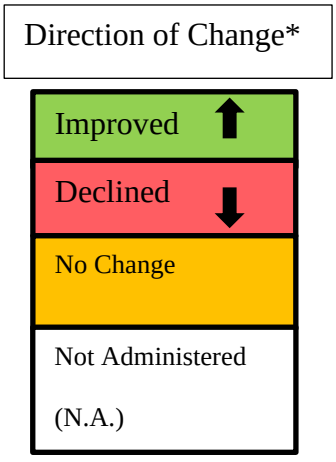
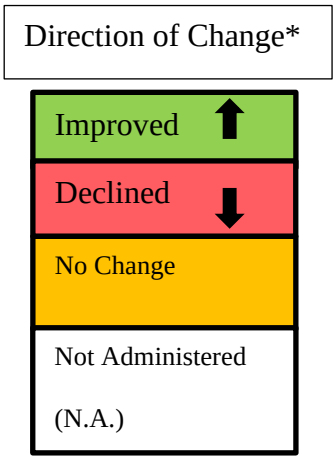


Table 11c. Change on Pre-Post TBS Measures for Participants Receiving Vertex Stimulation

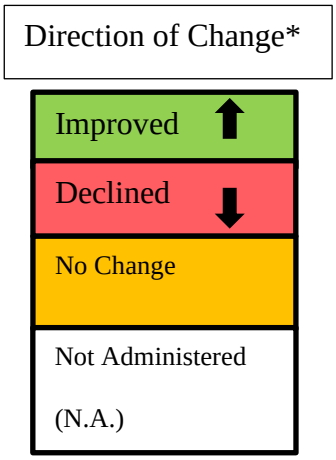
	RAN Change (Pre-TBS SPI - Post-TBS SPI)	**OA Change** (Pre-TBS RT - Post-TBS RT)	**TOWRE-2 Change** (Pre-TBS Raw Score - Post-TBS Raw Score)	**WJ-3 RF Change** (Pre-TBS W Score - Post-TBS W Score)
Vertex_1	N.A.	137.0	2	0
Vertex_2	0.03	-71.5	-3	N.A.
Vertex_3	0.05	138.0	-6	-12
Vertex_4	0.01	N.A.	-10	-2
Vertex_5	0.06	193.5	-7	-26
Vertex_6	0.04	144.5	-2	-31
Vertex_7	0.02	N.A.	2	-6
Mean	0.03	108.30	-3.43	-12.83
SD	0.02	103.20	4.54	12.91
Median	0.03	138.00	-3.00	-9.00
Min	0.01	-71.50	-10.00	-31.00
Max	0.06	193.50	2.00	0.00



**Direction of Change represents change from baseline, not statistical evaluations of significance*

Table 11d. Change (Time Point 1- Time Point 2) on Measures for NS Control Participants

	OA Change (Pre-TBS RT - Post-TBS RT)	**TOWRE-2 Change** (Pre-TBS Raw Score - Post-TBS Raw Score)
NS Control_1	82.00	-1
NS Control_2	102.00	-11
NS Control_3	162.00	-8
NS Control_4	53.50	N.A.
NS Control_5	-360.50	5
NS Control_6	100.50	0
Mean	23.25	-3.00
SD	191.34	6.44
Median	91.25	-1.00
Min	-360.50	-11.00
Max	162.00	5.00



**Direction of Change represents change from baseline, not statistical evaluations of significance*

Given the notable variability in the response of individual participants to stimulation (Tables 11a-11d), we wondered whether participants differed in how they responded to stimulation to a given region depending on their baseline reading and language skills. We tested this hypothesis by calculating the correlations between initial performance on each measure and the amount of change made in the measure from pre to post stimulation. These correlations are displayed in Tables 12a-12d.

Table 12a-12d. *Correlations Between Baseline Skills and ΔPre-Post TBS*

Table 12a. Correlations Between Baseline Skills and ΔPre-Post TBS For SMG Group

Measure	Pre-TBS RAN SPI	Pre-TBS OA RT	Pre-TBS TOWRE SWE Raw Score	Pre-TBS WJ-3 RF W Score	Pre-TBS WJ-3 Letter-Word ID
ΔRAN SPI (Pre-TBS – Post-TBS)	r = -.69, p = .31, N = 4	r = .85, p = .15, N = 4	r = .50, p = .50, N = 4	r = .69, p = .31, N = 4	r = -.13, p = .87, N = 4
ΔOA RT (Pre-TBS – Post-TBS)	r = -.88, p = .11, N = 4	r = .39, p = .19, N = 13	r = -.34, p = .36, N = 9	r = .08, p = .85, N = 8	r = -.31, p = .35, N = 11
ΔTOWRE SWE Raw Score (Pre-TBS – Post-TBS)	r = .51, p = .49, N = 4	*r = -.62, p = .08, N = 9	**r = .87, p < .01, N = 9	r = .49, p = .21, N =8	r = .56, p = .11, N = 9
ΔWJ-3 RF W Score (Pre-TBS – Post-TBS)	r = -.59, p = .41, N = 4	r = -.25, p = .55, N = 8	r = -.31, p = .46, N = 8	r = -.08, p = .86, N = 8	r = -.16, p = .71, N = 8

**significant at level of 0.05*
***significant at level of 0.01*

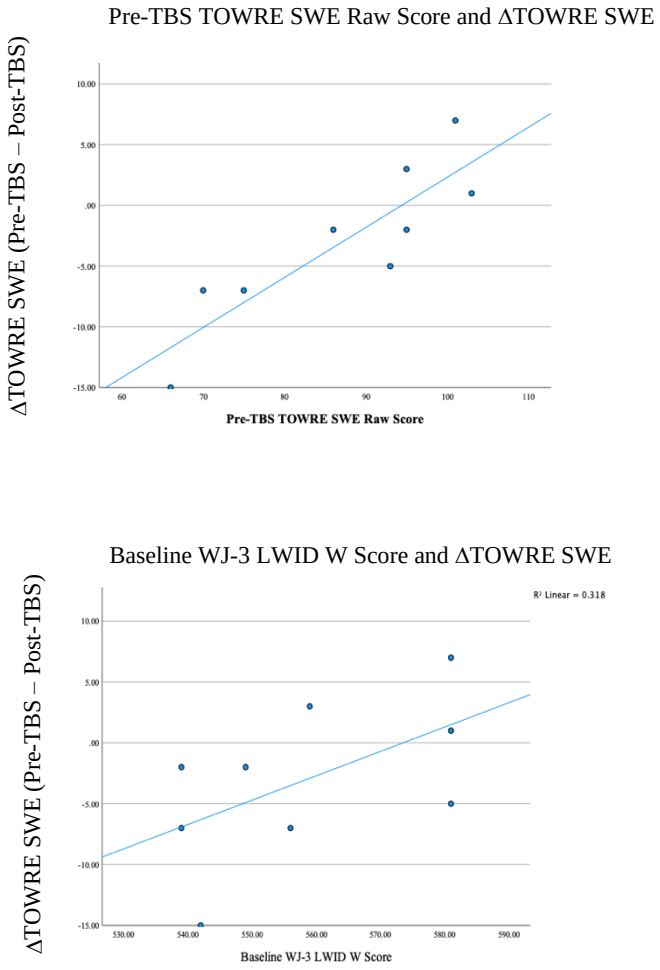


Figure 13. Correlations Between Baseline Skills and ΔPre-Post TBS For SMG Group

Table 12b. Correlations Between Baseline Skills and ΔPre-Post TBS For MTG Group

Measure	Pre-TBS RAN SPI	Pre-TBS OA RT	Pre-TBS TOWRE SWE Raw Score	Pre-TBS WJ-3 RF W Score	Pre-TBS WJ-3 Letter-Word ID
ΔRAN SPI (Pre-TBS – Post-TBS)	r = -.14, p = .86, N = 4	r = -.72, p = .28, N = 4	r = .56, p = .44, N = 4	r = .82, p = .18, N = 4	r = -.22, p = .78, N =4
ΔOA RT (Pre-TBS – Post-TBS)	r = -.11, p = .89, N = 4	**r = .76, p < .01, N = 11	r = .49, p = .23, N = 8	r = -.16, p = .68, N = 9	r = .40, p = .22, N = 11
ΔTOWRE SWE Raw Score (Pre-TBS – Post-TBS)	**r = .99, p = .01, N = 4	r = .21, p = .61, N = 8	**r = .74, p = .02, N = 9	r =.40, p = .33, N = 8	r = -.04, p = .93, N = 9
ΔWJ-3 RF W Score (Pre-TBS – Post-TBS)	r = .06, p = .94, N = 4	r = .17, p = .67, N = 9	r < .01, p = .99, N = 8	r = .44, p = .20, N = 8	r = .23, p = .53, N = 10

**significant at level of 0.05*

***significant at level of 0.01*

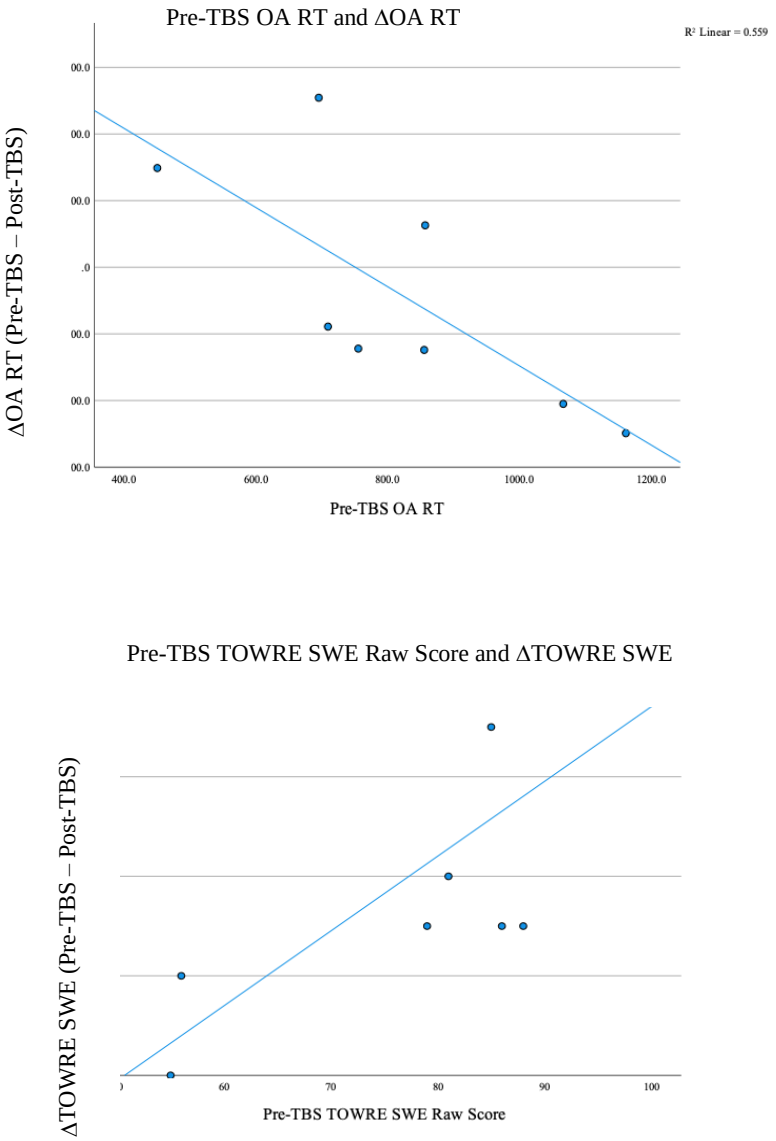


Figure 14. Correlations Between Baseline Skills and ΔPre-Post TBS For MTG Group

Table 12c. Correlations Between Baseline Skills and ΔPre-Post TBS For Vertex Group

Measure	Pre-TBS RAN SPI	Pre-TBS OA RT	Pre-TBS TOWRE SWE Raw Score	Pre-TBS WJ-3 RF W Score	Pre-TBS WJ-3 Letter-Word ID
ΔRAN SPI (Pre-TBS – Post-TBS)	*r* = -.05, *p* = .95, *N* = 4	*r* = .58, *p* = .42, *N* = 4	*r* = -.34, *p* = .58, *N* = 5	*r* = -.50, *p* = .50, *N* = 4	*r* = .28, *p* = .59, *N* = 6
ΔOA RT (Pre-TBS – Post-TBS)	*r* = -.22, *p* = .79, *N* = 4	*r* = .70, *p* = .18, *N* = 5	*r* = .07, *p* = .91, *N* = 5	*r* = -.11, *p* = .89, *N* = 4	*r* = .17, *p* = .79, *N* = 5
ΔTOWRE SWE Raw Score (Pre-TBS – Post-TBS)	*r* = .57, *p* = .32, *N* = 5	*r* = -.51, *p* = .38, *N* = 5	*r* = -.11, *p* = .81, *N* = 7	*r* = -.72, *p* = .28, *N* =4	*r* = -.12, *p* = .80, *N* = 7
ΔWJ-3 RF W Score (Pre-TBS – Post-TBS)	*r* = -.63, *p* = .37, *N* = 4	*r* = .21, *p* = .79, *N* = 4	*r* = -.41, *p* = .60, *N* = 4	*r* = -.13, *p* = .81, *N* = 6	*r* = -.41, *p* = .42, *N* = 6

**significant at level of 0.05*

***significant at level of 0.01*

Table 12d. Correlations Between Baseline Skills and ΔTime Point 1 – Time Point 2 TBS For No Stimulation Control Group

Measure	Pre-TBS OA RT	Pre-TBS TOWRE SWE Raw Score	Pre-TBS WJ-3 Letter-Word ID
ΔOA RT (Pre-TBS – Post-TBS)	*r* = .69, *p* = .14, *N* =6	*r* = -.18, *p* = .77, *N* = 5	*r* = .03, *p* = .95, *N* = 6
ΔTOWRE SWE Raw Score (Pre-TBS – Post-TBS)	**r* = -.95, *p* = .01, *N* = 5	*r* = .29, *p* = .64, *N* = 5	*r* = .09, *p* = .89, *N* = 5

**significant at level of 0.1*

***significant at level of 0.05*

For participants in the SMG group, the pattern of correlation results suggested that those with weaker initial reading skills showed greater improvement in those skills following stimulation**.** A positive correlation was found between pre-TBS TOWRE SWE scores and ΔTOWRE SWE scores (Table 12a, Figure 18). This indicates that participants with weaker initial performance on the TOWRE SWE (lower pre-TBS TOWRE SWE score) showed more improvement in TOWRE SWE following SMG stimulation (increasingly negative ΔTOWRE SWE), whereas participants with stronger initial performance on the TOWRE SWE showed less improvement in TOWRE SWE following SMG stimulation (increasingly positive ΔTOWRE SWE). This same pattern was found in the positive correlation between baseline untimed word identification skills (WJ-3 LWID) and ΔTOWRE SWE scores (Table 12a, Figure 18). Although

this relationship fell just below statistical significance, the pattern suggests that participants with weaker initial untimed word identification skills (WJ-3 LWID) showed more improvement in TOWRE-2 following SMG stimulation (increasingly negative ΔTOWRE SWE). Notably, neither of these relationships between baseline skills and change were found in the NS Control group.

A significant negative correlation was also found between pre-TBS OA RT and ΔTOWRE SWE, which may indicate that participants with slower initial performance on the OA task (larger pre-TBS OA RT) showed more improvement in TOWRE SWE following SMG stimulation (increasingly negative ΔTOWRE SWE). However, the negative correlation between pre-TBS OA RT and ΔTOWRE SWE was also found in the NS Control Group and may therefore be unrelated to stimulation. Overall, these results suggest that participants with weaker initial word recognition skills may show greater improvement in word recognition performance (TOWRE-2) following SMG stimulation. In contrast, participants with stronger initial skills in OA and single word recognition may show less improvement following SMG stimulation, with some even showing slight decreases in word recognition performance.

For participants in the MTG group, the pattern of results also suggested that those with weaker initial reading skills showed greater improvement following stimulation. Similar to the SMG group, a positive correlation was found between pre-TBS TOWRE SWE scores and change in TOWRE SWE scores. This indicates that participants with weaker initial performance on the TOWRE SWE (lower pre-TBS TOWRE SWE score) showed more improvement in TOWRE SWE following MTG stimulation (increasingly negative ΔTOWRE SWE), whereas participants with stronger initial performance on the TOWRE SWE showed less improvement in TOWRE SWE following MTG stimulation (increasingly positive ΔTOWRE SWE).

Interestingly, the MTG group also showed a strong negative correlation between pre-TBS OA RT and change in OA RT (Table 12b, Figure 19). This indicates that participants with slower initial performance on the OA task (larger pre-TBS OA RT) showed more improvement in OA RT following MTG stimulation (increasingly positive ΔOA RT), whereas participants with faster initial performance on the OA task (smaller pre-TBS OA RT) showed less improvement in OA RT following MTG stimulation (increasingly negative ΔOA RT). In other words, participants with slower initial performance on the OA task made the greatest gains in OA speed following MTG stimulation. This is consistent with the overall pattern of those with weaker initial skills showing increased improvement following stimulation. However, it is interesting that this strong relationship between pre-TBS OA and change in OA was not found in the SMG group, especially considering the fact that the SMG group showed overall greater improvement in OA following stimulation (see Table 5, Figure 7). This may be related to the particular sensitivity of the MTG to orthographic patterns, and the extent to which the MTG responses vary among readers of varying skill levels. As previously described, the MTG is part of the ventral reading pathway, conceptualized as the pathway that enables automatic word recognition in fluent readers through rapid recognition of orthographic patterns. It is known that readers of different skill levels vary in the extent to which they activate the MTG during reading-related tasks, with struggling readers showing comparably less activation in MTG (Hoeft et al., 2007; Younger et al., 2017). Weaker OA skills in certain individuals may be due to inconsistent neural excitation in the MTG during OA tasks. This may be normalized by the application of TBS, resulting in improvement in measured OA skills. In contrast, for individuals with adequate OA skills who activate MTG appropriately during OA tasks, application of TBS to this region may introduce excessive excitation, leading to worsened performance.

3.4.3 Summary of Post-Hoc Results

We found strong correlations between baseline (pre-TBS or Time Point 1) RAN, TOWRE, and WJ-3 RF across participants. There were no significant correlations between baseline OA and other baseline measures, possibly due to initial OA performance being partially influenced by the MRI environment. We also examined correlations between the amount of change (Pre-TBS -Post-TBS or Time Point 1 – Time Point 2) on each measure (RAN, OA, TOWRE SWE, and WJ-3 RF). While many of these correlations showed medium to large effect sizes, none reached statistical significance, likely due to insufficient power.

In addition, given variability in performance, we examined correlations between baseline measures and amount of change (Pre-TBS -Post-TBS or Time Point 1 – Time Point 2) for each stimulation group. We found significant correlations between pre-TBS TOWRE SWE and ΔTOWRE SWE in both the SMG and MTG groups. In addition, we found correlations that trended toward significance between pre-TBS WJ-3 LWID and ΔTOWRE in the SMG group, and between pre-TBS OA RT and ΔOA in the MTG group. None of these significant correlations between baseline performance and change were found in the Vertex group or the NS Control group. In general, these results demonstrated a pattern in which participants with lower baseline performance showed greater improvement in performance following TBS. Reasons for this finding are described in detail in the Discussion section.

3.5 Overall Summary of Results

Across all measures, a pattern emerged in which the SMG and Vertex groups showed greater change between time points on all measures compared to the MTG and NS Control groups did. These results were contrary to our hypothesis that change on measures of reading automaticity would be greater following both SMG and MTG stimulation as compared to Vertex,

which we theorized would serve as a control site. In addition, in both the SMG and MTG groups, a relationship was found between baseline performance and degree of improvement in performance following TBS, where individuals with weaker baseline performance showed greater improvement following TBS. Possible explanations for these findings and their implications are described in detail in the Discussion.

