Pairing Reading Treatment with Transcranial Direct Current Stimulation for Adults with Aphasia

by

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Abstract

Background. Damage to language areas of the brain often leads to a language disorder called aphasia, which impairs speech, writing, and understanding. Sixty-eight per cent of people with aphasia (PWA) also present with alexia, a reading impairment. There is an urgent need for efficacious therapies to remediate reading disorders as the ability to read independently is essential for life participation. Many existing reading treatments target single word reading and demonstrate little generalization to larger bodies of text. In contrast, multimodal reading therapies targeting different reading skills have resulted in functional treatment gains.

Recently, Transcranial Direct Current Stimulation (tDCS) has been explored as a potential adjunct to augment outcomes of traditional language treatment. tDCS modulates ongoing neural activity to prime the brain for long-term consolidation. Extensive research demonstrates the positive effects of tDCS on the spoken language treatments. However, there remains insufficient investigation on the effects of pairing tDCS with reading treatments.

This study explored the effects of tDCS paired with two multimodal intensive reading treatments with four individuals with alexia. In addition to behavioural outcome measures, eyetracking was also used as a real-time measure of cognitive mechanisms during reading, to provide further insight into treatment induced changes.

Methods. Two treatments were delivered within the present study. In Treatment 1, a reading fluency and phonological treatment (RF+PT) was delivered to two participants (P1 and P2) with chronic mild-moderate alexia, and impaired sublexical skills. In Treatment 2, a reading fluency and reading comprehension treatment (RF+RC) was delivered to another two individuals

(P3 and P4) with chronic mild alexia and intact sublexical skills. In a double-blinded, crossover design, all participants received 40 hours of reading treatment (2 hrs/day x 5 days/week x2 weeks = 20 hours for each phase with 4 week washout between phases = 40 hrs of treatment total), in conjunction with active anodal-tDCS (a-tDCS) and sham-tDCS (s-tDCS).

Individual's sublexical skills, reading fluency and reading comprehension were assessed before and after each treatment phase to determine if there were treatment gains. As well, eye-movement measures of dwell time, fixation count and regressions were taken during silent reading. Participants read passages with congruent or incongruent antecedents and anaphors. Treatment induced changes were determined by repeated measures ANOVA, treatment effect sizes (Cohen's *d*), and McNemar's Chi Square.

Results. Participants who received RF+PT treatment (P1 & P2) made gains in sublexical skills. Treatment with RF+PT and a-tDCS coincided with greater gains in reading comprehension in P1; P2 demonstrated limited behavioral and eye movement changes after treatment, regardless of tDCS condition. Following RF+RC treatment, greater gains in reading comprehension occurred in the first phase of treatment for both P3 and P4. A-tDCS with either treatment type did not appear to result in significant increases in sublexical skills or reading fluency of connected text. Across participants, there was generally a decrease in single word reading speed after treatment with a-tDCS relative to treatment alone.

In 3 participants, a-tDCS led to more changes in their eye movements when reading inconsistent passages, specifically in their dwell time and fixation counts. These larger shifts in dwell time and/or fixation count when reading inconsistent passages, tended to coincide with

gains in reading comprehension. However, gains in reading comprehension were not observed when there were changes in regressions as well.

Conclusion. The improvements in reading skills demonstrate that an RF+PT approach is effective for individuals with mild-moderate alexia and improving sublexical skills. The lack of behavioural and eye movement gains in P2 suggests that impaired and/or non-improving sublexical skills may hinder subsequent gains in reading fluency and comprehension. The pattern of results in P1 and P2 also provides evidence that a-tDCS promotes further gains in areas that were already improving.

Gains in reading comprehension in the first phase of RF+RC show that individuals with mild alexia respond optimally to the first 20 hours of treatment, regardless of tDCS condition. In these individuals, there may be limited treatment gains with ongoing treatment and/or with a-tDCS.

Preliminary eye-movement changes and corresponding reading comprehension gains suggest the mechanism underlying gains in reading comprehension may be treatment-induced modifications in dwell time and fixation count with minimal changes in regressions when encountering comprehension breakdowns. This study provides support for the use of multimodal reading therapies for individuals with mild and mild-moderate alexia. As well, the study corroborates growing evidence for the use of tDCS in conjunction with speech-language treatment for PWA.

Preface

This thesis is an original work by Grace Lee. The research project, of which this thesis is a part, received research ethics approval from the University of Alberta Research Ethics Board, Project Name "Combining tDCS with Reading Treatment for Individuals with Aphasia" Pro00064150, May 26, 2016.

This thesis may be modified for publication in a peer-reviewed journal. My role in this project was the development of the project idea, stimulus development, data collection, treatment delivery, data analysis and interpretation, and I will be involved in the writing of the manuscript along with E. Kim. The eyetracking stimulus created and used was based on the stimuli reported in Rayner, Chace, Slattery, & Ashby, 2006. There were other contributors to this project as well. C. Wilson assisted with data collection and treatment delivery. M. Figeys assisted with randomizing treatment conditions and programming the transcranial direct current stimulation equipment. R. Khaledan assisted with data collection and processing. E. Kim was the supervising author, assisted with the development of the project and edited the manuscript.

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The other students in the Aphasia Research Lab also played a crucial role in the completion of my project. Carlee Wilson was always willing to step in on days where I was unavailable to deliver the treatment sessions. Without her help, I would not have been able to adhere to the schedule of my treatment protocol. Roujan Khaledan assisted me with managing and processing the large amounts of data. Mat Figeys always ensured we had enough tDCS supplies and programmed the stimulation conditions on the tDCS device. Without their valuable contributions, I would not have been able to complete the project.

I would like to show appreciation for the contributions the Faculty of Rehabilitation Medicine and my professors have made towards my journey in becoming a Speech Language

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List of Abbreviations

a-tDCS: anodal transcranial direct current stimulation

ARCS: Attentive Reading and Constrained Summarization (a reading comprehension treatment approach)

MOR: Multiple Oral Rereading (a reading fluency treatment approach)

ORLA: Oral Reading for Language in Aphasia (a reading fluency treatment approach)

Phase 1: treatment phase 1 (i.e., the treatment block received first)

Phase 2: treatment phase 2 (i.e., the treatment block received second)

PWA: People with aphasia

RF+PT: Reading fluency and phonological treatment

RF+RC: Reading fluency and reading comprehension treatment

s-tDCS: sham transcranial direct current stimulation

tDCS: transcranial direct current stimulation

Assessments

ABRS: Arizona Battery of Reading and Spelling

CVC Reading: Consonant vowel consonant nonword reading

CVC Spelling: Consonant vowel consonant nonword spelling

DIBELS: Dynamic Indicators of Basic Early Literacy Skills

MAZE-CBM: Curriculum-Based Measurements of Maze Reading

SRA: Scientific Research Associates

Outcome Measures

Dfp/100w: deviations from print per 100 words (reading accuracy)

WPM: words per minute (reading rate)

Glossary of Terms

Eyetracking measures

Consistent: condition of a passage where the target anaphor is congruent with the preceding antecedent.

e.g., "Allison decided to order some **carrot** sticks to snack on. The waiter brought her some water and **carrot** sticks after only a few minutes. Alison enjoyed the rest of her meal, chatting with her friend. Once they finished their meal, they paid their bill."

Inconsistent: condition of a passage where the target anaphor is incongruent with the preceding antecedent.

e.g., "Allison decided to order some **carrot** sticks to snack on. The waiter brought her some water and **celery** sticks after only a few minutes. Alison enjoyed the rest of her meal, chatting with her friend. Once they finished their meal, they paid their bill."

Consistency Effect: an inferred measure of the participant's comprehension; specifically, it quantifies their ability to discriminate and respond to consistent passages compared to inconsistent passages. In this study, the consistency effect is characterized by the *difference* in eye-movement measures (i.e., dwell time, fixation count, number of regressions) made when reading *consistent passages relative to inconsistent passages*.

Efficiency: the ease of reading and the individual's reading fluency; characterized by the participant's dwell time, fixation count and the number of regressions they make as they read *consistent* passages.

Introduction

Damage to the language areas of the brain can result in a communication disorder called *aphasia*. People with aphasia (PWA) experience a combination of deficits in speaking, comprehension and writing, with varying degrees of severity. Often the language regions required for reading are damaged as well (Beeson & Insalaco, 1998). Approximately 2/3 of PWA are estimated to also have *alexia*, the loss of the ability to read with proficiency (Brookshire, Wilson, Nadeau, Gonzalez Rothi, & Kendall, 2014). The ability to read independently is essential for navigating and functioning in daily life. In addition to the text heavy environment in modern society, the increasing prevalence of electronic communication channels (e.g., email, texting, websites) presents significant barriers to participation and activity for individuals with alexia. Reading impairments are devastating and impact quality of life for many PWA. Thus, there is an urgent need for efficacious therapies to maximize the functioning for individuals with alexia.

Reading is a complex process, requiring the integration of visual, phonological and semantic representations (Beeson, Rising, & Rapcsak, 2007), as depicted in Figure 1. Models of single word reading describe the process in which readers must first recognize and decode the orthographic representations of the words they are seeing, then retrieve the corresponding meaning from their mental lexicon (Ellis, 1993; Hillis & Caramazza, 1992). The dual route model of reading delineates the contributes of both the lexical-semantic and the sublexical route in skilled oral single word reading (Coltheart et al., 2001). The sublexical route (depicted by "b" in Figure 1) is engaged when readers encounter unfamiliar or novel words that are not yet established in their lexicon. The letters or graphemes in the word are "sounded" out, segmented and blended, using grapheme-to-phoneme conversion mechanisms. The sublexical route is known as the *indirect* reading route because the semantic representations of words are not accessed directly from the word forms. Sublexical reading strategies require intact phonemic awareness, which involves skills such as letter to sound correspondence and how sounds can be combined. On the other hand, familiar words and irregular words that do not have direct orthography to sound representations (e.g., yacht) are read using the lexical-semantic route. Through this *direct* reading route, the visual word form activates the corresponding representations in the lexicon and meaning is accessed directly (depicted by the main vertical sequence in Figure 1). The lexical-semantic route is also known as the "whole-word" reading route, as words are recognized and understood immediately without being "sounded out". However, the dual route model of reading is limited to single word oral reading and does not fully describe how longer paragraphs are read and subsequently comprehended.