4 DISCUSSION

The purpose of this study was to determine whether TBS to dorsal and/or ventral nodes of the reading network leads to increased automaticity in word recognition across readers of different skill levels. This proposition is theoretically based on studies suggesting that in struggling readers, lack of automaticity in reading results from unstable neural responses to word stimuli in the brain's reading network (e.g., Kimpa et al., 2018; Lam et al., 2017). This is thought to occur due to inconsistent levels of neural noise in these regions (Hancock et al., 2017; Kimpa et al., 2018; Perrachione et al., 2016) which we propose can be modulated via TBS.

In general, we did find some evidence that TBS to reading network nodes resulted in improvement in automatic word recognition, as well as in the underlying component processes that support automatic word recognition (OA and RAN). The group receiving SMG stimulation showed significant change in performance on multiple measures including RAN, OA, and WJ-3, whereas the NS Control group did not show any significant pre-post change across measures that were available for such a comparison. The fact that the NS Control group did not show any significant pre-post change makes it unlikely that the observed changes in these measures across time points were simply due to practice effects. It is also noteworthy that the SMG group showed larger improvement across all measures as compared to the MTG stimulation group, even though

some were not significantly different due to the limited samples, suggesting some potential differential effect of stimulation to different reading network nodes. In addition, the observed relationships between change following stimulation and baseline reading skills were somewhat different between the SMG and MTG groups, and largely not present in the NS Control group. For TOWRE and OA RT, this is further evidence of differential effects of stimulation to the reading network nodes which cannot be fully explained by practice effects. As the NS Control group did not have data for RAN and WJ-3, it is harder to determine whether the observed changes in RAN and WJ-3 were due to stimulation or influenced by practice effects. However, the fact that the same pattern of change (greater SMG compared to MTG change) persisted in these measures is encouraging and may indicate that some of this observed change represents more than simple practice effects.

It is also interesting that the correlations between pre-TBS and post-TBS measures differed between groups, with significant correlations between pre-TBS and post-TBS OA and TOWRE in the SMG, MTG, and Vertex groups but no significant correlations between these measures in the NS Control group (Table 16). This is especially compelling given that the same version of the TOWRE (Version A) was administered at both time points for the NS Control group, but different versions of the TOWRE were administered at each time point for the SMG, MTG, and Vertex groups (version A at pre-TBS and version B at post-TBS). The NS Control group should theoretically have shown the strongest correlations between time points if these correlations were due to practice effects. The fact that the NS Control group instead showed non-significant correlations between pre and post time points further suggests that the relationships between pre-TBS and post-TBS measures in the stimulation groups were not due solely to practice effects.

4.1 The Effects of SMG vs. MTG Stimulation

We also hypothesized whether or not SMG or MTG stimulation led to the greatest increase in automatic word recognition and associated skills. We had suggested that if stimulation to the SMG, an early node in the reading network, would result in the greatest change in word recognition automaticity, it would suggest that precise synchronization of signals across the entire reading network has the strongest impact on word recognition automaticity. In contrast, if MTG stimulation had resulted in comparably more change in word recognition automaticity, it would indicate that the efficiency of cognitive processes subserved by the MTG (e.g., orthographic awareness) has the strongest impact on automatic word recognition. Given that we observed somewhat more significant change across RAN, OA RT, and WJ-3 following SMG stimulation, we suggest that TBS may have created a more precise, consistent neural signal in the SMG which in turn led to increased synchronicity across the entire reading network and improved automaticity. This suggested significant finding following SMG stimulation is consistent with past findings (e.g., Costanzo et al., 2012; 2013) which found that rTMS to dorsal nodes of the network led to improvement on tasks requiring the integration of the entire reading network (e.g., reading aloud both words and reading of texts), rather than improvement only in phonological tasks typically associated with the dorsal reading network. Similarly, the current study did not use any tasks that isolate phonological processes typically associated with dorsal nodes. Instead, SMG stimulation was found to improve performance on tasks requiring integration across the entire network (e.g., single word recognition, sentence reading fluency), and on tasks traditionally associated with the ventral reading network and MTG, such as orthographic awareness. This supports our hypothesis that the improved performance following

SMG stimulation resulted from downstream effects leading to increased coherence across the entire reading network.

It is particularly compelling that even on the OA task, significant change was found following SMG stimulation but not following MTG stimulation, given that the MTG has been shown to be heavily involved in orthographic awareness (e.g., Pleisch et al., 2019). This differential effect could be explained if reading automaticity is most improved via increased coherence across the entire reading network (through downstream effects of stimulation of SMG) rather than through the effects of increased excitability in MTG following direct stimulation. This hypothesis of downstream effects of SMG stimulation leading to increased coherence across the network could be tested directly through combining TBS with fMRI functional connectivity analyses. It would be interesting to explore whether the increase in behaviorally measured reading automaticity following SMG stimulation is associated with increases in the strength of functional correlations between SMG and the rest of the reading network. In addition, it would be interesting to investigate whether changes in variability in functional MRI activation (e.g., Malins et al., 2018) following SMG stimulation are associated with the observed TBS-induced change in reading automaticity.

4.2 Unexpected Findings in Vertex Stimulation Group

The vertex has long been considered a TBS control site that does not result in cognitive changes and has been used as such in multiple TMS studies of reading and language related processes (e.g., Costanzo et al., 2012; Duncan et al., 2010; Leff et al., 2001; Laycock et al., 2009; Nakamura et al., 2014; Zhu et al., 2015; for a review, see Arrington et al., 2021). Therefore, the most unexpected findings in this study were the significant changes in performances that occurred in the Vertex group. While the notable changes between time points in the Vertex group

could be attributed to practice effects, this explanation is complicated by the fact that the NS Control group did not show substantial changes between time points, making practice effects unlikely to be solely responsible for these effects. In addition, in three of the four outcome measures (RAN, OA, and WJ-3), the Vertex group and SMG group showed significant pre-post TBS change whereas the MTG group did not. This pattern of results is not consistent with simple practice effects, as we would expect similar results across all stimulation groups if there was no direct effect of stimulation. Instead, we suggest that the most likely explanation for these results is that vertex stimulation resulted in TBS-induced electric fields in adjacent cortical regions involved in motor control and reading. A full discussion of the emerging potential issues with the use of vertex as a control site is beyond the scope of this discussion; however, we highlight relevant potential confounds with the use of vertex in our study due to 1) outcome measures dependent on motor speed and 2) excitation in reading-relevant brain regions resulting from vertex stimulation.

We initially selected vertex as an active control site in this study given that no change was found after vertex stimulation in the small number of existing TMS studies of reading, and that vertex has been generally considered a control site throughout the TMS literature. However, after data collection for this study had been completed, a critical study questioned the utility of vertex as a control region in TBS (Pizem et al., 2022). This study took a novel approach by using TBS to the vertex alongside electric field modeling. The authors found that TBS to vertex led to TBS-induced electric fields in adjacent cortical regions involved in motor control including the paracentral lobule (PCL) and the supplementary motor area (SMA) leading to faster behaviorally measured motor response times (Pizem et al, 2022). If vertex stimulation enhances motor response times, this could have a substantial impact on performance on outcome measures in this

study as most of the measures involve a speeded motor component (pressing a button for OA, writing for WJ-3 RF, and speaking for RAN and TOWRE). It is therefore possible that TBS-induced excitation in regions affecting motor response speed also led to improved performance on these measures in the Vertex group. Vertex stimulation-induced changes in motor response speed could also explain why the largest amount of change in both WJ-3 and OA tasks occurred in the Vertex group, as these are the tasks that require fast coordinated motor responses in the hands**.**

There is also evidence that the brain regions that have been proposed to be excited by vertex stimulation in the recent paper by Pizem et al (e.g., PCL and SMA) may play a role within the reading network. Findings from fMRI studies (e.g., Cummine et al., 2017) have found that SMA activation is associated with overt word reading response times. Therefore, if TBS to the vertex leads to increased excitation in the SMA, this could result in improved performance on RAN and TOWRE. In addition, the possibility of vertex stimulation inducing SMA and PCL excitation is particularly relevant given evidence for the role of the SMA within the "print to speech" network (Cummine et al., 2016; 2017). Notably, functional neuroimaging and graphical analyses have revealed task-related coherence between SMA and SMG during reading-related tasks (Cummine et al., 2017). Therefore, in addition to modulating motor response speed, TBS-induced excitation in SMA could have led to secondary effects in SMG and enhanced overt reading speed. This would explain why we observed similar patterns of results in the SMG and Vertex groups as compared to the MTG groups, particularly considering evidence of substantial functional connections between SMA and SMG during overt reading tasks (Cummine et al., 2016; 2017). If this is the case, the Vertex group may have received a combination of secondary

TBS-induced excitation in the SMG as well enhanced TBS-induced excitation in regions facilitating motor response (PCL and SMA), leading to improved performance following TBS.

Our results support the concerns raised by Pizem et al (2022) about the use of vertex as a control site and have future implications for the use of vertex in TBS studies using reading outcome measures that include motor response speed components. However, further research is needed to confirm the extent of the spread of vertex-induced excitation to adjacent cortical regions, as well as factors which may influence its effects on reading-related outcome variables. For example, it could be the case that vertex stimulation only affects behaviorally measured reading outcomes in the case of overt reading tasks or tasks dependent heavily on motor speed. If this is the case, secondary effects of vertex stimulation may have less of an effect on outcomes for which no time restrictions are in place. This could explain why certain other studies (e.g., Costanzo et al., 2012) did not find any effects of vertex stimulation during a reading task. This study (Costanzo et al., 2012) found effects on task accuracy rather than response speed in word reading, as there was no time constraint on the word reading task. Secondary effects of vertex stimulation could have had less of an effect in this case due the lack of a time constraint and reduced motor speed demands.

It is also the case that many earlier studies of TMS effects on reading did not use e-field based EEG landmarks to identify the vertex stimulation site. Many earlier studies of TMS effects on reading also did not use MRI-based neuronavigation as we did in the current study. MRI-based neuronavigation allows for precise localization of stimulation sites and helps to ensure reliability of stimulation sites across studies. It is therefore possible that the effects of vertex stimulation depend on which precise coordinates are selected for the vertex stimulation site. The extent of these unintended effects of vertex stimulation could also depend on other group level

factors (e.g., precise angle and location of the TMS coil or method of locating the vertex via neuronavigation), which is a critical subject for future research studies.

Reconsideration of the effects of vertex stimulation means that in terms of the current study, a stimulation control site is lacking. To interpret our results, we must rely on comparisons of the different active stimulation groups with one another (e.g., differential results in MTG vs. SMG) and comparisons of these stimulation groups with the NS Control group. It is particularly relevant that, unlike the SMG and Vertex groups, the NS Control group (available for OA and TOWRE) did not show significant change across time points. This is particularly remarkable for the TOWRE given that the NS Control was the only group to receive the same version of the TOWRE at both time points and should in theory be the most susceptible to practice effect-driven change across time points. Instead, this group showed the least amount of change between time points on both TOWRE and OA, lending support to our hypothesis that change in the stimulation groups is at least partially due to the effects of TBS.

4.3 The Relationship Between Baseline Performance and Response to TBS

We found substantial variability in the responses of individual participants to TBS (Tables 11a-11d). This variability in the responses of individual participants to stimulation is consistent with several studies suggesting that response to TMS varies between individuals, due to a variety of neurobiological and cognitive differences that are not yet fully understood (e.g., Hoy et al, 2015; Jannati et al., 2017; Nicolo et al, 2015; Pabst et al, 2022). Specifically, a general trend was noted in the SMG and MTG groups wherein individuals with lower baseline scores showed greater changes following TBS. This pattern is consistent with the small but growing literature about the influence of baseline characteristics on response to neurostimulation. In particular, one study that also used intermittent theta-burst stimulation (Brisson and Tremblay,

2018) found a pattern of results similar to the current study. The authors found that individuals with lower scores on a baseline speech perception task showed greater improvement on the task following iTBS. This finding is similar to our finding that individuals with lower initial reading scores showed greater improvement in reading tasks following iTBS.

Studies using tDCS in various cognitive tasks have found a similar relationship between baseline performance and improvement following stimulation (Hsu et al., 2014; Juan et al., 2017; Tseng et al., 2012). Silvanto et al. (2018) found a similar negative association between baseline performance and effects of TMS on a visual priming task and suggested a mechanistic explanation for this relationship (Silvanto et al., 2017; 2018). We review this mechanistic hypothesis below and describe how it can apply to the findings in the current study.

First, it is important to note that TMS behavioral effects differ in whether they are facilitatory or inhibitory based on the level of TMS intensity. Single pulse studies (e.g., Silvanto et al., 2017; 2018) have demonstrated that as TMS is applied at increasing levels of intensity, previously facilitatory behavioral effects slowly decrease until eventually reaching a threshold at which they become inhibitory instead of facilitatory. This is thought to occur because of the non-linear relationship between neural excitation and behavioral performance (see Figure 20). In the curvilinear relationship outlined in this figure, two key points are relevant. First, before the vertex is reached, the amount of gain in performance per each unit of increase in neural excitation is decreasing. Therefore, the lower the initial level of neural excitation is, the larger the gain in performance will be with the addition of a single unit of excitation. Second, at certain level of neural excitation (the vertex of the curve), adding additional excitation into the system hinders performance rather than facilitating it. Silvanto et al. (2018) consider baseline reaction times as a measure of initial neural excitability, and therefore posit that individuals who show

weaker initial performance show lower baseline neural excitability in task-relevant brain regions. Induced excitation via TMS therefore raises the level of excitation in these regions to a level that facilitates behavior as the threshold at which excitation becomes inhibitory has not been reached. In contrast, individuals who show stronger baseline performance are thought to have higher levels of baseline neural excitability in task-relevant regions. Therefore, adding the same amount of excitation via TMS may lead to less of an increase in behavior, or in some instances (if the baseline level of excitation is high enough) may raise the overall level of excitation to a level that becomes inhibitory of behavior.

We can apply this framework to the current study if we consider individuals with lower baseline performance on reading measures as having lower baseline neural excitability within reading network nodes, which is consistent with multiple ERP and neuroimaging studies (e.g., Christodolou et al., 2014; Kimpa et al., 2018; Lam et al., 2017; Langer et al., 2015). The effect of iTBS to these regions would have then increased neural excitability to a level that facilitates performance, resulting in large improvements in performance compared to baseline. However, the individuals in our study who had higher initial baseline performance on reading measures may have shown higher baseline levels of neural excitation in the reading network nodes. Therefore, adding the same amount of additional excitation as was added in the individuals with lower baseline neural excitation may have resulted in comparably less gain in reading performance. In a few cases, if baseline neural excitation was high enough, the introduction of additional excitation via TBS could then have increased the overall excitation in the reading network to a level that inhibits performance.

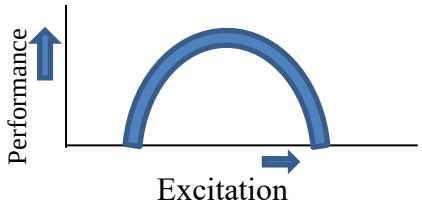


Figure 15. Relationship Between Behavioral Performance and Neural Excitation

This explanation for the relationship between baseline skill and response to TMS also is consistent with the neural noise hypothesis of dyslexia (Hancock et al., 2017). In theory, inconsistent levels of neural noise are found in reading network regions in those with RD, leading to reduced neural response adaptation and inability to automatize word reading. Overall reductions in excitability in these regions could contribute to inconsistent levels of neural noise in these regions, and in turn less consistent responses in these regions to reading-related tasks. The application of TBS to reading network nodes in those with weaker initial reading skill could introduce excitability to make noise levels more consistent, leading to an optimal level of excitability and neural noise within the network and improved reading. However, a typical reader is likely to have a baseline optimal level of neural excitation within the reading network, which results in the necessary balance of background neural noise and neural stimulus response to allow for relatively efficient word recognition. Therefore, introducing additional excitation to the network via TBS may have a smaller effect on word recognition speed, as the pre-TBS level of excitation is already close to the optimal level to overcome the background noise. In some cases, if the level of initial excitation is high enough, TBS being applied to the network may introduce additional excitation that is excessive. This may then increase the previously optimal background level of neural noise, leading to a less efficient neural signal and in turn less efficient word recognition. It would be interesting in future studies to see if there are differential effects in

neuroimaging or electrophysiological responses of these regions to TMS depending on baseline reading level. Further studies are needed to refine our conceptualization of the relationship between baseline performance and response to TBS. However, the presence of this established pattern in the current study further establishes that TMS to nodes of the reading network has a measurable impact on reading automaticity, likely through the same mechanisms that underly response to TMS in other cognitive and motor domains.

4.4 Limitations

There are several limitations to this study. As described in detail at the beginning of this section, this study lacks a stimulation control site due to the unexpected effects of vertex stimulation. This could arguably make it more difficult to infer that change in the SMG and MTG groups was due to stimulation rather than practice effects. Future identification of a more appropriate control stimulation site would be helpful for future research of the effects of TBS to these sites. However, although this study lacks an active control site, the lack of change in the NS Control group, as well as different effects of stimulation in the MTG and SMG groups suggests that changes in reading skills occurred at least partially due to TBS rather than due to practice effects. The fact that a previously established relationship between baseline performance and change following TMS was found in both the MTG and SMG groups also supports the claim that TBS to these regions had an effect on reading skills. Analyses for the WJ-3 are likely the most susceptible to practice effects because 1) WJ-3 data was not collected from the NS Control group and 2) the same version of the WJ-3 was conducted at both time points. However, it is encouraging that the same pattern of results (SMG > MTG) was found in the WJ-3 data.

In addition, the small sample sizes within each stimulation group could be considered a barrier to being able to draw strong conclusions, especially given the non-normality of the

distribution of several of the measures. However, most results remained significant even when more stringent non-parametric tests were performed, and the use of bootstrapped confidence intervals in the parametric tests provided some correction for over-estimation of parameters. Nevertheless, it would be beneficial to repeat the study with larger sample sizes in each each group. Such larger sample sizes would allow for more thorough analyses of the relationships between change on each variable.

In terms of our sample, it is also important to note that the mix of participants with different levels of reading skills may have made our results less clear. In particular, given that we found a relationship between baseline skills and magnitude of improvement following TBS, it would be interesting to examine potential effects of on a group of individuals with more uniform reading skills. We observed that individuals with weaker initial reading skills showed greater increases in skills following TBS. Therefore, repeating this study with a larger group of individuals who all show below average reading skills would be informative. Our sample was also limited due to the fact that most participants showed only mild reading impairments as measured by standardized reading assessments. If our sample had also included individuals with more severe reading impairments (e.g., a sample of individuals with current diagnoses of RD determined through comprehensive assessment batteries), it is possible that our results may have been more consistent or even showed larger effect sizes across participants, given that weaker initial reading skills appear to be associated with stronger TBS-induced gains. Recruitment of such a sample of participants would be difficult but is a worthwhile goal for future studies.

Finally, we must address the limitations related to the outcome measures of reading used in this study. We selected the measures of OA and RAN as these are the component cognitive skills most strongly associated with reading fluency and TOWRE SWE and WJ-3 RF as outcome

measures of single word reading and sentence reading efficiency respectively. Unsurprisingly, we found strong correlations between baseline RAN, TOWRE SWE, and WJ-3 RF. However, contrary to our hypotheses, pre-TBS OA RT was not strongly correlated with other baseline measures. This measure showed no meaningful correlations with pre-TBS TOWRE (r = -.16, p = .43) or with pre-TBS RAN (r = -.19, p = .55), and showed only a slight non-significant relationship with pre-TBS WJ-3 (r = -.33, p = .15). This lack of relationship between pre-TBS OA RT and the other baseline measures of reading efficiency may be partially due to differences in the setting in which these measures were collected. While pre-TBS TOWRE, RAN, and WJ-3 were collected outside of the MRI scanner, the OA measure was collected within the MRI scanner. It is possible that completing the pre-TBS OA task during the MRI scan introduced additional factors or variance that could have affected initial OA response time such as apprehension, physical discomfort in the MRI, etc. This would cause participants' pre-TBS OA RT to be influenced by extraneous variables other than word recognition speed and orthographic awareness, and to therefore show less strong correlations with other pre-TBS word recognition skills. While the additional variables particular to the MRI environment were likely still present during the post-TBS scan, the effects of these variables were likely smaller given that participants would have had time to adjust to the MRI environment. This would explain why post-TBS OA RT showed comparatively stronger correlations with post-TBS TOWRE-2 (r = -0.43, p = .16), post-TBS RAN SPI (r = .47, p = .12), and post-TBS WJ-3 (r = -0.29, p = .20). It is encouraging that the pattern of results for OA in terms of different responses for stimulation groups was similar to other measures. However, it would have been ideal to have all of these measures administered in the same setting.

More generally, our study used a relatively limited number of outcome measures. This is partially due to the time limitations that occur when attempting to measure TMS-induced effects, as the literature suggests that effects of a single TBS session wane 20 minutes after stimulation (for a review, see Suppa et al., 2016). Given our limited window of TBS-induced effects, we chose a small battery of measures (RAN, OA, TOWRE SWE, and WJ-3) that are most strongly associated with reading efficiency and fluency, which was the main focus of this study. However, it is true that other cognitive constructs such as phonological awareness and morphological awareness are also related to reading fluency, though comparatively less strongly according to meta-analytic studies (for a review, see Landerl et al., 2022). It would nevertheless be interesting to see if changes in these skills are also affected by TBS to reading network nodes. In terms of enhancing our understanding of the reading network, it would be especially interesting to investigate whether phonological awareness is differentially affected by SMG stimulation compared to MTG stimulation, given the traditional view of the SMG as part of the dorsal "phonological" network.

To overcome the limitation of the window of TBS-induced effects, future studies could potentially have participants receive stimulation on different days, with different outcome measures applied at each time point, to be able to compare the effects of TBS to the reading network on multiple components of reading. This was not feasible in the design of the current study, but it is an exciting idea for future work.

4.5 Future Directions

Pairing our TBS protocol with real-time functional neuroimaging could be beneficial in elucidating the TBS-induced mechanisms associated with TBS-induced behavioral change. For example, our hypothesis that TBS to SMG results in overall improved reading automaticity by

promoting increased coherence throughout the reading network could be tested through analyses of changes in functional connectivity from the SMG following TBS. It would also be interesting to test whether the relationship between baseline reading skill and improvement following TBS is driven by parallel changes in functional activation in various reading network nodes, as hypothesized.

In general, the results of this study are promising as they confirm that TBS to reading network nodes, especially the SMG, can modulate reading automaticity. We can hypothesize that a TBS protocol such as the one used in this study could be paired with an educational intervention to improve reading automaticity in struggling readers. Extensive further research is required to determine the most optimal parameters for a combined TBS and reading intervention study. However, we are hopeful that in the future, a protocol using iTBS to the SMG will be able enhance the ability of a struggling reader to develop automaticity in word recognition through educational intervention. This would lead to remediation of persistent automaticity and reading fluency deficits and in turn improved quality of life for adult struggling readers.

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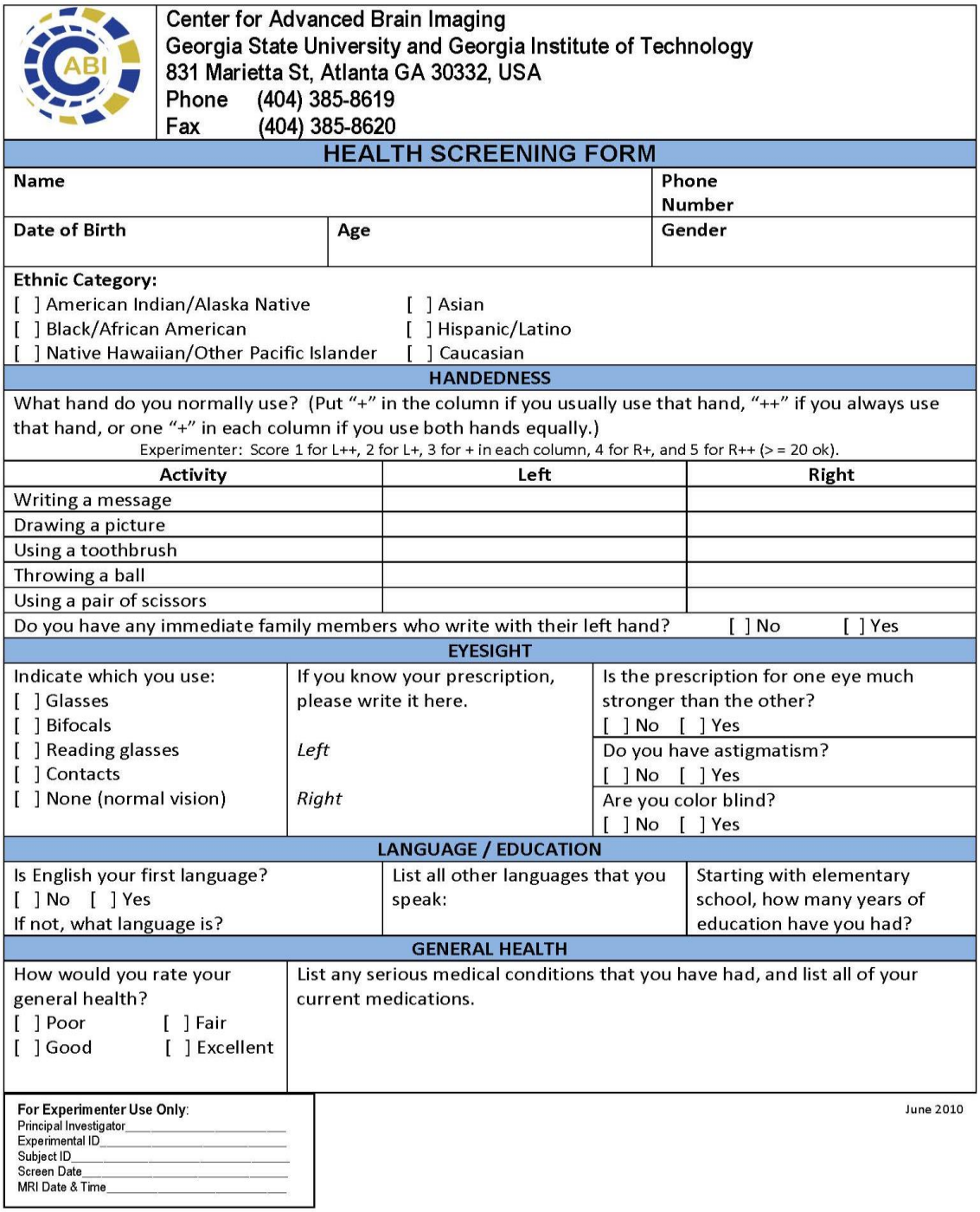
APPENDIX A. PARTICIPANT SCREENING FORMS

Appendix A. Participant Screening Forms



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HEALTH SCREENING FORM

Name		Phone Number
Date of Birth	**Age**	**Gender**

Ethnic Category:
[ ] American Indian/Alaska Native [ ] Asian
[ ] Black/African American [ ] Hispanic/Latino
[ ] Native Hawaiian/Other Pacific Islander [ ] Caucasian

HANDEDNESS

What hand do you normally use? (Put "+" in the column if you usually use that hand, "++" if you always use that hand, or one "+" in each column if you use both hands equally.)

Experimenter: Score 1 for L++, 2 for L+, 3 for + in each column, 4 for R+, and 5 for R++ (> = 20 ok).

Activity	Left	Right
Writing a message		
Drawing a picture		
Using a toothbrush		
Throwing a ball		
Using a pair of scissors		

Do you have any immediate family members who write with their left hand? [ ] No [ ] Yes

EYESIGHT

Indicate which you use:	If you know your prescription, please write it here.	Is the prescription for one eye much stronger than the other? [ ] No [ ] Yes
[ ] Glasses [ ] Bifocals [ ] Reading glasses [ ] Contacts [ ] None (normal vision)	*Left* *Right*	Do you have astigmatism? [ ] No [ ] Yes Are you color blind? [ ] No [ ] Yes

LANGUAGE / EDUCATION

Is English your first language? [ ] No [ ] Yes If not, what language is?	List all other languages that you speak:	Starting with elementary school, how many years of education have you had?

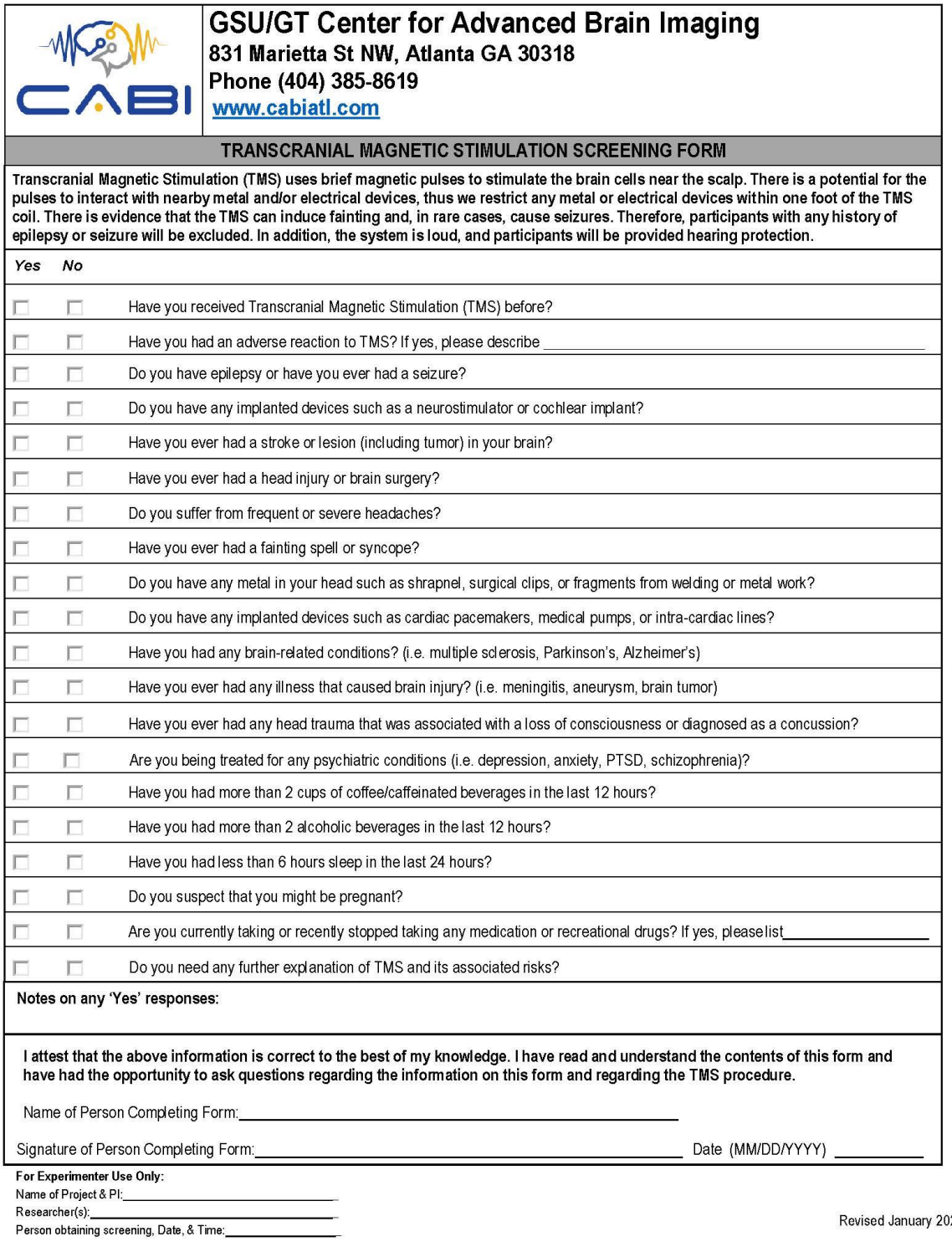
GENERAL HEALTH

How would you rate your general health? [ ] Poor [ ] Fair [ ] Good [ ] Excellent	List any serious medical conditions that you have had, and list all of your current medications.

For Experimenter Use Only:
Principal Investigator_____
Experimental ID_____
Subject ID_____
Screen Date_____
MRI Date & Time_____

June 2010

Figure A.1. CABI Health Screening Questionnaire



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TRANSCRANIAL MAGNETIC STIMULATION SCREENING FORM

Transcranial Magnetic Stimulation (TMS) uses brief magnetic pulses to stimulate the brain cells near the scalp. There is a potential for the pulses to interact with nearby metal and/or electrical devices, thus we restrict any metal or electrical devices within one foot of the TMS coil. There is evidence that the TMS can induce fainting and, in rare cases, cause seizures. Therefore, participants with any history of epilepsy or seizure will be excluded. In addition, the system is loud, and participants will be provided hearing protection.

Yes	*No*	
☐	☐	Have you received Transcranial Magnetic Stimulation (TMS) before?
☐	☐	Have you had an adverse reaction to TMS? If yes, please describe _____
☐	☐	Do you have epilepsy or have you ever had a seizure?
☐	☐	Do you have any implanted devices such as a neurostimulator or cochlear implant?
☐	☐	Have you ever had a stroke or lesion (including tumor) in your brain?
☐	☐	Have you ever had a head injury or brain surgery?
☐	☐	Do you suffer from frequent or severe headaches?
☐	☐	Have you ever had a fainting spell or syncope?
☐	☐	Do you have any metal in your head such as shrapnel, surgical clips, or fragments from welding or metal work?
☐	☐	Do you have any implanted devices such as cardiac pacemakers, medical pumps, or intra-cardiac lines?
☐	☐	Have you had any brain-related conditions? (i.e. multiple sclerosis, Parkinson's, Alzheimer's)
☐	☐	Have you ever had any illness that caused brain injury? (i.e. meningitis, aneurysm, brain tumor)
☐	☐	Have you ever had any head trauma that was associated with a loss of consciousness or diagnosed as a concussion?
☐	☐	Are you being treated for any psychiatric conditions (i.e. depression, anxiety, PTSD, schizophrenia)?
☐	☐	Have you had more than 2 cups of coffee/caffeinated beverages in the last 12 hours?
☐	☐	Have you had more than 2 alcoholic beverages in the last 12 hours?
☐	☐	Have you had less than 6 hours sleep in the last 24 hours?
☐	☐	Do you suspect that you might be pregnant?
☐	☐	Are you currently taking or recently stopped taking any medication or recreational drugs? If yes, please list_____
☐	☐	Do you need any further explanation of TMS and its associated risks?

Notes on any 'Yes' responses:

I attest that the above information is correct to the best of my knowledge. I have read and understand the contents of this form and have had the opportunity to ask questions regarding the information on this form and regarding the TMS procedure.

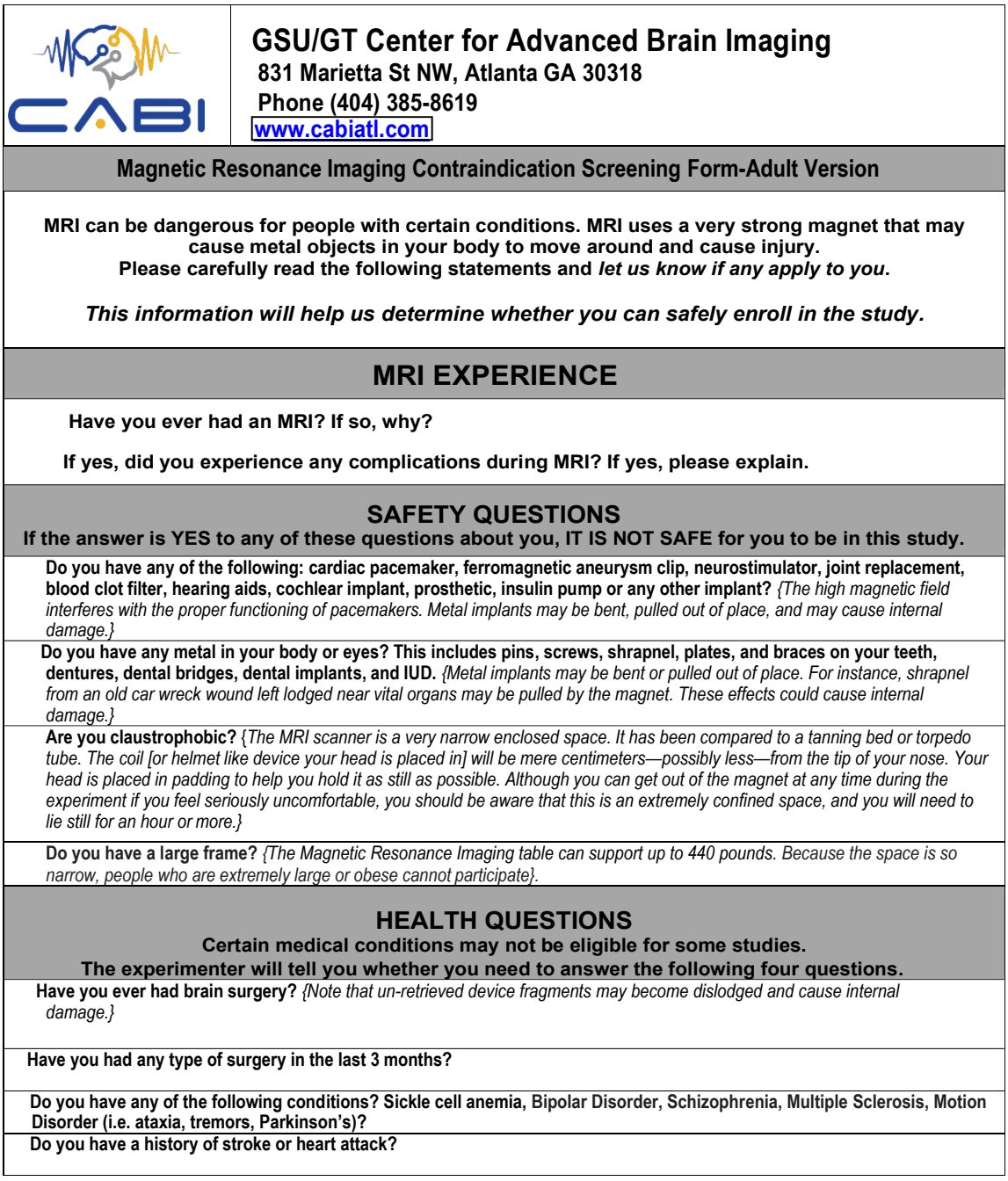
Name of Person Completing Form:_____

Signature of Person Completing Form:_____ Date (MM/DD/YYYY) _____

For Experimenter Use Only:
Name of Project & PI:_____
Researcher(s):_____
Person obtaining screening, Date, & Time:_____

Revised January 2021

Figure A.2. CABI TMS Screening Form



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Magnetic Resonance Imaging Contraindication Screening Form-Adult Version

MRI can be dangerous for people with certain conditions. MRI uses a very strong magnet that may cause metal objects in your body to move around and cause injury.
Please carefully read the following statements and *let us know if any apply to you*.