To understand how connected text is read, models of text-level reading comprehension must also be considered. There has been robust research completed in the developmental reading literature on the components required for reading comprehension. In Chall's Stages of Reading Development, children who are first learning to read, devote most of their attentional resources to decoding via the sublexical route. As they become more proficient, they automate the decoding process. The automaticity results in increased availability of cognitive resources to be direct towards reading comprehension. This allows the reader to "read to learn" rather than focusing on "learning to read" as in the earlier stages. Later stages of reading development involve "reading for ideas" and "critical reading" (Chall, 1983; Paul & Norbury, 2012). In the Simple View of Reading model, reading comprehension is described as the product of the ability to decode the text and to understand what has been decoded (i.e., reading comprehension = decoding*understanding of decoded text) (Gough & Tumner, 1986). Reading comprehension may be weakened if there are impairments in either decoding or understanding as skilled reading comprehension requires the contribution of both skills.

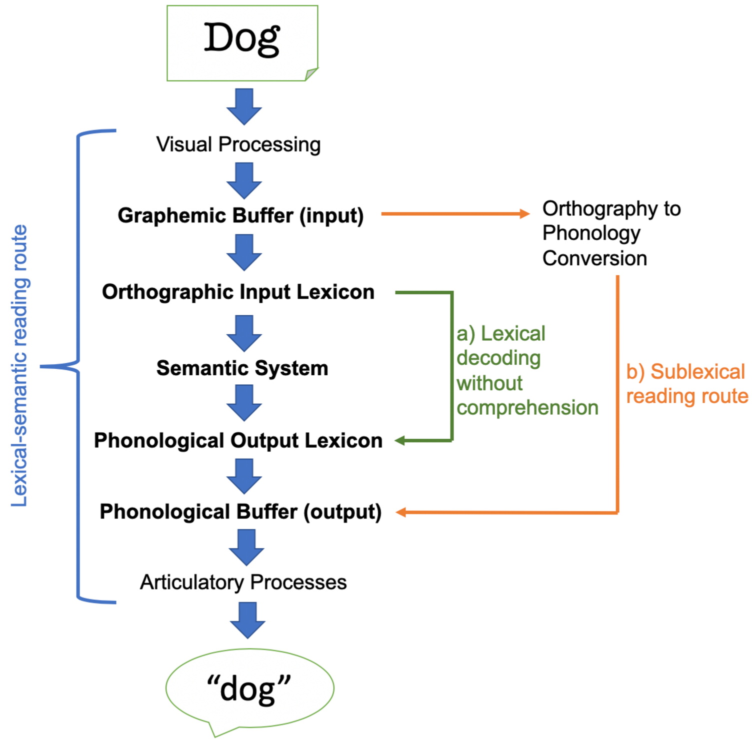
There are parallels between developing readers and those with acquired reading impairments. Some impairments in reading comprehension in adults with alexia have also been attributed to poor reading fluency. It is postulated that when these readers use the majority of their cognitive resources for decoding, it results in limited cognitive resources to then devote towards comprehension (Cherney, 2004). The relationship between single word sublexical and lexical-semantic reading, text-level reading fluency and reading comprehension could also be described as a continuum (see Figure 3). In the reading skills continuum, proficient single word sublexical decoding is required to establish word forms for increasingly automatic single word reading via the lexical-semantic route. Increased automatic single word reading then facilitates faster and more accurate text level reading. Higher reading fluency is a precursor to reading comprehension in PWA (Cherney, 2004), as reading with more ease and automaticity results in more cognitive resources being available to be directed towards reading comprehension. On this continuum, if individuals with acquired reading impairments have impairments in precursory skills, such as sublexical skills, their reading comprehension will likely be more impaired.

Acquired Alexia

Most individuals formulate and process language predominately in the left hemisphere of the brain. Thus, damage to the left hemisphere often results in aphasia when the neural networks required for reading, writing and linguistic processing are affected. Different regions of the brain are known to be associated with varying components involved with reading comprehension (Beeson et al., 2007). For example, phonological processing is commonly associated with the perisylvian regions of the brain (Rapcsak et al., 2009), while semantic knowledge is typically associated with the extrasylvian regions of the brain (Binder, Desai, Graves, & Conant, 2009; Price et al., 2003). Thus, depending on the extent and location of the injury, different components of the reading pathway can be affected, resulting in different profiles of alexia (Beeson et al., 2007; Cherney, 2004). Impaired access to linguistic processing can cause impairments in the ability to decode or to understand text, resulting in the inability to read. In the following paragraphs, a brief description of acquired alexia subtypes will be described. These subtypes are based on the cognitive model of single word reading described by Ellis (1993) and Hillis and Caramazza (1992).

Figure 1. Model of cognitive processing for single-word reading (adapted from Ellis, 1993; Hillis & Caramazza, 1992; Beeson & Insalaco, 1998).

The lexical-semantic reading route is shown by the vertical sequence; Path (a) reflects lexical decoding without comprehension; Path (b) is the sublexical reading route.