This information will help us determine whether you can safely enroll in the study.

MRI EXPERIENCE

Have you ever had an MRI? If so, why?

If yes, did you experience any complications during MRI? If yes, please explain.

SAFETY QUESTIONS
If the answer is YES to any of these questions about you, IT IS NOT SAFE for you to be in this study.

Do you have any of the following: cardiac pacemaker, ferromagnetic aneurysm clip, neurostimulator, joint replacement, blood clot filter, hearing aids, cochlear implant, prosthetic, insulin pump or any other implant? *{The high magnetic field interferes with the proper functioning of pacemakers. Metal implants may be bent, pulled out of place, and may cause internal damage.}*

Do you have any metal in your body or eyes? This includes pins, screws, shrapnel, plates, and braces on your teeth, dentures, dental bridges, dental implants, and IUD. *{Metal implants may be bent or pulled out of place. For instance, shrapnel from an old car wreck wound left lodged near vital organs may be pulled by the magnet. These effects could cause internal damage.}*

Are you claustrophobic? *{The MRI scanner is a very narrow enclosed space. It has been compared to a tanning bed or torpedo tube. The coil [or helmet like device your head is placed in] will be mere centimeters—possibly less—from the tip of your nose. Your head is placed in padding to help you hold it as still as possible. Although you can get out of the magnet at any time during the experiment if you feel seriously uncomfortable, you should be aware that this is an extremely confined space, and you will need to lie still for an hour or more.}*

Do you have a large frame? *{The Magnetic Resonance Imaging table can support up to 440 pounds. Because the space is so narrow, people who are extremely large or obese cannot participate}.*

HEALTH QUESTIONS
Certain medical conditions may not be eligible for some studies.
The experimenter will tell you whether you need to answer the following four questions.

Have you ever had brain surgery? *{Note that un-retrieved device fragments may become dislodged and cause internal damage.}*

Have you had any type of surgery in the last 3 months?

Do you have any of the following conditions? Sickle cell anemia, Bipolar Disorder, Schizophrenia, Multiple Sclerosis, Motion Disorder (i.e. ataxia, tremors, Parkinson's)?

Do you have a history of stroke or heart attack?

Figure A.3. CABI MRI Contraindications Form

Page 2

If the answer is YES to any of the following questions about yourself, IT MAY NOT BE SAFE for you to be in this study. You will need to discuss these points with the experimenter.

Do you wear a medicated adhesive patch? *{Medicated adhesive patches with metal backing may heat up and burn the skin during MRI. If so, the experimenter may ask whether the patch can be removed during MRI.}*

Do you have any non-removable jewelry, facial piercing, or artificial cosmetics enhancements (i.e. hair extensions, magnetic eyelashes, etc.)? *{Some materials used in jewelry and artificial cosmetic enhancements like surgical steel may heat up and become uncomfortably warm. Some materials used in hair extensions may cause images to be blurry.}*

Do you have any tattoos or permanent makeup? *{Some tattoo and permanent makeup dyes contain metal fragments that may heat up and become uncomfortably warm or cause swelling.}*

Do you have now (or ever had) any of the following? ADD/ADHD or any other neurological or psychological disorder?

Do you have now (or ever had) any of the following? Epilepsy, a seizure, loss of consciousness for more than a few seconds, or brain damage? *{If so, the completion of a special seizure protocol by your doctor may be required before you can be in this study.}*

Have you ever been seen by a neurologist, psychiatrist, or psychologist (not counselor)?

Do you take tranquilizers, sleeping pills, anxiety or depression medication, or other psychological medications?

Do you have now (or ever had) any of the following? Heart disease, anemia, diabetes, or high or low blood pressure?

Do you use prescription or recreational drugs?

Do you now or have you ever used or abused alcohol?

Do you have now (or ever had) untreated respiratory problems (e.g., severe asthma, emphysema)?

Do you have now (or ever had) any of the following vision conditions? Untreated cataracts, untreated glaucoma or macular degeneration?

Do you need glasses and cannot wear contact lenses? *{Most studies require responses to visual cues or instructions, so normal vision is usually required. In these studies, contact lens corrected vision is considered the same as normal vision}.*

Do you have any hearing difficulties? *{If so, you might be asked about your hearing in each ear.}*

Do you have any orthopedic issues such as arthritis or back pain that would make it difficult for you to sit or lie still for at least an hour or to use a keyboard?

Do you have any other physical or mental concerns that you have not mentioned so far?

Are you pregnant or breastfeeding? *{WOMEN OF CHILDBEARING POTENTIAL WHO ARE CONSIDERING BEING IN THIS STUDY SHOULD ESPECIALLY NOTE: THE RISK TO FETUSES FROM EXPOSURE TO MRI ARE CURRENTLY UNKNOWN.}*

Please tell the experimenter about any safety concerns that you may have.

THANK YOU FOR YOUR INTEREST

Jan 2021

Figure A.3. CABI MRI Contraindications Form

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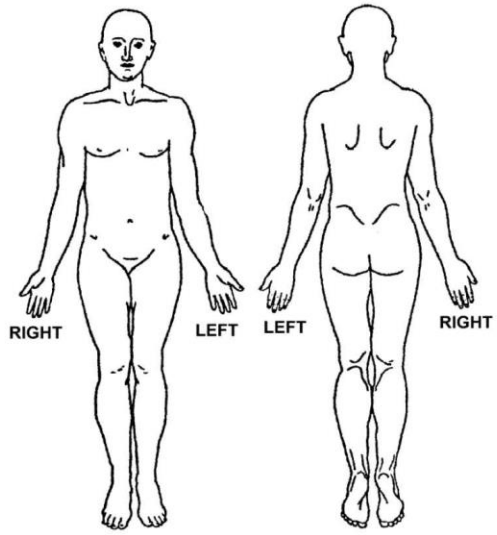
MAGNETIC RESONANCE SCREENING FORM- Adult Version

The MR suite contains a very strong magnet. Some metal objects can interfere with your scan or even be dangerous. Before you are allowed to enter, we must know if you have any metal objects in your body or have experienced any of the conditions listed below.

Please indicate if you have any of the following:

☐ Yes	☐ No	Metal in your skin, head or eyes
☐ Yes	☐ No	Epilepsy or history of seizure
☐ Yes	☐ No	Sickle cell anemia or blood disorder
☐ Yes	☐ No	Parkinson/Dementia/Alzheimer's
☐ Yes	☐ No	Cardiac pacemaker
☐ Yes	☐ No	Implanted cardioverter defibrillator (ICD)
☐ Yes	☐ No	Heart valve prosthesis
☐ Yes	☐ No	Metallic stent, filter, or coil
☐ Yes	☐ No	Vascular access port and/or catheter
☐ Yes	☐ No	Electric or Mechanical implant or device
☐ Yes	☐ No	Magnetic implant or device
☐ Yes	☐ No	Aneurysm clip(s) or Spinal cord stimulator
☐ Yes	☐ No	Shunt (spinal or intraventricular)
☐ Yes	☐ No	Wire mesh implant
☐ Yes	☐ No	Insulin or other infusion pump
☐ Yes	☐ No	Internal electrodes or wires
☐ Yes	☐ No	Radiation seeds or implants
☐ Yes	☐ No	Swan-Ganz or thermodilution catheter
☐ Yes	☐ No	Surgery
☐ Yes	☐ No	Surgical staples, clips, or metallic sutures
☐ Yes	☐ No	Bone/joint pin, screw, nail, wire, plate, etc.
☐ Yes	☐ No	Joint replacement (hip, knee, etc.)
☐ Yes	☐ No	Artificial or prosthetic limb
☐ Yes	☐ No	Bone growth/bone fusion stimulator
☐ Yes	☐ No	Any type of prosthesis (eye, penile, etc.)
☐ Yes	☐ No	Tissue expander (e.g., breast)
☐ Yes	☐ No	Eyelid spring or wire
☐ Yes	☐ No	Hearing aid
☐ Yes	☐ No	Cochlear, otologic, or another ear implant
☐ Yes	☐ No	Medication patch (Nicotine, Nitroglycerine)
☐ Yes	☐ No	Dentures, partial plates, or braces
☐ Yes	☐ No	Tattoo or permanent makeup/eyeliner
☐ Yes	☐ No	Amateur or prison tattoo
☐ Yes	☐ No	Shrapnel, bullet, or metallic foreign body
☐ Yes	☐ No	IUD, diaphragm, or pessary
☐ Yes	☐ No	Pregnant or breastfeeding
☐ Yes	☐ No	Jewelry that cannot be removed
☐ Yes	☐ No	Artificial cosmetic enhancements (hair extensions, magnetic eyelashes, nail polish etc.)

Please mark on the figure(s) below the location of any implant or metal inside of or on your body.



Please consult the MRI Technologist if you have any questions or concerns BEFORE you enter the MRI scanner.

NOTE: You may be advised or required to wear earplugs or other hearing protection during the MR procedure to prevent possible problems or hazards related to acoustic noise.

WARNING: Certain implants, devices, or objects may be hazardous to you and/or may interfere with the MR procedure (i.e., MRI, functional MRI, MR spectroscopy). Do not enter in the MR system room or MR environment if you have any question or concern regarding an implant, device, or object. Consult the MRI Technologist BEFORE entering the MR system room. The MR system magnet is ALWAYS ON.

Figure A.4. CABI MRI Screening Form

IMPORTANT INSTRUCTIONS FOR YOUR SAFETY		
Before entering the MR environment, you must remove all metallic objects including hearing aids, dentures, removable partial plates, keys, beeper, mobile phone, eyeglasses, hair pins, barrettes, jewelry, body piercing, watch, safety pins, paper clips, money clips, credit cards, bank cards, magnetic strip cards, coins, pens, pocketknife, nail clipper, tools, shoes, clothing with metal fasteners (excluding pants & bra).		
Name of Participant:		
Date of Birth (MM/DD/YYYY)	Weight (Pounds)	Height (Feet, Inches)
I attest that the above information is correct to the best of my knowledge. I have read and understand the contents of this form and have had the opportunity to ask questions regarding the information on this form and regarding the MR procedure that I am about to undergo.		
Signature of Person Completing Form:	Date (MM/DD/YYYY)	
Form Completed by: Participant Relative _____ If relative, print your name	_____ State your relationship to participant	
FOR OFFICE USE ONLY ***Notes on any checked items:***	**COINS Study Name: _____** **Principal Investigator: _____** **Researcher(s): _____** **Person obtaining screening: _____** **Screening date & time: _____**	

Figure A.4. CABI MRI Screening Form

APPENDIX B. PARTICIPANT DEMOGRAPHICS

Table B.1. Demographics for Participants Receiving SMG Stimulation

SMG	
Gender	62% Female (*N* = 8) 39% Male (*N* = 5)
Ethnicity	54% Caucasian (*N* = 7) 46% Black/African American (*N* = 6)
Education	*M* = 14.50 years (1.29)
Age	*M* = 27.33 (7.98)

Table B.2. Demographics for Participants Receiving MTG Stimulation

MTG	
Gender	83% Female (*N* = 10) 17% Male (*N* = 2)
Ethnicity	34 % Caucasian (*N* = 4) 58% Black/African American (*N* = 7) 8% Not Reported (*N* = 1)
Education	*M* = 14 years (1.22)
Age	*M* = 21.59 years (6.07)

Table B.3. Demographics for Participants Receiving Vertex Stimulation

Vertex	
Gender	86% Female (*N* = 6) 14% Male (*N* = 1)
Ethnicity	43% Caucasian (*N* = 3) 29% Black/African American (*N* = 2) 14% Hispanic/Latino (*N* = 1) 14% Not Reported (*N* = 1)
Education	*M* = 17.16 years (2.80)
Age	*M* = 27.57 (7.96)

Table B.4. Demographics for No-Stimulation Control Participants

Behavioral Control	
Gender	67% Female (*N* = 4) 33% Male (*N* = 2)
Ethnicity	33% Caucasian (*N* = 2) 67% Black/African American (*N* = 4)
Education	NR, all > 12 years
Age	*M* = 23.35 (3.47)

APPENDIX C. OVERALL MEANS FOR EACH MEASURE BY PARTICIPANT GROUP

Table C.1. Overall Means for Each Group by Measure

Group	***RAN SPI***		***OA RT (ms)***		***TOWRE SWE***		***WJ-3 RF W Score***	
	Pre*	***Post*** ***	***Pre****	***Post*** *	***Pre****	***Post*** *	***Pre****	***Post*** *
SMG	0.45 (0.06)	0.40 (0.06)	820.35 (171.78)	735.35 (162.62)	87.11 (13.65)	90.11 (8.62)	525.25 (15.07)	534.88 (18.04)
MTG	0.50 (0.06)	0.54 (0.16)	841.00 (199.46)	776.23 (129.15)	78.78 (13.78)	80.56 (11.87)	525.60 (21.39)	531.70 (19.21)
Vertex	0.44 (0.07)	0.41 (0.06)	854.80 (94.50)	746.50 (76.48)	84.29 (14.94)	87.71 (16.10)	528.50 (36.52)	541.33 (40.25)
NS Control	---	----	804.17 (87.81)	780.92 (145.68)	91.20 (9.83)	94.20 (10.09)	---	

**Pre = Pre-TBS for SMG, MTG, and Vertex groups, Time Point 1 for NS Control Group*

***Post = Post-TBS for SMG, MTG, and Vertex groups, Time Point 2 for NS Control Group*

APPENDIX D. DESCRIPTIVE STATISTICS FOR EACH MEASURE BY STIMULATION GROUP

Table D.1. Orthographic Awareness (OA) Descriptive Statistics for Participants Receiving SMG Stimulation

	N	***M***	***SD***	***Skewness***	***SE Skewness***	***Kurtosis***	***SE Kurtosis***	***SW Test for Normality (p-value)***
OA Accuracy % (Pre-TBS)	13	0.94	0.06	-0.71	.62	-0.45	1.19	.04
OA Accuracy % (Post-TBS)	13	0.87	0.18	-2.53	.62	7.43	1.19	<.001
OA Accuracy % Change (Pre-TBS – Post-TBS)	13	0.07	0.18	3.22	.62	10.98	1.19	<.001
OA Response Time ms (Pre-TBS)	13	820.35	171.78	0.64	.62	-0.26	1.19	.32
OA Response Time ms (Post-TBS)	13	735.35	162.62	1.94	.62	4.65	1.19	.006
ΔOA Response Time in ms (Pre-TBS – Post-TBS)	13	85.00	104.36	0.43	.62	-0.73	1.19	.48

N *= sample size for variable,* ***M*** *= mean of variable,* ***SD*** *= standard deviation of variable,* ***SE*** *= standard error,* ***SW Test*** *= Shapiro-Wilk Test of Normality*

Table D.2. Orthographic Awareness (OA) Descriptive Statistics for Participants Receiving MTG Stimulation

	N	***M***	***SD***	***Skewness***	***SE Skewness***	***Kurtosis***	***SE Kurtosis***	***SW Test for Normality (p-value)***
OA Accuracy % (Pre-TBS)	11	0.89	.14	-2.09	-0.66	4.59	1.28	< .01
OA Accuracy % (Post-TBS)	11	0.92	.09	-1.48	-0.66	2.09	1.28	.03
OA Accuracy % Change (Pre-TBS – Post-TBS)	11	-0.03	.06	-1.79	-0.66	5.03	1.28	< .01
OA Response Time ms (Pre-TBS)	11	841.00	199.46	-0.17	-0.66	0.37	1.28	.70
OA Response Time ms (Post-TBS)	11	776.23	129.15	-0.03	-0.66	-1.67	1.28	.25
ΔOA Response Time in ms (Pre-TBS – Post-TBS)	11	64.77	156.98	-1.02	-0.66	5.03	1.28	.16

N *= sample size for variable,* ***M*** *= mean of variable,* ***SD*** *= standard deviation of variable,* ***SE*** *= standard error,* ***SW Test*** *= Shapiro-Wilk Test of Normality*

Table D.3. Orthographic Awareness Descriptive Statistics for Participants Receiving Vertex Stimulation

	N	***M***	***SD***	***Skewness***	***SE Skewness***	***Kurtosis***	***SE Kurtosis***	***SW Test for Normality (p-value)***
OA Accuracy % (Pre-TBS)	5	0.85	0.15	-0.71	0.91	-0.70	2.00	.65
OA Accuracy % (Post-TBS)	5	0.89	0.08	-0.60	0.91	-0.95	2.00	.79
OA Accuracy % Change (Pre-TBS – Post-TBS)	5	-0.04	0.12	-1.60	0.91	3.26	2.00	.17
OA Response Time ms (Pre-TBS)	5	854.80	94.50	-0.28	0.91	-1.55	2.00	.71
OA Response Time ms (Post-TBS)	5	746.50	76.48	-0.32	0.91	-1.73	2.00	.78
ΔOA Response Time in ms (Pre-TBS – Post-TBS)	5	108.30	103.20	-1.93	0.91	4.13	2.00	.03

N *= sample size for variable,* ***M*** *= mean of variable,* ***SD*** *= standard deviation of variable,* ***SE*** *= standard error,* ***SW Test*** *= Shapiro-Wilk Test of Normality*

Table D.4. Orthographic Awareness Descriptive Statistics for No-Stimulation Control Group

	N	***M***	***SD***	***Skewness***	***SE Skewness***	***Kurtosis***	***SE Kurtosis***	***SW Test for Normality (p-value)***
OA Accuracy % (Time Point 1)	6	0.93	0.10	-1.51	0.85	1.69	1.74	.05
OA Accuracy % (Time Point 2)	6	0.91	0.15	-2.36	0.85	5.66	1.74	< .01
ΔOA Accuracy % (Time Point 1 – Time Point 2)	6	0.02	0.20	1.64	0.85	3.48	1.74	.14
OA Response Time ms (Time Point 1)	6	804.17	87.81	0.14	0.85	-1.48	1.74	.86
OA Response Time ms (Time Point 2)	6	780.92	145.68	1.61	0.85	2.91	1.74	.16
ΔOA Response Time in ms (Time Point 1 – Time Point 2)	6	23.25	0.20	-2.26	0.85	5.32	1.74	< .01

***N** = sample size for variable, **M** = mean of variable, **SD** = standard deviation of variable, **SE** = standard error, **SW Test** = Shapiro-Wilk Test of Normality*

Tables D.5-D.7. RAN Descriptive Statistics for Each Stimulation Group

Table D.5. RAN Descriptive Statistics for Participants Receiving SMG Stimulation

Measure	***N***	***M***	***SD***	***Skewness***	***SE Skewness***	***Kurtosis***	***SE Kurtosis***	***SW Test for Normality (p-value)***
RAN Composite seconds/item (Pre-TBS)	4	0.45	0.06	1.57	1.01	2.77	2.62	.26
RAN Composite seconds/item (Post-TBS)	4	0.40	0.06	1.71	1.01	3.05	2.62	.15
ΔRAN Composite seconds/item (Pre-TBS – Post-TBS)	4	0.05	0.01	-0.28	1.01	-0.58	2.62	.98

N *= sample size for variable,* ***M*** *= mean of variable,* ***SD*** *= standard deviation of variable,* ***SE*** *= standard error,*