Damage to the sublexical route (depicted by "b" in Figure 1) can result in *phonological alexia*. These individuals lack phonological awareness and are unable to use grapheme-to-phoneme conversion mechanisms to "sound out" unfamiliar, low frequency, or nonwords. However, they can read familiar and high frequency words and access meaning through their intact lexical-semantic route. Further testing of individuals with phonological alexia, reveals frequency, word class, and imageability effects (Papathanasiou & Coppens, 2017). High frequency words are read with more accuracy than low frequency, content words read better than functors, and concrete words are easier than abstract words. There are often lexicalization errors, where nonwords are read as similar real words (e.g., "glip" read as "flip") or visual errors, where another word with similar orthography is read instead (e.g., "debt" read as "debit"). Individuals with phonological alexia often recognize their own spelling errors, but may be unable to use phonologically-based strategies to correct their mistakes (Papathanasiou & Coppens, 2017).

Damage to the lexical-semantic route (depicted by "a" in Figure 1) can result in *surface alexia*. Individuals with surface alexia are unable to recognize words as their whole orthographic units and access meaning directly. Instead of reading with ease and efficiency, they read by evaluating each grapheme through their intact sublexical route. They can read aloud nonwords and even access the meaning of regular words through the indirect route. Lexical-semantic impairments are most apparent when reading irregular words (i.e., words whose orthography does not correspond to the pronunciation such as *rough* or *vague*). The lexicon of skilled adult readers contains the pronunciation of irregular words, in addition to their semantics (Papathanasiou & Coppens, 2017). Since individuals with surface alexia cannot access the stored pronunciation of irregular words, they rely on grapheme-to-phoneme strategies to "sound out" irregular words, which often result in regularization errors. Their reading and spelling are marked with phonologically plausible reading and spelling errors, and they are often aware of the errors as their semantic system is still intact.

Individuals with damage to both the lexical-semantic and sublexical route present with *deep alexia*. They may be unable to recognize words from their orthographic representations and are also often unable to utilize phonological reading strategies. Characteristically, they make semantic errors where target words are substituted with other words that have related meanings (e.g., "apple" read as "orange") because there is still partial access to the semantic information (Papathanasiou & Coppens, 2017).

Treatments for Acquired Alexia

There are multiple skills required for skilled and efficient reading of connected text. Therefore, reading treatments should be *restitutive*, restoring the abilities of damaged reading pathways, *substitutive* in recruiting and capitalizing on residual/intact neural resources, or *compensatory* by capitalizing on other intact skills. There have been a whole host of reading treatments published in the literature, which can generally be categorized as single word, text-based or multimodal treatment approaches.

Single word treatments. Single word treatments are generally designed to train a pre-determined list of single words that are presented in isolation. Single word approaches can be further classified as whole word reading approaches, targeting the lexical-semantic reading route, or phonological approaches that focus on strengthening the sublexical pathway. Whole-word treatment protocols have been designed for specific categories of words, such as irregular words or words with ambiguous orthographic correspondence (Coltheart & Byng, 1989; Friedman & Robinson, 1991; Moss, Rothi, & Fennell, 1991; Weekes & Coltheart, 1996) or homophones (e.g., "peak" versus "peek") to facilitate comparisons between different orthographic forms and semantic meanings (Friedman, Sample, & Lott, 2002; Hillis, 1993; Moss et al., 1991; Scott & Byng, 1989; Weekes & Coltheart, 1996). Phonological treatment approaches typically train sound-to-letter conversion using key words and nonwords, as a reading strategy or to self-cue (Beeson, Rising, Kim, & Rapcsak, 2010; De Partz, 1986; Friedman & Lott, 1996; Kendall, McNelil, & Small, 1998; Kiran, Thompson, & Hashimoto, 2001; Laine & Niemi, 1990; Mitchum & Berndt, 1991; Nickels, 1992). Phonological treatment also involves increasing phonological awareness skills such as blending, and segmentation (Bowes & Martin, 2007; Brookshire, Conway, Pompon, Oelke, & Kendall, 2014; Conway et al., 1998; Riley & Thompson, 2015; Yampolsky & Waters, 2002).

Text level treatments. Text-based reading treatments utilize connected texts as stimuli, such as newspaper articles of varying difficulties tailored to the client's reading abilities. Connected text provides additional semantic and syntactic cues, hypothesized to facilitate top-down processing, which can lead to increased reading comprehension and scaffold the retraining of lexical-semantic reading. There are text-based approaches targeting reading fluency (speed and accuracy) and other approaches targeting reading comprehension directly. Oral reading approaches such as Oral Reading for Language in Aphasia (ORLA; Cherney, 2010) and Multiple Oral Re-reading (MOR; Moyer, 1979) involve repeated choral and independent readings of passages, engaging the auditory, motor and visual modality as well. ORLA and MOR are examples of text-based approaches capitalizing on increasing reading fluency to indirectly improve reading comprehension. Other text-based reading approaches that target reading comprehension directly include summarization techniques, such as Attentive Reading and Constrained Summarization (ARCS; Rogalski & Edmonds, 2008) and Proposition Identification and Constrained Summarization therapy (PICS; Webster et al., 2013). There have also been reading approaches that utilize general reading strategies, such as mind maps and highlighting key words (Cocks, Pritchard, Cornish, Johnson, & Cruice, 2013) or integrated semantic feature analysis with sublexical training to increase semantic access (Kiran and Viswanatha, 2008).

Although there have been positive results reported in studies utilizing single-word reading treatments, gains are often restricted to trained words, and show poor generalization to connected texts (Cherney, 2004) . Many clients share the personal treatment goal of being able to read larger bodies of text, as functional reading in daily life rarely involves single words presented in isolation (Beeson & Insalaco, 1998). Therefore, reading treatments need to target skills beyond reading single words without context. Reading treatments that facilitate the use of both reading pathways may engender functional reading outcomes.

Multimodal treatments. Recently, there has been a shift towards multimodal reading approaches integrating training at the single word level and reading strategies in connected text (Brown, Hux, & Fairbanks, 2016; Johnson, Ross, & Kiran, 2017). These approaches capitalize on targeting multiple components on the reading skills continuum within the same treatment protocol (see Figure 3 for the reading skills continuum). For instance, the multicomponent treatment outlined by Brown and colleagues involved reading a trained word list, grapheme-to-phoneme conversion practice, repeated and choral reading, modified Anagram and Copy Treatment (ACT) and Copy and Recall Treatment (CART) procedures (Beeson, 1999), and functional reading (Brown et al., 2016). Using a single subject design, their participant, an 86-year-old right-handed female, 5 months post-onset of stroke demonstrated positive gains in letter naming, sublexical decoding abilities, phonological awareness, and functional reading skills after treatment. Prior to treatment the individual had global reading impairments. After treatment, the individual re-established orthographic representations and could read letter-by-letter. In contrast, Johnson and colleagues' multimodal approach to single word reading and writing treatment comprised a comprehensive multimodal approach that resembled a treatment hierarchy. Using the same word, the protocol involved lexical decision tasks, oral reading, repetition, word-picture matching, semantic feature analysis, grapheme-to-phoneme conversion, anagram spelling, phoneme-to-grapheme conversion, oral reading and delayed reading (Johnson et al., 2017).

Treatment resulted in widespread gains in both reading and writing modalities, including trained items and related untrained items. Results from both multicomponent studies demonstrate that there is value in combining multiple treatment approaches that target different skills along the continuum required for reading.

Treatment Intensity

In addition to the specific treatment activities targeting different language modalities, the schedule of treatment delivery can also affect the success of a treatment protocol. There has been a correlation demonstrated between increased treatment intensity and greater treatment induced change (Cherney, Patterson, Raymer, Frymark, & Schooling, 2008; Dignam, Rodriguez, & Copland, 2016; Robey, 1998). Protocols that consisted of two hours or more per week, in comparison to under one and a half hours per week, resulted in larger treatment gains (Bhogal, Teasell, & Speechley, 2003; Robey, 1998). Researchers in neuroscience and clinical stroke rehabilitation posit that intensive treatment schedules reduce deficits and promote the reestablishment of previous associations in chronic aphasia (Dignam et al., 2016; Raymer et al., 2008). Intensive delivery schedules allow for the repetitive and massed learning required for neurological changes, and are therefore more likely to result in maintenance of functional changes (Kleim & Jones, 2008; Raymer et al., 2008). Neurophysiologically, providing treatment at high frequencies within a condensed time frame meets the threshold of stimulation that is proposed to elicit brain-derived neurotrophic factors required for long term potentiation and thus, the recovery of skills (MacLellan et al., 2011). Both multicomponent treatments described above were delivered at relatively standard intensities. The Brown et al., (2016), protocol consisted of 40 hours over months (one to three one-hour sessions per week). Participants in Johnson et al., (2017)'s study received a total of 32 hours of treatment over 2 months (two two-hour sessions per week). Multicomponent treatments delivered at standard intensities have demonstrated treatment gains, but a multicomponent treatment delivered in an intensive manner has yet to be investigated. Given the extant literature on experience-dependent neuroplasticity in chronic aphasia, it is cogent that intensive treatment will result in greater and more sustained behavioural and functional treatment gains.

Transcranial Direct Current Stimulation

Many reading treatments are efficacious in remediating language impairments, however, most yield small effects in comparison to the time investment. There has been recent development in the field of speech and language rehabilitation with the integration of complementary modalities. Non-invasive brain stimulation, such as Transcranial Direct Current Stimulation (tDCS), was first applied to the rehabilitation of motor domains (Nitsche & Paulus, 2000, 2001), and is now being explored with traditional speech and language therapy. tDCS involves applying a weak electrical current (1-2 mA) to the scalp through two saline-soaked surface electrodes. The current is subthreshold, and thus does not generate action potentials, like other stimulation techniques such as transcranial magnetic stimulation (TMS). tDCS modulates ongoing neural activity by altering resting membrane potentials in brain neurons and therefore cortical excitability (Holland & Crinion, 2012). Anodal tDCS (a-tDCS) depolarizes the resting membrane potentials and increases cortical excitability, whereas cathodal (c-tDCS) hyperpolarizes and decreases cortical excitability (Nitsche & Paulus, 2000, 2001). Mediating the action potentials of neurons activated during specific speech and language tasks is postulated to "prime" the brain to induce long-term consolidation (Holland & Crinion, 2012). Pairing traditional speech and language therapy with tDCS could potentially result in increased treatment gains by capitalizing on neuroplasticity.