SW Test *= Shapiro-Wilk Test of Normality*

Table D.6. RAN Descriptive Statistics for Participants Receiving MTG Stimulation

Measure	***N***	***M***	***SD***	***Skewness***	***SE Skewness***	***Kurtosis***	***SE Kurtosis***	***SW Test for Normality (p-value)***
RAN Composite seconds/item (Pre-TBS)	4	0.50	0.06	0.91	1.01	-0.54	2.62	.55
RAN Composite seconds/item (Post-TBS)	4	0.54	0.16	1.20	1.01	0.45	2.62	.24
ΔRAN Composite seconds/item (Pre-TBS – Post-TBS)	4	-0.04	0.14	-1.99	1.01	3.97	2.62	< .01

N *= sample size for variable,* ***M*** *= mean of variable,* ***SD*** *= standard deviation of variable,* ***SE*** *= standard error,*

SW Test *= Shapiro-Wilk Test of Normality*

Table D.7. RAN Descriptive Statistics for Participants Receiving Vertex Stimulation

Measure	***N***	***M***	***SD***	***Skewness***	***SE Skewness***	***Kurtosis***	***SE Kurtosis***	***SW Test for Normality (p-value)***
RAN Composite seconds/item (Pre-TBS)	6	0.44	0.07	0.39	0.85	-1.23	1.74	.67
RAN Composite seconds/item (Post-TBS)	6	0.41	0.06	0.58	0.85	-1.81	1.74	.20
ΔRAN Composite seconds/item (Pre-TBS – Post-TBS)	6	0.03	0.02	0.10	0.85	-2.01	1.74	.63

N *= sample size for variable,* ***M*** *= mean of variable,* ***SD*** *= standard deviation of variable,* ***SE*** *= standard error,*

SW Test *= Shapiro-Wilk Test of Normality*

Tables D.8-D.11. TOWRE SWE Descriptive Statistics for Each Stimulation Group

Table D.8. TOWRE SWE Descriptive Statistics for Participants Receiving SMG Stimulation

	N	***M***	***SD***	***Skewness***	***SE Skewness***	***Kurtosis***	***SE Kurtosis***	***SW Test for Normality (p-value)***
TOWRE SWE (Version A) (Pre-TBS)	9	87.11	13.65	-.53	.72	-1.37	1.40	.26
TOWRE SWE (Version B) (Post-TBS)	9	90.11	8.62	-.25	.72	-1.32	1.40	.69
Δ TOWRE SWE (Pre-TBS –Post TBS)	9	3.00	6.46	.35	.72	0.47	1.40	.95

N *= sample size for variable,* ***M*** *= mean of variable,* ***SD*** *= standard deviation of variable,* ***SE*** *= standard error,*

SW Test *= Shapiro-Wilk Test of Normality*

Table D.9. TOWRE SWE Descriptive Statistics for Participants Receiving MTG Stimulation

	N	***M***	***SD***	***Skewness***	***SE Skewness***	***Kurtosis***	***SE Kurtosis***	***SW Test for Normality (p-value)***
TOWRE SWE (Version A) (Pre-TBS)	9	78.78	13.78	-1.26	0.72	0.21	1.40	.02
TOWRE-2 B SWE (Version B) (Post-TBS)	9	80.56	11.87	-1.26	0.72	0.21	1.40	< .01
Δ TOWRE SWE (Pre-TBS –Post TBS)	9	1.78	2.82	-0.27	0.72	-1.12	1.40	.23

N *= sample size for variable,* ***M*** *= mean of variable,* ***SD*** *= standard deviation of variable,* ***SE*** *= standard error,* ***SW Test*** *= Shapiro-Wilk Test of Normality*

Table D.10. TOWRE-2 Descriptive Statistics for Participants Receiving Vertex Stimulation

	N	***M***	***SD***	***Skewness***	***SE Skewness***	***Kurtosis***	***SE Kurtosis***	***SW Test for Normality (p-value)***
TOWRE SWE (Version A) (Pre-TBS)	7	84.29	14.94	-0.47	0.79	0.15	1.59	.66
TOWRE-2 B SWE (Version B) (Post-TBS)	7	87.71	16.10	-1.08	0.79	2.08	1.59	.56
Δ TOWRE SWE (Pre-TBS –Post TBS)	7	3.43	4.54	0.06	0.79	-1.22	1.59	.62

N *= sample size for variable,* ***M*** *= mean of variable,* ***SD*** *= standard deviation of variable,* ***SE*** *= standard error,* ***SW Test*** *= Shapiro-Wilk Test of Normality*

Table D.11. TOWRE-2 Descriptive Statistics for No-Stimulation Control Group

	N	***M***	***SD***	***Skewness***	***SE Skewness***	***Kurtosis***	***SE Kurtosis***	***SW Test for Normality (p-value)***
TOWRE SWE (Version A) (Time Point 1)	5	91.2	9.83	-2.01	0.91	4.07	2.00	.01
TOWRE-2 B SWE (Version A) (Time Point 2)	5	94.2	10.09	0.19	0.91	-0.60	2.00	.76
Δ TOWRE SWE (Time Point 1 – Time Point 2)	5	3.00	6.44	0.14	0.91	-1.53	2.00	.75

N *= sample size for variable,* ***M*** *= mean of variable,* ***SD*** *= standard deviation of variable,* ***SE*** *= standard error,* ***SW Test*** *= Shapiro-Wilk Test of Normality*

Tables D.12-D.14. WJ-3 Descriptive Statistics for Each Stimulation Group

Table D.12. WJ-3 RF Descriptive Statistics for Participants Receiving SMG Stimulation

	N	***M***	***SD***	***Skewness***	***SE Skewness***	***Kurtosis***	***SE Kurtosis***	***SW Test for Normality (p-value)***
WJ-3 RF W Score (Pre-TBS)	8	525.25	15.07	0.59	0.75	-0.87	1.48	.57
WJ-3 RF W Score (Post-TBS)	8	534.88	18.04	0.99	0.75	-0.21	1.48	.10
ΔWJ-3 RF W Score (Pre-TBS – Post-TBS)	8	-9.62	8.86	0.51	0.75	-0.38	1.48	.29

N *= sample size for variable,* ***M*** *= mean of variable,* ***SD*** *= standard deviation of variable,* ***SE*** *= standard error,* ***SW Test*** *= Shapiro-Wilk Test of Normality*

Table D.13. WJ-3 RF Descriptive Statistics for Participants Receiving MTG Stimulation

	N	***M***	***SD***	***Skewness***	***SE Skewness***	***Kurtosis***	***SE Kurtosis***	***SW Test for Normality (p-value)***
WJ-3 RF W Score (Pre-TBS)	10	525.60	21.39	0.63	0.69	-0.67	1.33	.54
WJ-3 RF W Score (Post-TBS)	10	531.70	19.21	-0.18	0.69	0.03	1.33	.70
ΔWJ-3 RF W Score (Pre-TBS – Post-TBS)	10	-6.10	9.99	-0.26	0.69	0.23	1.33	.94

N *= sample size for variable,* ***M*** *= mean of variable,* ***SD*** *= standard deviation of variable,* ***SE*** *= standard error,*

SW Test *= Shapiro-Wilk Test of Normality*

Table D.14. WJ-3 RF Descriptive Statistics for Participants Receiving Vertex Stimulation

	N	***M***	***SD***	***Skewness***	***SE Skewness***	***Kurtosis***	***SE Kurtosis***	***SW Test for Normality (p-value)***
WJ-3 RF W Score (Pre-TBS)	6	528.50	36.52	0.43	0.85	-1.84	1.74	.19
WJ-3 RF W Score (Post-TBS)	6	541.33	40.25	-0.45	0.85	-1.79	1.74	.30
ΔWJ-3 RF W Score (Pre-TBS – Post-TBS)	6	-12.83	12.91	-0.64	0.85	-1.66	1.74	.31

N *= sample size for variable,* ***M*** *= mean of variable,* ***SD*** *= standard deviation of variable,* ***SE*** *= standard error,*

SW Test *= Shapiro-Wilk Test of Normality*

APPENDIX E. PRE AND POST CHANGE FOR INDIVIDUAL PARTICIPANTS

Table E.1. Pre-Post Means by Stimulation Group: Individual Participants

Group	***RAN SPI***		***OA RT (ms)***		***TOWRE SWE Raw Score***		***WJ-3 RF W Score***	
	Pre*	***Post*****	***Pre****	***Post*****	***Pre****	***Post*****	***Pre****	***Post*****
SMG_1	---	---	762.50	844	66	81	525	519
SMG_2	0.53	0.49	716	711	75	82	510	529
SMG_3	0.40	0.35	929	718	95	97	508	519
SMG_4	0.43	0.37	959.50	692	86	88	532	551
SMG_5	0.44	0.39	1001.50	883	101	94	550	568
SMG_6	---	---	614	595	93	98	---	---
SMG_7	---	---	951	721	---	---	---	---
SMG_8	---	---	750	687	---	---	---	---
SMG_9	---	---	821	663	---	---	---	---
SMG_10	---	---	1179	1186	95	92	518	524
SMG_11	---	---	632.50	579.50	---	---	---	---
SMG_12	---	---	722.50	703	103	102	542	546
SMG_13	---	---	626	577	70	77	517	523
MTG_1	---	---	696	950.50	86	84	511	536
MTG_2	---	---	---	---	79	82	510	513
MTG_3	0.51	0.77	1162	913	56	60	498	497
MTG_4	0.46	0.42	710	621	88	91	519	526
MTG_5	0.44	0.42	1067	862	81	83	521	535
MTG_6	0.58	0.56	856	732	55	61	507	519
MTG_7	---	---	756	634	93	91	544	535
MTG_8	---	---	811	745.50	---	---	---	---

Group	***RAN SPI***		***OA RT (ms)***		***TOWRE SWE Raw Score***		***WJ-3 RF W Score***	
	Pre*	***Post*****	***Pre****	***Post*****	***Pre****	***Post*****	***Pre****	***Post*****
MTG_9	---	---	451	600	86	89	551	560
MTG_10	---	---	857.50	920.50	85	84	531	538
MTG_11	---	---	832	705	---	---	564	558
MTG_12	---	---	1052.50	855	---	---	---	---
MTG_9	---	---	451	600	86	89	551	560
Vertex_1	---	---	968	831	59	57	489	489
Vertex_2	0.52	0.49	733.50	805	82	85	---	---
Vertex_3	0.41	0.36	784	646	102	108	572	584
Vertex_4	---	---	---	---	83	93	495	497
Vertex_5	0.54	0.49	888.50	695	75	82	520	546
Vertex_6	0.44	0.40	900	755.50	88	90	522	553
Vertex_7	0.40	0.38	---	---	101	99	573	579
NS-Control_1	---	---	832	750	96	97	---	---
NS-Control_2	---	---	923	821	97	108	---	---
NS-Control_3	---	---	876	714	74	82	---	---
NS-Control_4	---	---	762.5	709	---	---	---	---
NS-Control_5	---	---	692	1052.5	92	87	---	---
NS-Control_6	---	---	739.5	639	97	97	---	---

**Pre = Pre-TBS for SMG, MTG, and Vertex groups, Time Point 1 for NS Control Group*

***Post = Post-TBS for SMG, MTG, and Vertex groups, Time Point 2 for NS Control Group*

APPENDIX F. ORTHOGRAPHIC AWARENESS ACCURACY

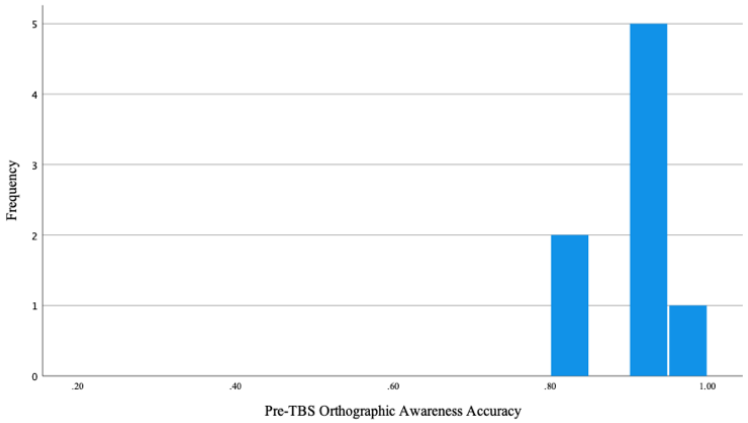
Table F.1. Paired T-Test Results for Pre-TBS and Post-TBS TBS Orthographic Awareness Accuracy

Stimulation Group	*N*	Mean*	*t*	*p*	Cohen's *D*	Bootstrapped CI	Wilcoxon *Z*	Wilcoxon *p*
SMG	13	.07	1.29	.22	0.18	[-0.06, .01]	-1.28	.20
MTG	11	.03	1.36	.20	-0.41	[-.07, .01]	-1.28	.20
Vertex	5	-0.04	-0.84	.45	0.12	[-0.13, .03]	-0.73	.47
NS Control	6	0.02	0.25	.81	0.10	[-0.19, .24]	-0.27	-.79

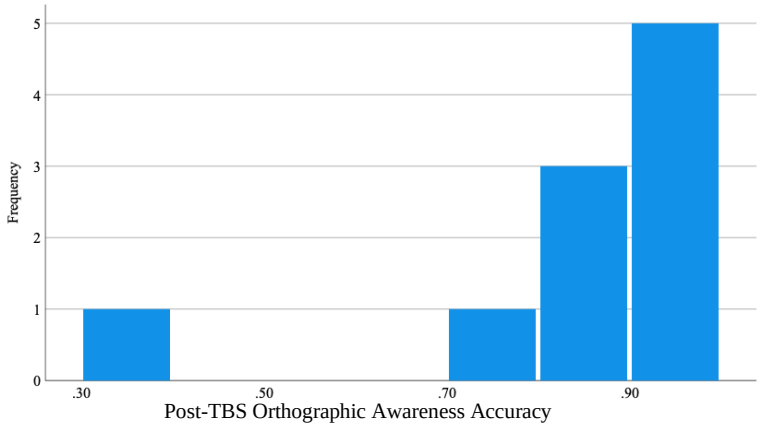
APPENDIX G. HISTOGRAMS OF MEASURE SCORES FOR EACH STIMULATION GROUP

Figures G.1.a-G.8.c. Orthographic Awareness Distributions for Each Stimulation Group (Accuracy and Median Response Time)

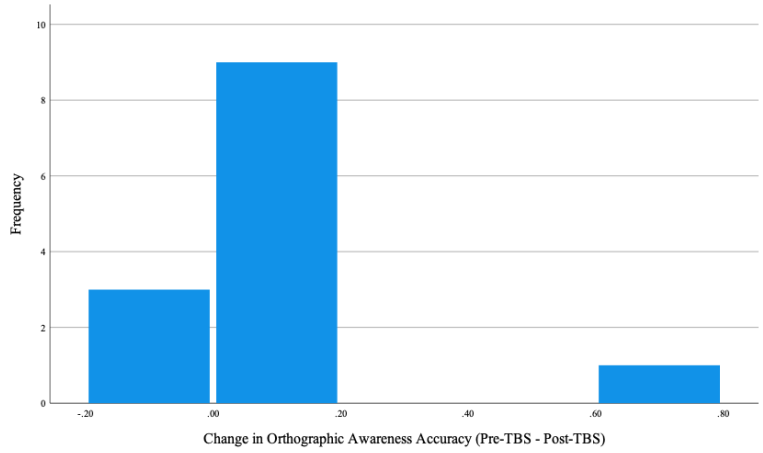
Figure G.1.a-G.5.c. Histograms of Orthographic Awareness Accuracy for Participants Receiving SMG Stimulation



G.1.a. Pre-TBS Orthographic Awareness Accuracy for Participants Receiving SMG Stimulation

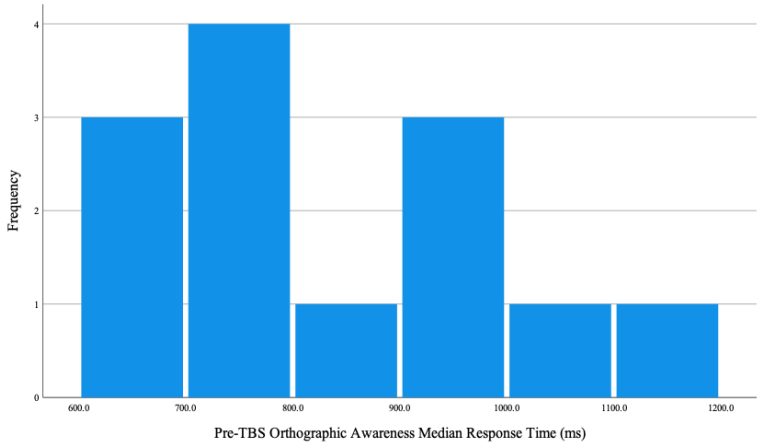


G.1.b. Post-TBS Orthographic Awareness Accuracy for Participants Receiving SMG Stimulation

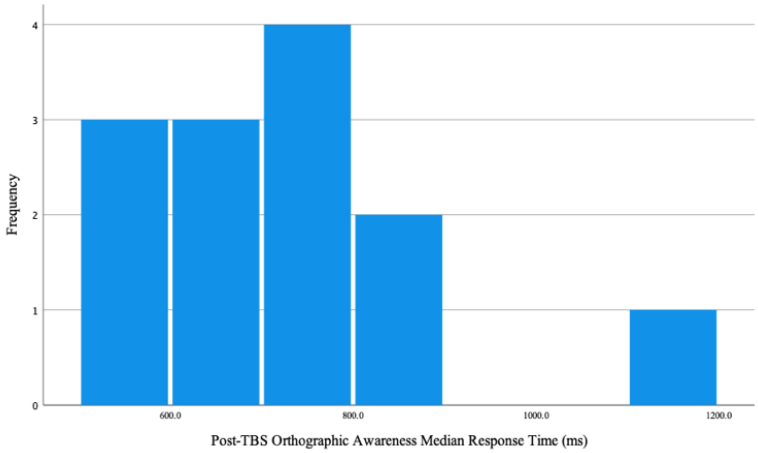


G.1.c. Pre-Post TBS Change in Orthographic Awareness Accuracy for Participants Receiving SMG Stimulation

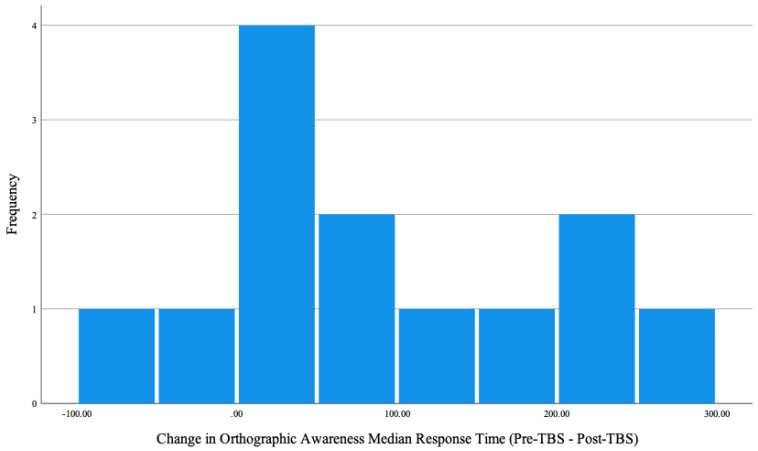
Figures G.2.a-G.2.c Histograms of Orthographic Awareness Median Response Time for Participants Receiving SMG Stimulation



G.2.a. Pre-TBS Orthographic Awareness Accuracy for Participants Receiving SMG Stimulation