tDCS has been paired with several types of language treatment. The current understanding is that tDCS can be combined with different behavioural interventions to result in augmented language recovery gains (Galletta, Conner, Vogel-Eyny, & Marangolo, 2016). Researchers have coupled tDCS with single-word naming therapy (Baker, Rorden, & Fridriksson, 2010; Fiori et al., 2011; Flöel et al., 2011; Fridriksson, Richardson, Baker, & Rorden, 2011; Kang, Kim, Sohn, Cohen, & Paik, 2011; Woodhead et al., 2018), spoken language treatment (Marangolo et al., 2013, 2016), and melodic intonation therapy (Vines, Norton, & Schlaug, 2011). However, investigations on the effects of tDCS paired with reading treatment are limited. There has been one case study of tDCS paired with a text-based oral reading therapy (Cherney et al., 2013). Although, the participant in Cherney and colleagues' study made some language gains following treatment paired with tDCS, the study design did not include a control condition. Thus, further research is needed to elucidate the effects of treatment combined with tDCS compared to treatment alone. Given the promising results of Brown et al., (2016) and Johnson et al., (2017)'s, a multicomponent intensive reading protocol that integrates tDCS, may result in the greatest potential for augmented treatment gains and maintenance. Reading is becoming increasingly important for independence in today's digital society, thus, there is an urgent need to improve existing reading therapies for maximal reading rehabilitation for PWA.

Further, exploring the mechanisms underpinning gains after reading treatment will result in a better understanding of the effects of therapy and how to enhance existing reading treatments. Behavioral measures are effective in measuring the accuracy of higher-level reading comprehension. However, they do not reveal an individual's reading process. A more thorough understanding on the actual processing changes underlying behavioral gains can allow for better identification of which treatment techniques are the most effective. This would require investigations that extend beyond behavioral measures into the domain of elucidating underlying cognitive mechanisms.

Eye Movements as an Outcome Measure for Reading Treatment

Eye movements are an outcome measure that can be used to image real-time cognitive processes during reading (Rayner, 1998, 2009). As PWA often have challenges with oral reading and verbal responses, tracking of eye movements serves as useful outcome measure for reading. Eye-movements can also provide a fine-grained measure to examine the minute changes in reading strategy and processing after reading treatment. This methodology involves quantifying the movements of the eye as the individual reads a passage. Three types of eye movements are associated with reading (Rayner, 1998; Rayner et al., 2006). *Saccades* are quick forward eye movements. *Fixations* are intermittent pauses around 200-250ms, in between saccades, where visual processing occurs. *Regressions* are backwards movement to previously read texts. Eyetracking allows the speed of reading to be quantified, but also for the measurement and analysis of eye movement quality to understand changes in movement patterns.

Eye movements during reading are reflective of the proficiency of the reader. In comparison to typical skilled adult readers, children and less proficient readers have longer fixation durations, increased frequency of short saccades and more regressions (Rayner, 1998; Rayner et al., 2006). Typically, farther regressions occur if there is an initial lack of comprehension, and shorter regressions happen if a saccade has advanced too far. Aberrations from typical eye movement patterns results in decreased reading efficiency, which also suggests difficulties in decoding text and comprehension (Ashby, Rayner, & Clifton, 2005; Chace, Rayner, & Well, 2005). Eye movement patterns have been studied extensively in developmental reading disorders but are not as commonly used to investigate individuals with acquired reading disorders. The limited research that exists examining eye movements of PWA, illustrates differences between typical healthy adults and PWA in saccade movements, number of fixations, number of regressions and reading speed (DeDe, 2017; Huck, Thompson, Cruice, & Marshall, 2017; Klingelhofer & Conrad, 1984; Schattka, Radach, & Huber, 2010). In comparison to behavioural reading comprehension measures, eyetracking provides a finer-grained measure of reading comprehension and cognitive processing in real-time (Rayner et al., 2006). Recently, eye movement analyses have been used to elucidate treatment induced changes to underlying reading strategies (Ablinger, Huber, et al., 2014; Kim & Lemke, 2016).

Results of Pilot Study

We have conducted a previous pilot study where preliminary evidence of augmented outcomes was observed when multimodal reading treatment was combined with active tDCS (Lee, Sahadevan, & Kim, 2017). In a cross-over, double-blinded, single subject design, two PWA (PA and PB) received a multimodal reading treatment combining text-based reading fluency treatment (ORLA/MOR) and phonological treatment (see Beeson, Rising, Kim, & Rapcsak, 2010 for protocol) paired with and without tDCS.

Pilot data results are shown in Tables 1 and 2. Although both participants improved after both conditions of therapy, the participants demonstrated slightly greater gains after receiving treatment paired with active tDCS. Specifically, augmented improvements were seen in measures targeting reading fluency and reading comprehension (see Table 1 and Table 2). With active tDCS, participants made greater gains as quantified by overall language functioning (WAB-R) and reading comprehension (MAZE-CBM, GORT-4 comprehension), speed (RCBA-2 time, GORT-4 words per minute, ABRS reaction time) and accuracy (GORT-4 accuracy, ARBS Reading Accuracy). Interestingly, the gains in sublexical measures were comparable between conditions in both participants. The present study builds upon the pilot investigations and provides the opportunity to replicate the study in additional participants with a more rigorous experimental design. Eyetracking methodology was also integrated to better delineate the cognitive processing during reading comprehension, providing more robust insight into treatment effects.