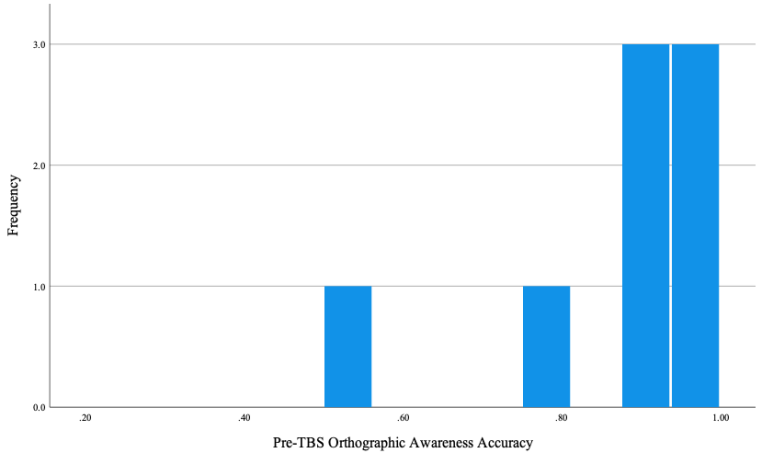


G.2.b. Post-TBS Orthographic Awareness Median Response Time for Participants Receiving SMG Stimulation

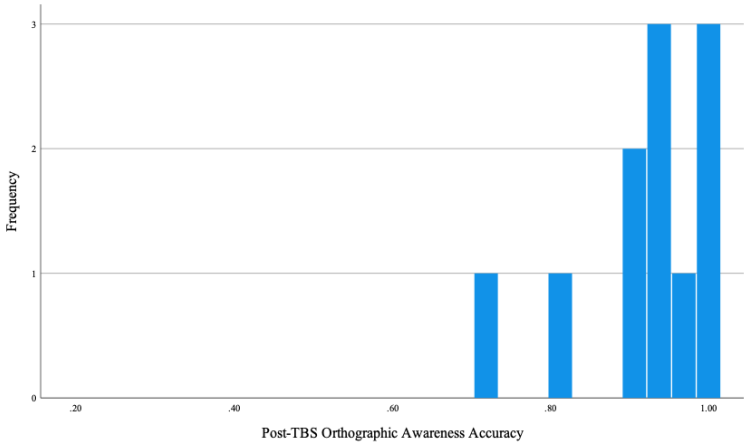


G.2.c. Pre-Post TBS Change in Orthographic Awareness Median Response Time for Participants Receiving SMG Stimulation

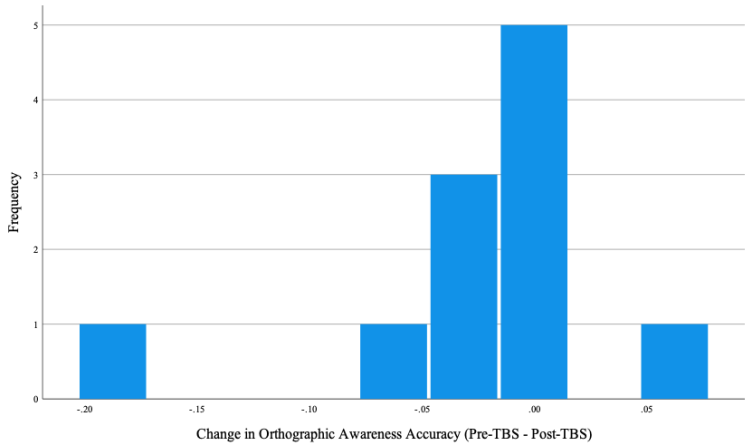
Figure G.3.a-G.3.c. Histograms of Orthographic Awareness Accuracy for Participants Receiving MTG Stimulation



G.3.a. Pre-TBS Orthographic Awareness Accuracy for Participants Receiving MTG Stimulation

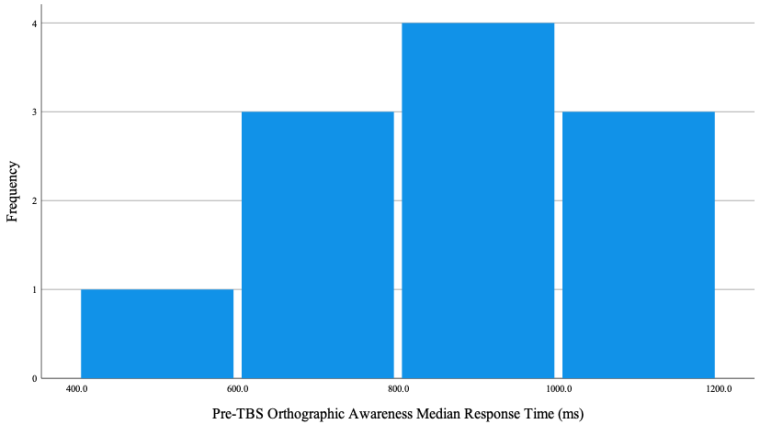


G.3.b. Post-TBS Orthographic Awareness Accuracy for Participants Receiving MTG Stimulation

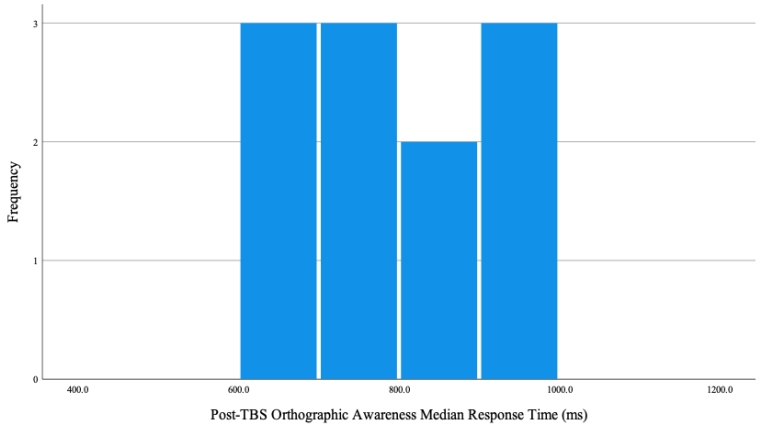


G.3.c. Pre-Post TBS Change in Orthographic Awareness Accuracy for Participants Receiving MTG Stimulation

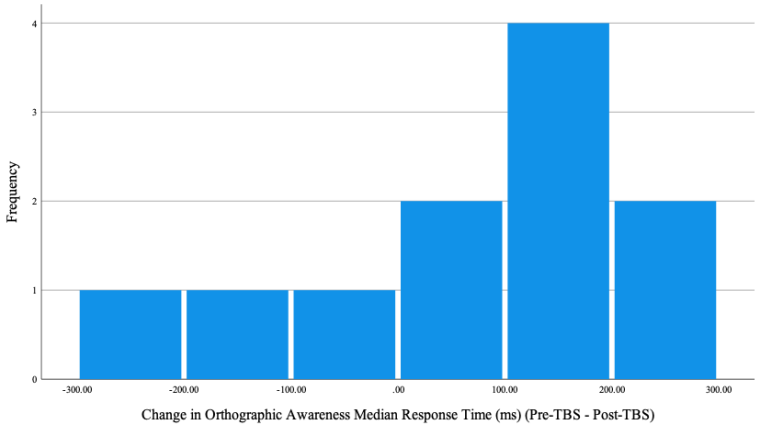
Figure G.4.a-G.4.c. Histograms of Orthographic Awareness Median Response Time for Participants Receiving MTG Stimulation



G.4.a. Pre-TBS Orthographic Awareness Median Response Time for Participants Receiving MTG Stimulation

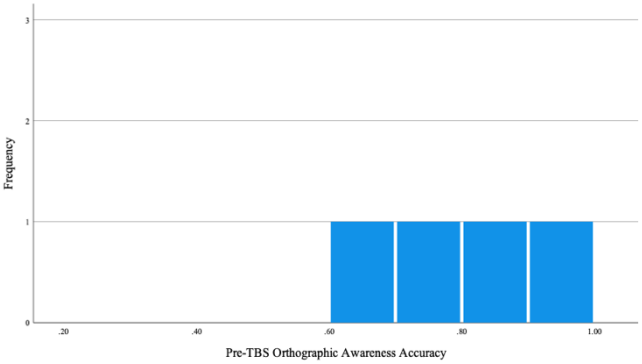


G.4.b. Post-TBS Orthographic Awareness Median Response Time for Participants Receiving MTG Stimulation

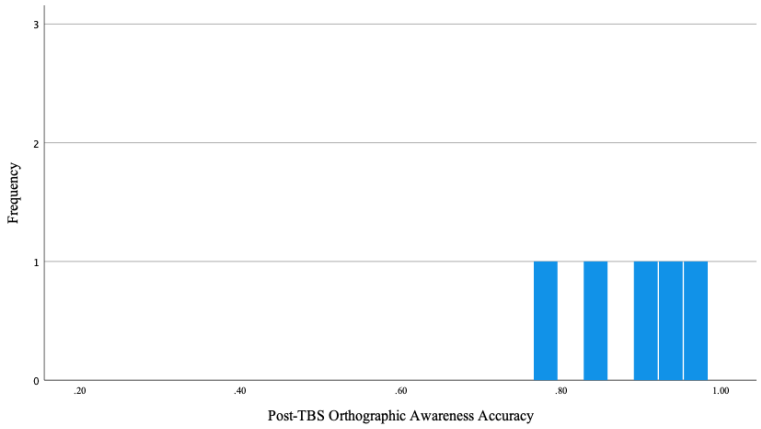


G.4.c. Pre-Post TBS Change in Orthographic Awareness Median Response Time for Participants Receiving MTG Stimulation

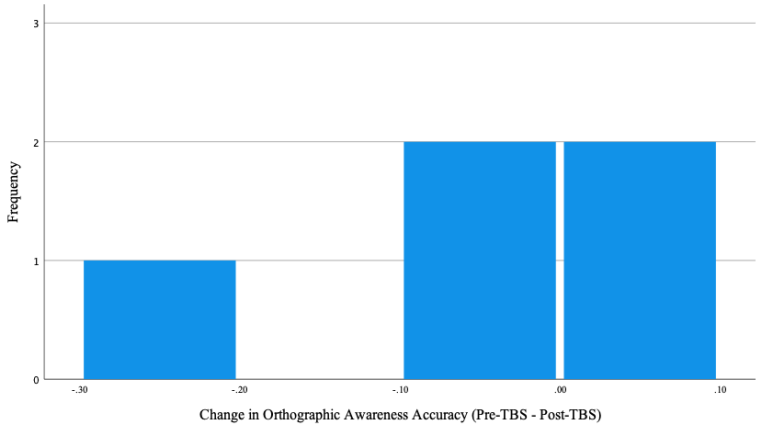
Figure G.5.a-G.5.c. Histograms of Orthographic Awareness Accuracy for Participants Receiving Vertex Stimulation



G.5.a. Pre-TBS Orthographic Awareness Accuracy for Participants Receiving Vertex Stimulation

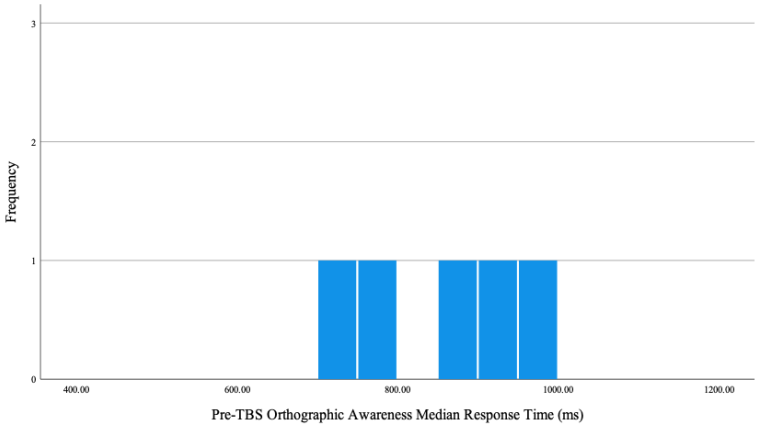


G.5.b. Post-TBS Orthographic Awareness Accuracy for Participants Receiving Vertex Stimulation

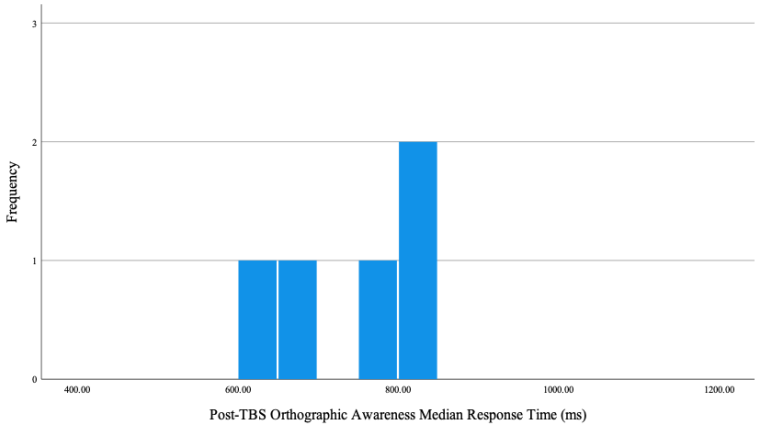


G.5.c. Pre-Post TBS Change in Orthographic Awareness Accuracy for Participants Receiving Vertex Stimulation

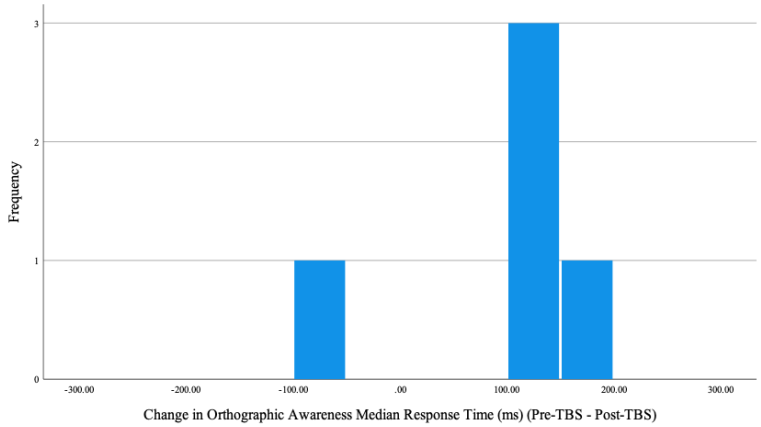
Figure G.6.a-G.8.c. Histograms of Orthographic Awareness Median Response Time for Participants Receiving Vertex Stimulation



G.6.a. Pre-TBS Orthographic Awareness Median Response Time for Participants Receiving Vertex Stimulation

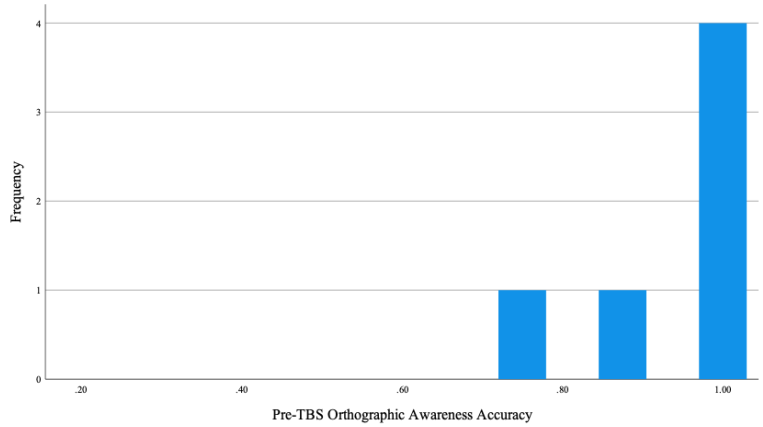


G.6.b. Post-TBS Orthographic Awareness Median Response Time for Participants Receiving Vertex Stimulation

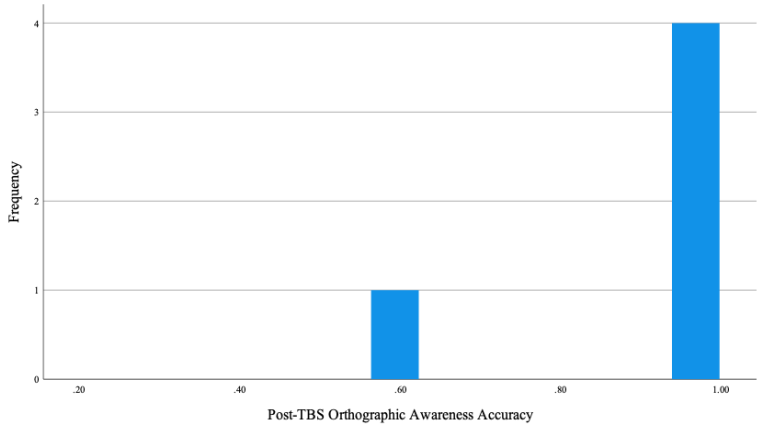


G.6.c. Pre-Post TBS Change in Orthographic Awareness Median Response Time for Participants Receiving Vertex Stimulation

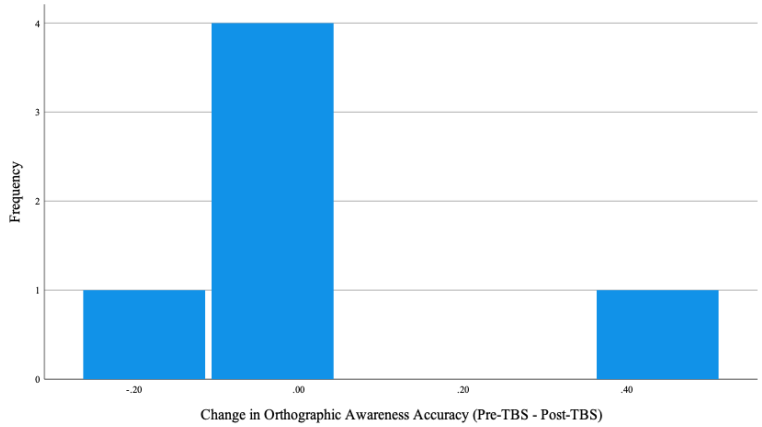
Figure G.7.a-G.7.c. Histograms of Orthographic Awareness Accuracy for No-Stimulation Control Participants



G.7.a. Pre Time Point Orthographic Awareness Accuracy for No-Stimulation Control Group

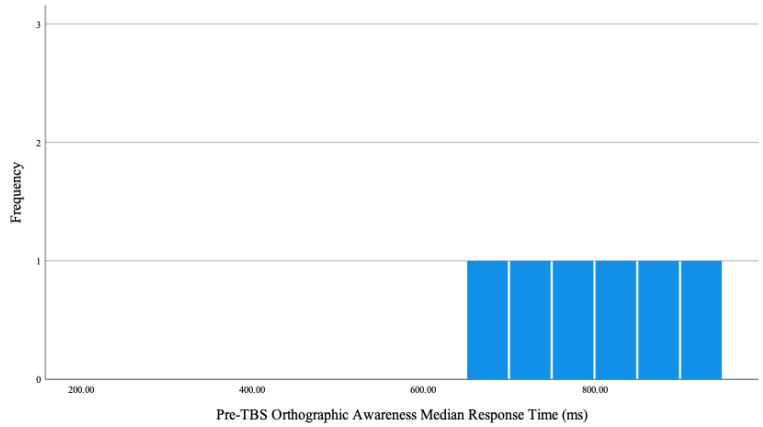


G.7.b. Post Time Point Orthographic Awareness Accuracy for No-Stimulation Control Group