Table 1. Behavioural Outcome Measures from Participant A in Pilot Study.

PA Pre-treatment and Post-treatment Behavioural Measures						
	Phase 1 s- tDCS			Phase 2 a-tDCS		
	Pre	Post	Gain	Pre	Post	Gain
WAB	38.5	40.8	2.3	40.1	45.1*	5
Sublexical						
CVC Nonword Spelling Accuracy *(%)*	32%	62%	30%	40%	62%	22%
CVC Nonwords Reading Accuracy (%)	83%	83%	0%	80%	82%	2%
Sound-Letter Probes (%)	70%	90%	20%	80%	100%	20%
Reading Fluency – Word Level						
ABRS Spelling Accuracy *(%)*	70%	75%*	5%	78%	87%*	9%
Reading Fluency – Text Level						
RCBA-2 (mins:sec)	19:15	21:43	2:28	22:28	22:36	0:08
Reading Comprehension						
Multiple Choice Questions Accuracy (%)	71%	79%	9%	71%	95%	24%
MAZE-CBM Accuracy (%)	N/A	N/A		76%	75%	1%
RCBA-2	76%	87%*	11%	87%	87%	0

* $p < 0.025$; WAB-R = Western Aphasia Battery Revised; RCBA-2 = Reading Comprehension Battery for Aphasia 2nd Edition; GORT-4 = Gray Oral Reading Test 4th Edition; ABRS = Arizona Battery for Reading and Spelling.
Note: Shading indicates when active (anodal) tDCS was paired with treatment

Table 2. Behavioural Outcome Measures from Participant B in Pilot Study.

PB Pre-treatment and Post-treatment Behavioural Measures						
	Phase 1 s- tDCS			Phase 2 a-tDCS		
	Pre	Post	Gain	Pre	Post	Gain
WAB-R	77	80	2	78.6	80.9	2.3
Sublexical						
CVC Nonword Spelling Accuracy *(%)*	53%	50%	-3%	42%	48%	6%
CVC Nonwords Reading Accuracy (%)	62%	57%	-5%	42%	48%	6%
Reading Fluency – Word Level						
ABRS Reading Accuracy (%*)*	76%	84%*	8%	84%	90%*	6%
ABRS Reading Reaction Time (ms)	696.79	570.15*	-126.64	660.62	759.48	98.86
Reading Fluency – Text Level						
Accuracy (deviations from print per 100 words)	20.18	14.825	-5.36	16.82	14.952	-1.87
Rate (Words per minute)	32.58	38.575	2.99	46.58	44.92	-1.66
RCBA-2 (time)	21:50	15:15	-6:35	12:48	13:51	1:3
Reading Comprehension						
Multiple Choice Questions Accuracy (%)	70%	75%	5%	88%	80%	-8%
MAZE-CBM Accuracy (%)	60%	67%	7%	64%	66%	2%
RCBA-2	93%	88%*	-5%	92%	94%	2%

* $p < 0.025$; WAB-R = Western Aphasia Battery Revised; RCBA-2 = Reading Comprehension Battery for Aphasia 2nd Edition; GORT-4 = Gray Oral Reading Test 4th Edition; ABRS = Arizona Battery for Reading and Spelling
Note: Shading indicates when active (anodal) tDCS was paired with treatment

Purpose of Study

The purpose of the current study was to examine the effects of tDCS coupled with multicomponent reading treatments for PWA with concomitant alexia. The secondary purpose was to examine treatment induced changes in the eye movements in relation to reading therapy itself and therapy in conjunction with tDCS. Integrating eye movement analyses allows for greater understanding of the cognitive mechanisms underlying behavioral treatment changes when reading treatment is paired with non-invasive brain stimulation.

The present study consisted of two treatments. The first treatment was a replication of the treatment protocol described in the pilot project above. In the first treatment (RF+PT), two participants (P1, P2) received a text-based reading fluency treatment (ORLA and MOR) and a phonological treatment approach designed to improve sublexical reading skills. In the second treatment (RF+RC), two additional participants (P3, P4) received a different multimodal reading treatment for individuals with higher reading abilities, namely, a reading fluency treatment (MOR) combined with a reading comprehension (ARCS) and reading strategies (e.g., mind maps) approach.

Research Question and Hypothesis

The following two research questions will be applied to both treatments.

Research Question 1. Do individuals with aphasia/alexia demonstrate augmented treatment results in reading comprehension and reading fluency when treatment is coupled with active-tDCS, relative to treatment alone?

Hypothesis 1. Individuals with aphasia/alexia will demonstrate augmented treatment results in reading comprehension and reading fluency after receiving treatment coupled with active-tDCS, compared to treatment with sham-tDCS. Based on previous findings, there were larger gains in reading speed, comprehension, overall spoken language and spelling after treatment paired with active-tDCS (Lee et al., 2017).

Research Question 2. Does reading treatment paired with active-tDCS result in a larger shift in eye movement patterns during reading, relative to treatment alone?

Hypothesis 2. Participants' eye movements will change more during reading following treatment paired with a-tDCS, relative to treatment alone.