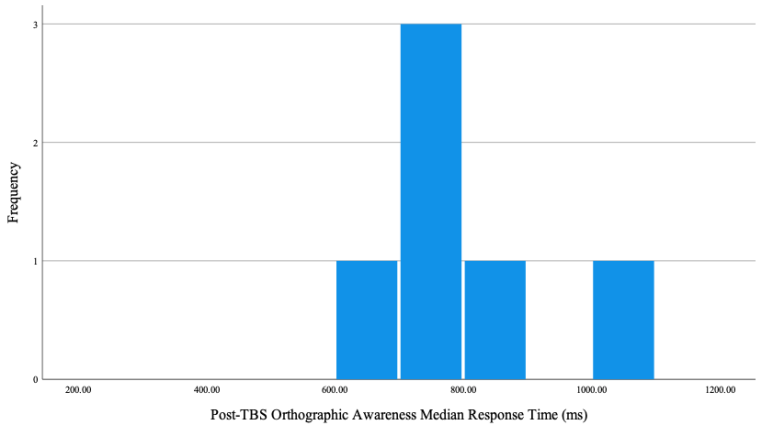


G.7.c. Pre-Post Change in Orthographic Awareness Accuracy for No-Stimulation Control Group

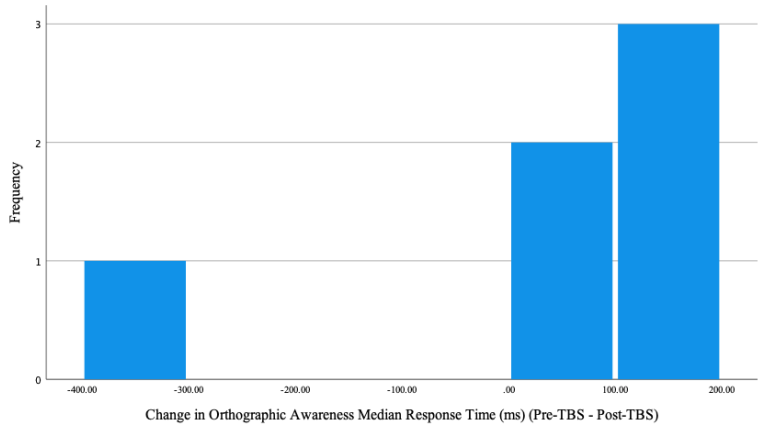
Figure G.8.a-G.8.c. Histograms of Orthographic Awareness Median Response Tine for No-Stimulation Control Participants



G.8.a. Pre Time Point Orthographic Awareness Median Response Time for No-Stimulation Control Group



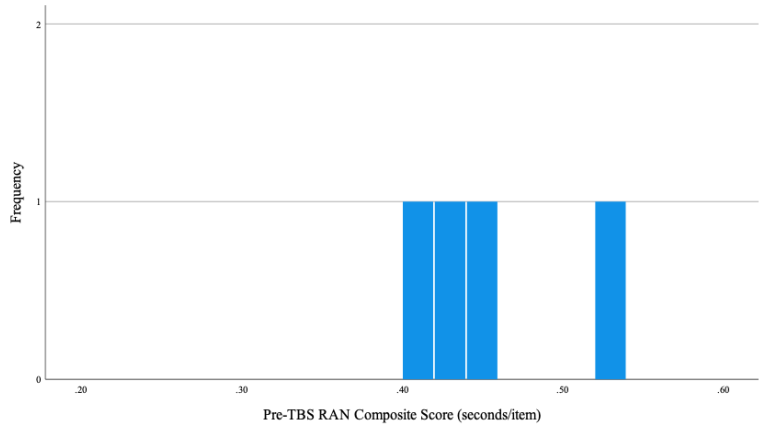
G.8.b. Post Time Point Orthographic Awareness Median Response Time for No-Stimulation Control Group



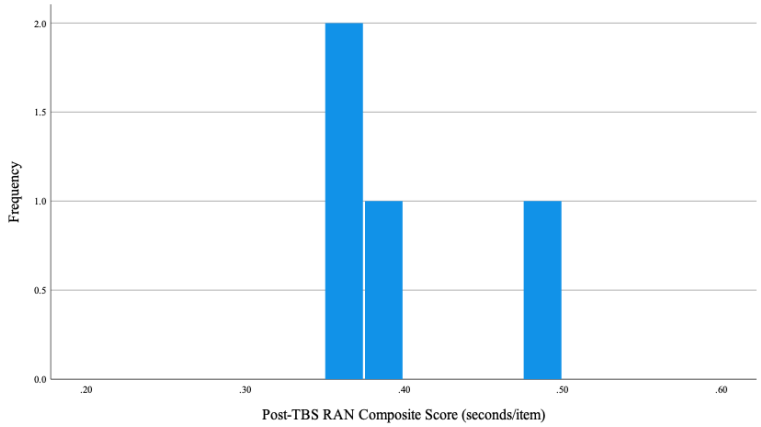
G.8.c. Pre-Post Change in Orthographic Awareness Median Response Time for No-Stimulation Control Group

Figures G.9.a-G.10.c RAN Composite Distributions for Each Stimulation Group

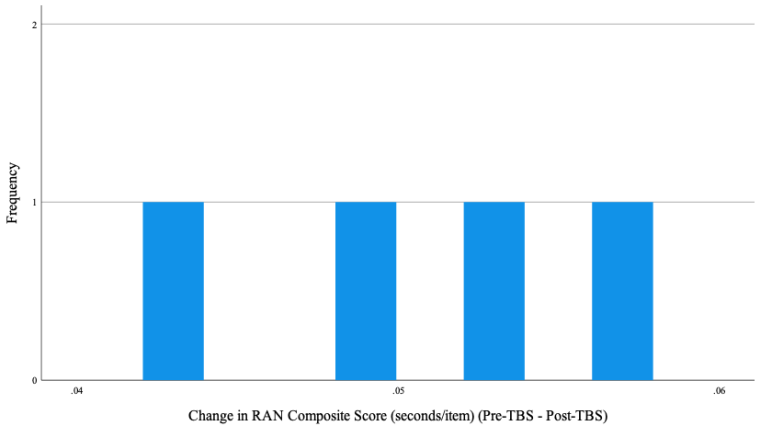
Figure G.9.a-G.9.c. Histograms of RAN Composite Scores for Participants Receiving SMG Stimulation



G.9.a. Pre-TBS RAN Composite Scores for Participants Receiving SMG Stimulation

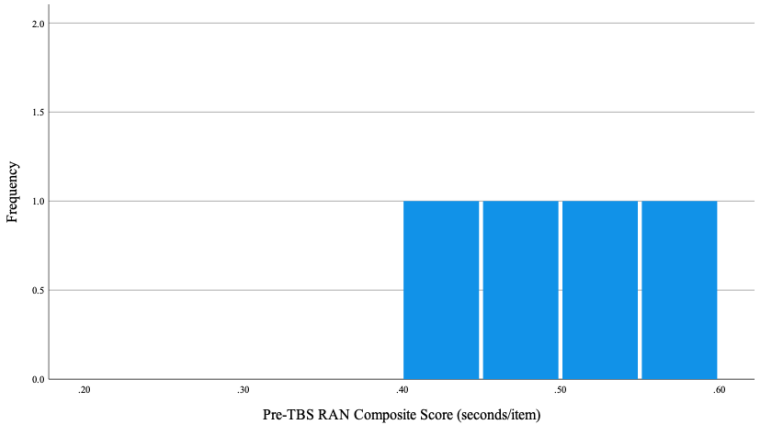


G.9.b. Post-TBS RAN Composite Scores for Participants Receiving SMG Stimulation

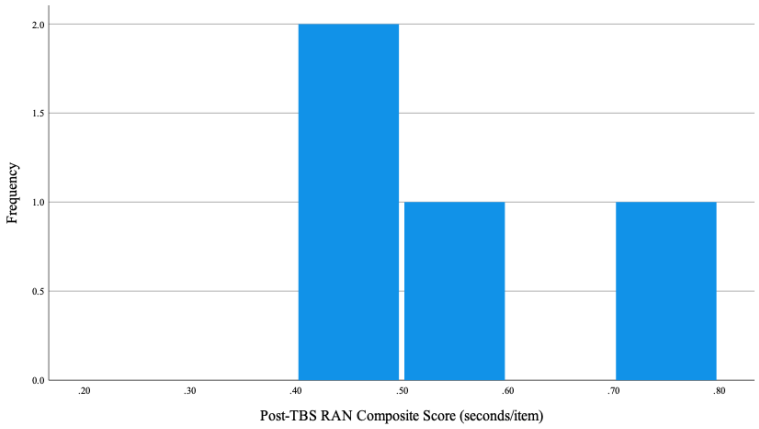


G.9.c. Pre-Post TBS Change in RAN Composite Scores for Participants Receiving SMG Stimulation

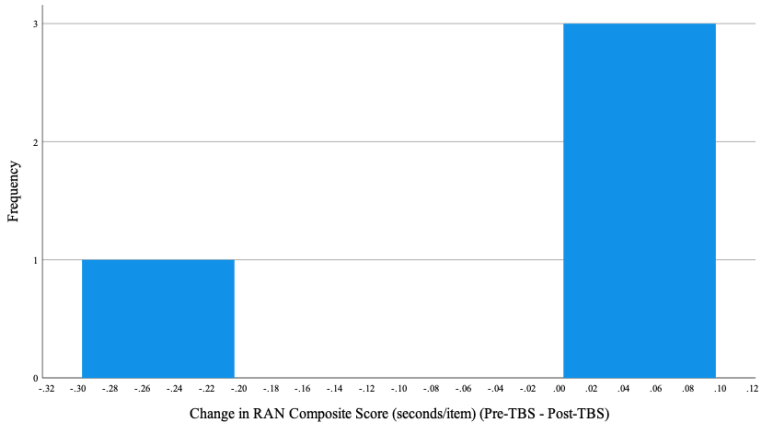
Figure G.10.a-G.10.c. Histograms of RAN Composite Scores for Participants Receiving MTG Stimulation



G.10.a. Pre-TBS RAN Composite Scores for Participants Receiving MTG Stimulation

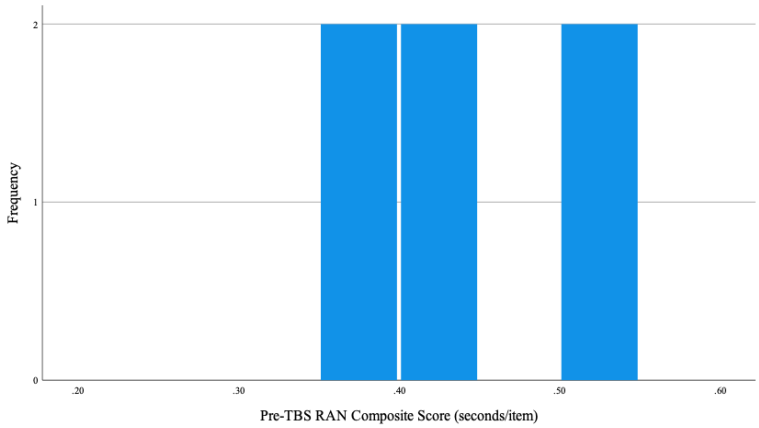


G.10.b. Post-TBS RAN Composite Scores for Participants Receiving MTG Stimulation

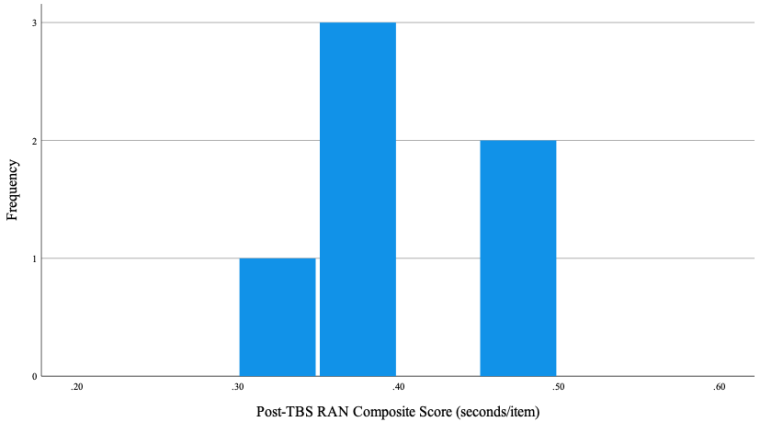


G.10.c. Pre-Post TBS Change in RAN Composite Scores for Participants Receiving MTG Stimulation

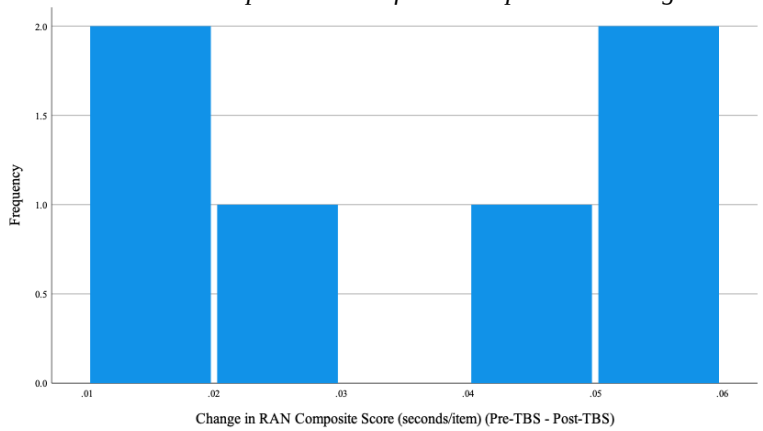
Figure G.11.a-G.11.c. Histograms of RAN Composite Scores for Participants Receiving Vertex Stimulation



G.11.a. Pre-TBS RAN Composite Scores for Participants Receiving Vertex Stimulation



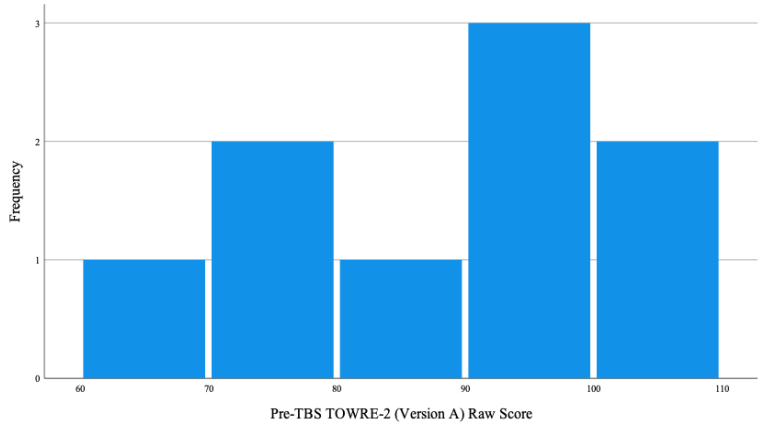
G.11.b. Post-TBS RAN Composite Scores for Participants Receiving Vertex Stimulation



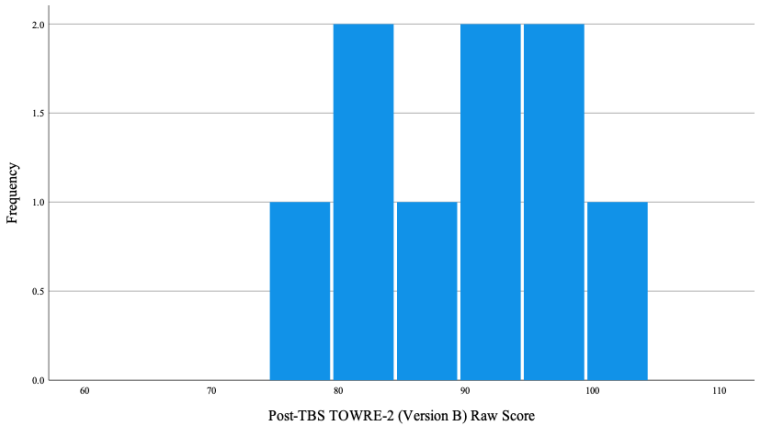
G.11.c. Pre-Post TBS Change in RAN Composite Scores for Participants Receiving Vertex Stimulation

Figures G.12.a-G.14.c. TOWRE SWE Raw Scores Distributions for Each Stimulation Group

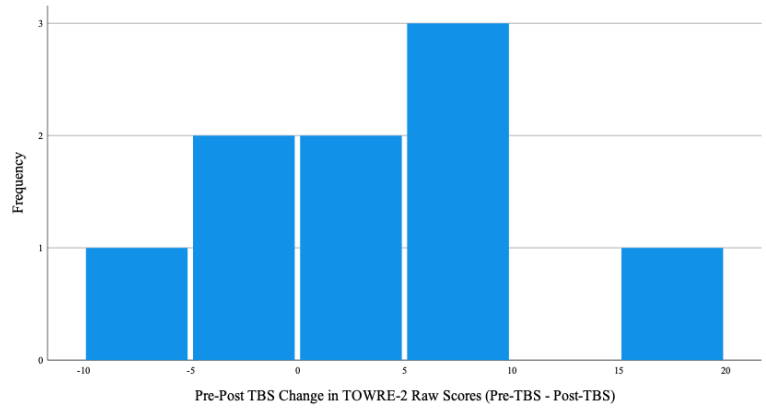
Figure G.12.a-G.12.c. Histograms of TOWRE SWE Scores for Participants Receiving SMG Stimulation



G.12.a. Pre-TBS TOWRE SWE (Version A) Raw Scores for Participants Receiving SMG Stimulation

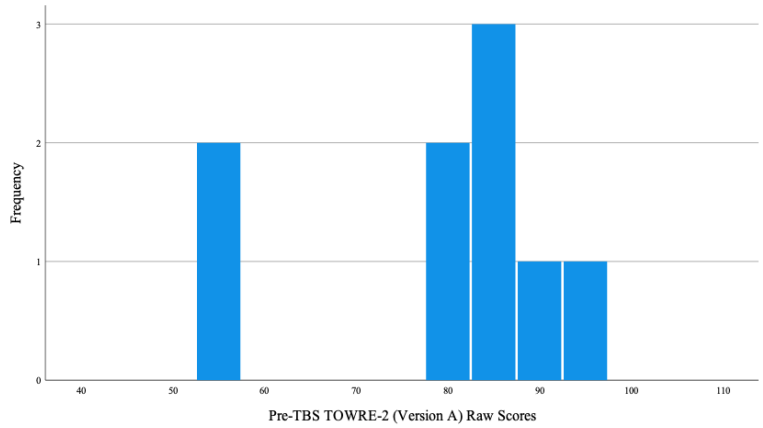


G.12.b. Post-TBS TOWRE SWE (Version B) Raw Scores for Participants Receiving SMG Stimulation

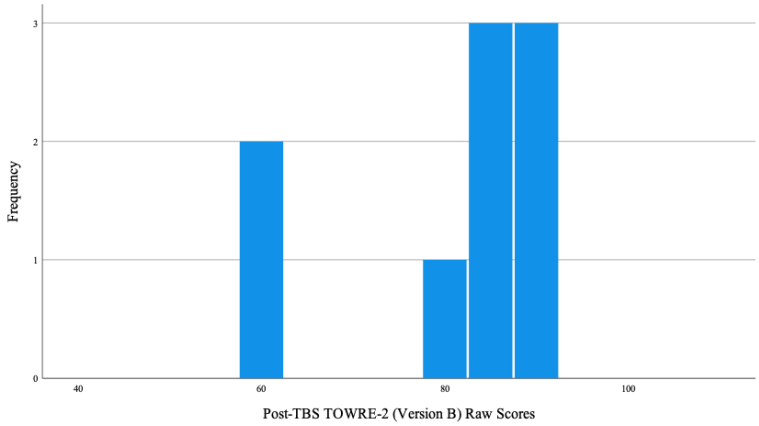


G.12.c. Pre-Post TBS Change in TOWRE SWE Raw Scores for Participants Receiving SMG Stimulation

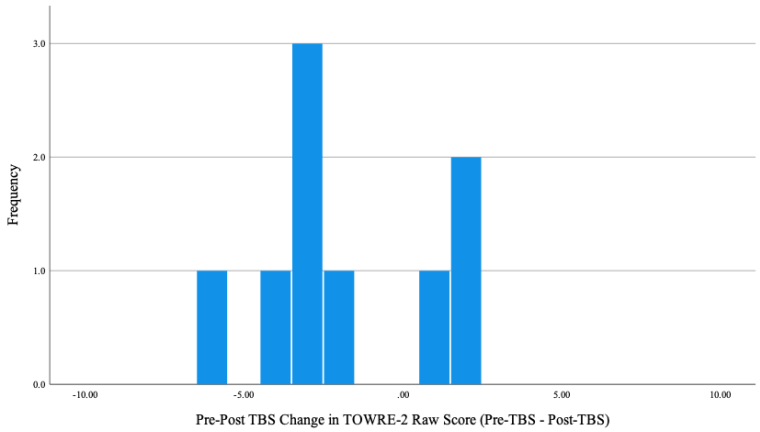
Figure G.13.a-G.13.c. Histograms of TOWRE SWE Scores for Participants Receiving MTG Stimulation



G.13.a. Pre-TBS TOWRE SWE (Version A) Raw Scores for Participants Receiving MTG Stimulation

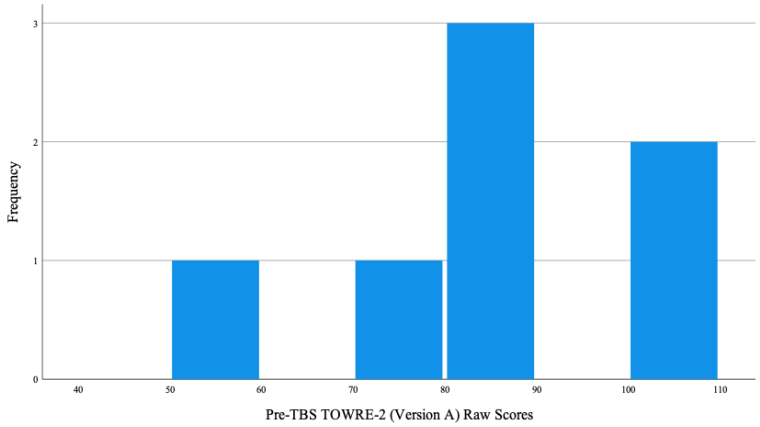


G.13.b. Post-TBS TOWRE SWE (Version B) Raw Scores for Participants Receiving MTG Stimulation

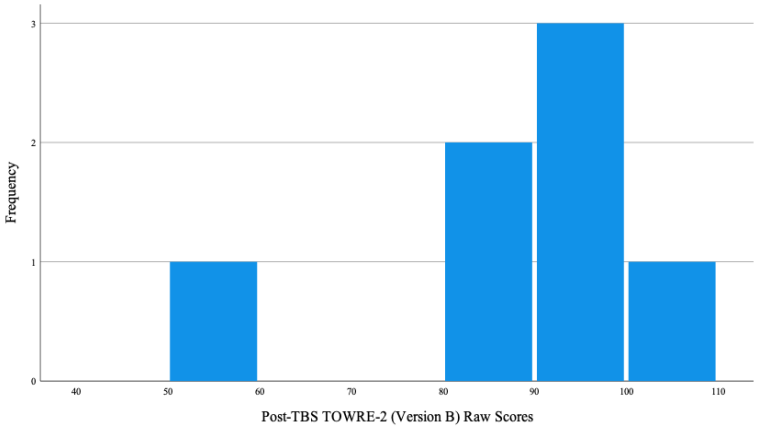


G.13.c. Pre-Post TBS Change in TOWRE SWE Raw Scores for Participants Receiving MTG Stimulation

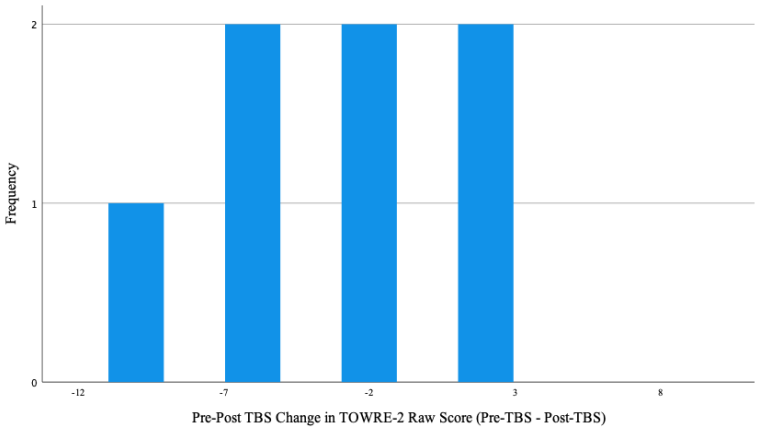
Figure G.14.a-G.14.c. Histograms of TOWRE-2 Scores for Participants Receiving Vertex Stimulation



G.14.a. Pre-TBS TOWRE SWE (Version A) Raw Scores for Participants Receiving Vertex Stimulation

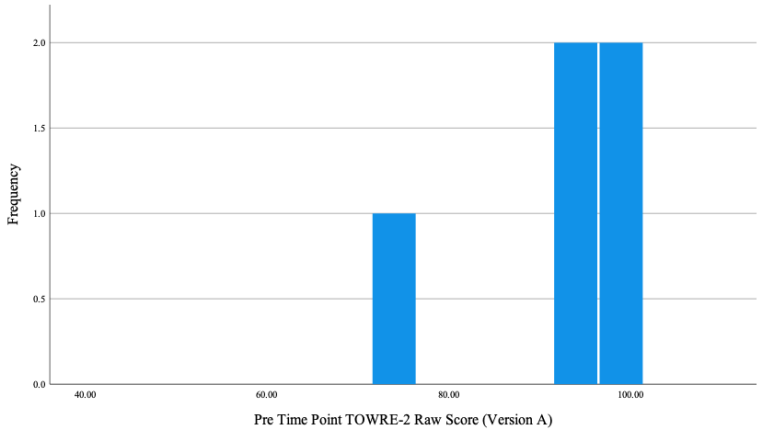


G.14.b. Post-TBS TOWRE SWE (Version B) Raw Scores for Participants Receiving Vertex Stimulation

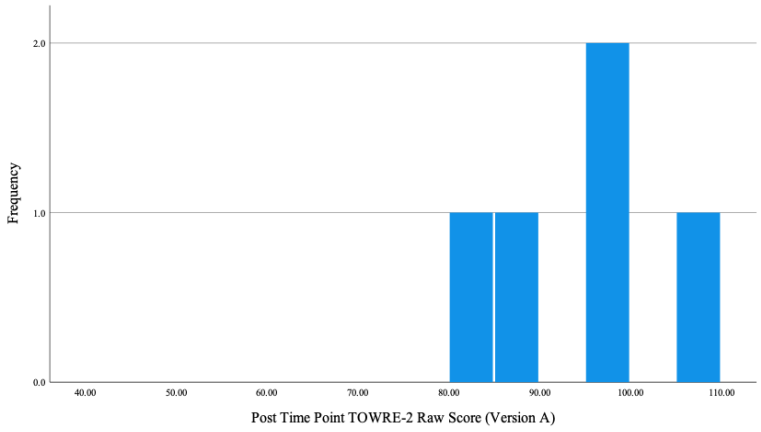


G.14.c. Pre-Post TBS Change in TOWRE SWE Raw Scores for Participants Receiving Vertex Stimulation

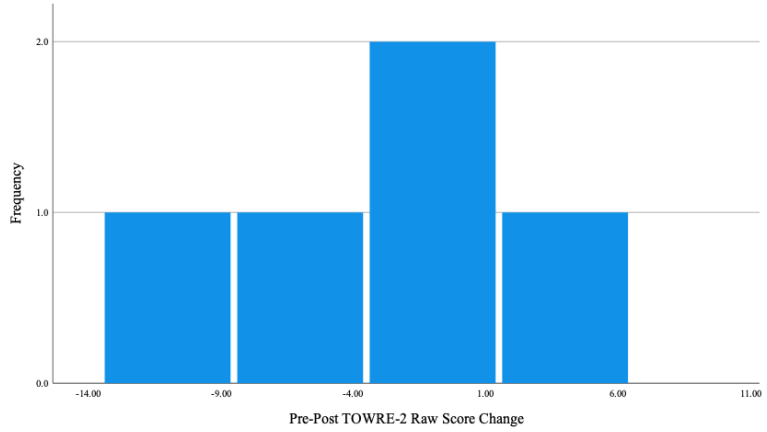
Figure G.15.a-G.15.c. Histograms of TOWRE SWE Scores for No-Stimulation Control Group



G.15.a. Time Point 1 TOWRE SWE Raw Score for No-Stimulation Control Group



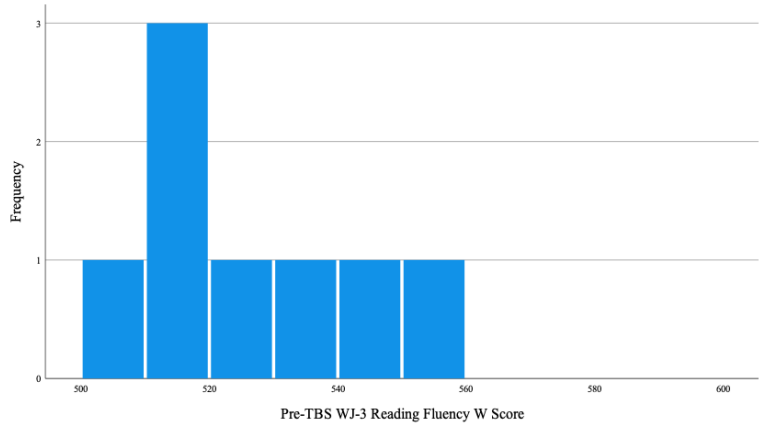
G.15.b. Time Point 2 TOWRE SWE Raw Score for No-Stimulation Control Group



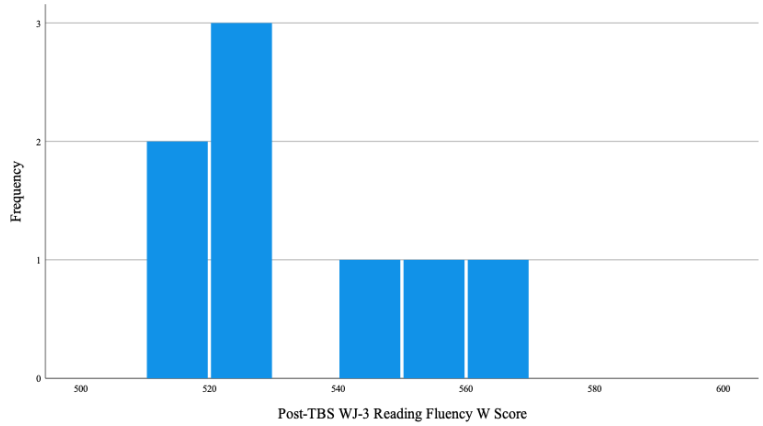
G.15.c. Time Point 1 – Time Point 2 TOWRE SWE Raw Score for No-Stimulation Control Group

Figures G.16.a-G.18.c. WJ-3 Reading Fluency (RF) Distributions for Each Stimulation Group

Figure G.16.a-G.16.c. Histograms of WJ-3 RF W Scores for Participants Receiving SMG Stimulation



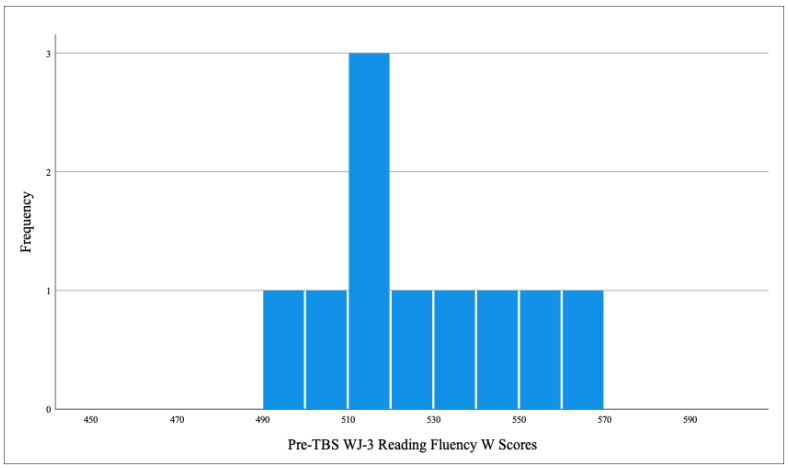
G.16.a. Pre-TBS WJ-3 RF W Scores for Participants Receiving SMG Stimulation



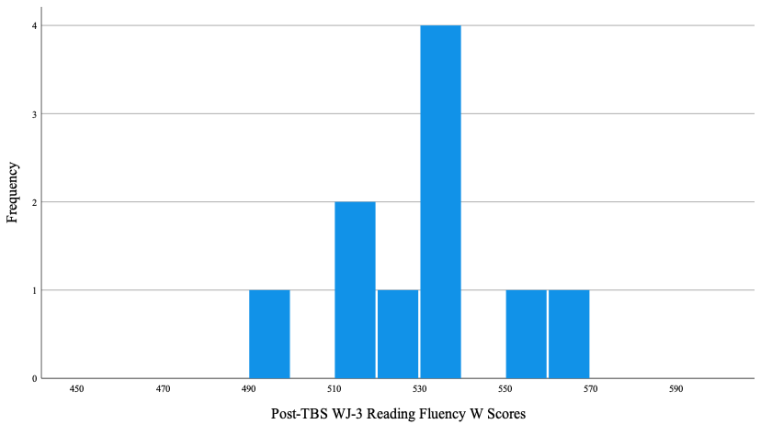
G.16.b. Post-TBS WJ-3 RF W Scores for Participants Receiving SMG Stimulation

G.16.c. Pre-Post TBS WJ-3 RF W Score Change for Participants Receiving SMG Stimulation

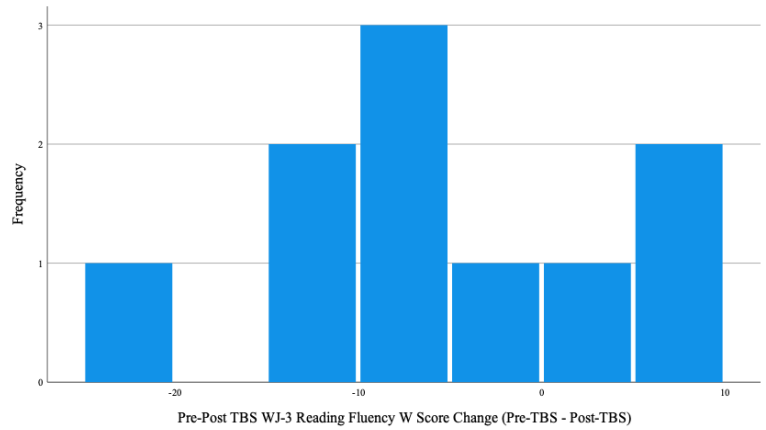
Figure G.17.a-G.17.c. Histograms of WJ-3 Reading Fluency (RF) W Scores for Participants Receiving MTG Stimulation



G.17.a. Pre-TBS WJ-3 RF W Scores for Participants Receiving MTG Stimulation

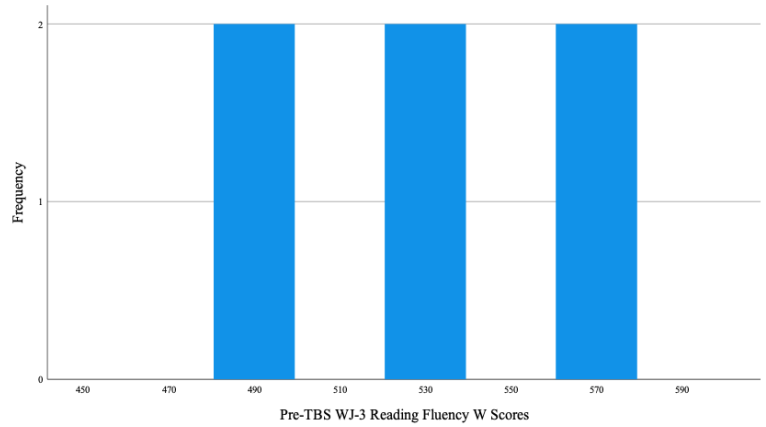


G.17.b. Post-TBS WJ-3 RF W Scores for Participants Receiving MTG Stimulation

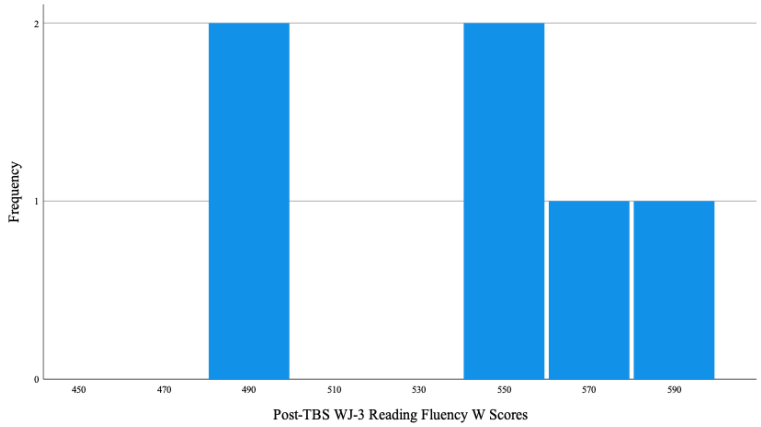


G.17.c. Pre-Post TBS WJ-3 RF W Score Change for Participants Receiving MTG Stimulation

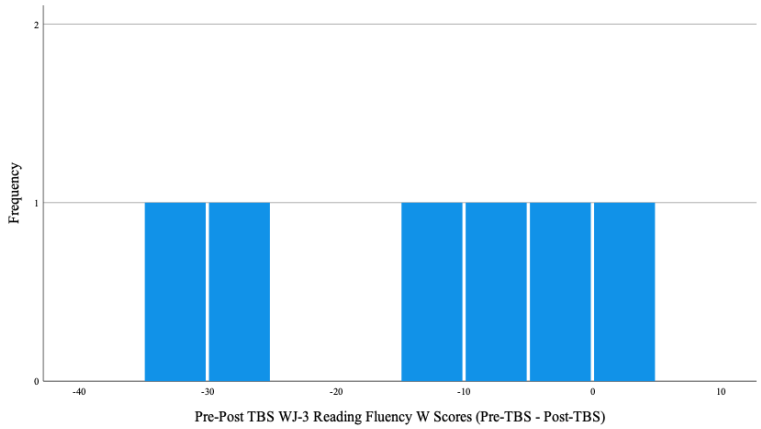
Figure G.18.a-G.18.c. Histograms of WJ-3 Reading Fluency (RF) W Scores for Participants Receiving Vertex Stimulation



G.18.a. Pre-TBS WJ-3 RF W Scores for Participants Receiving Vertex Stimulation



G.18.b. Post-TBS WJ-3 RF W Scores for Participants Receiving Vertex Stimulation



G.18.c. Pre-Post TBS WJ-3 RF W Score Change for Participants Receiving Vertex Stimulation