METHODS

Participants

Treatment 1: Reading fluency treatment and phonological treatment approach (RF+PT). Research participation calls were disseminated primarily through the study supervisor's community contacts. Description of the study and treatment were given to community speech language pathologists to share with interested clients. Also, experimenters contacted interested individuals who had participated in other studies conducted by the research lab. Potential participants were then narrowed down based on schedule availability and ability to commit to intensive treatment.

The first treatment (RF+PT) involved two participants who had mild-moderate alexia and aphasia. All participants passed visual, hearing and cognitive screeners. Participants did not have other contraindications to the tDCS and did not receive concurrent speech and language therapy at the same time. Overall, participants were all highly motivated for therapy and home practice.

The *Western Aphasia Battery-Revised* (WAB-R; Kertesz, 2007), was administered to characterize each participant's aphasia and determine their general language comprehension and production. Each participant's equivalent reading grade level was established using assessment results from the *Kaufman Test of Education Achievement* (KETA-3).

P1. P1 was a 48 year old right-handed female, 9 years post onset of stroke. She worked as a paralegal prior to her stroke and had 14 years of education. P1 presented with anomic aphasia (WAB-R Aphasia Quotient (AQ) score = 85.6) and phonological alexia. Her conversational speech was characterized by phonemic and semantic paraphasias and circumlocution, secondary to word finding difficulties and a mild apraxia of speech. Her oral reading had moderate dysfluencies and errors, characterized by hesitations, agrammatical/prosodic pauses, and phonological and semantic paraphasias.

P2. P2 was a 61 year old right-handed male, 3 years post onset of stroke. He worked as an executive for a business prior to his stroke and had 12 years of education. P2 presented with anomic aphasia (WAB-R AQ score = 95.1) characterized by word finding difficulties, semantic paraphasias and imprecise/general spoken language. P2 had deep alexia and had a relatively fast oral reading rate marked by gross and frequent semantic paraphasias and imprecise paraphrasing of the text. Instead of reading each of the words in the text exactly, P2 would often interpret the gist of what the text meant and generate his own version instead, indicating he had relatively preserved ability to derive semantic meaning from what he read. For instance, when the target text for oral reading was “some volcanic eruptions are very quiet”, P2 read “some volcanos erupt very quietly”. At times, P2’s semantic paraphasias led him to an incorrect interpretation of the text, which directly affected his comprehension (e.g., target text for oral reading: “Have you ever contemplated the origin of baseball?”, P2 read “Have you ever encountered the original baseball?”). P2 expressed that spelling was one of his weaknesses. He often appeared to blindly guess when he did not know the spelling and sometimes perseverated on inaccurate attempts.

Table 3. Participant demographics in Treatment 1 (RF+PT).

Participant Demographics		
	P1	P2
Demographics		
Age	48	61
Years post onset of stroke	9	3
Years of Education	14	12
WAB-R AQ	85.6	95.1
Aphasia Type	Anomic	Anomic
Reading Grade	5	10

Treatment 2: Reading fluency and reading comprehension treatment (RF + RC). Treatment 2 also involved two participants. Participants were recruited in the same way as described in Treatment 1. They did not have contraindications to tDCS and did not receive other concurrent speech and language therapy. The two participants who received Treatment 2 presented with a mild aphasia and alexia.

P3. P3 was a 73 year old right-handed male, 3 years post onset of stroke. He worked as a social worker prior to his stroke and had 20 years of education. P3 presented with anomic aphasia (WAB-R AQ score = 95.1) characterized by word finding difficulties, imprecise/general and over-formalized spoken and written language.

P4. P4 was a 63 year old right-handed male, 6 years post onset of stroke. He worked as a firefighter captain prior to his stroke and had 14 years of education. P4 presented with anomic aphasia (WAB-R AQ score = 96.4) characterized by circumlocution secondary to word finding difficulties, and imprecise/general spoken and written language.

Both P3 and P4 had mild alexia. They were able to orally read with high accuracy however, had challenges with conceptualization of main ideas, establishing connections within the text and making inferences.

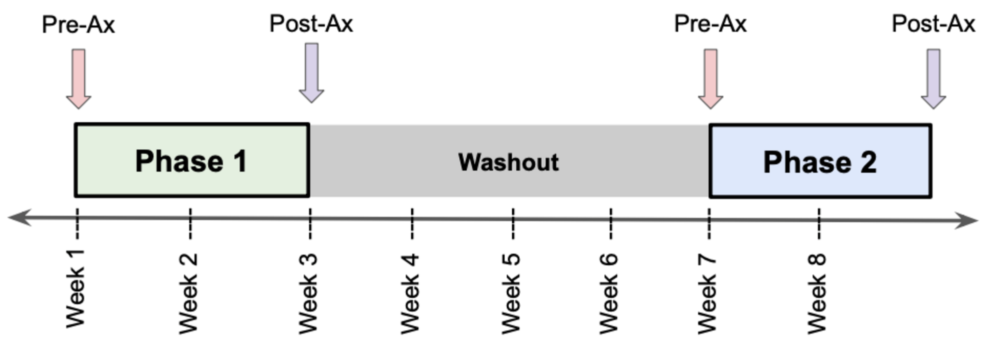
Table 4. Participant demographics in Treatment 2 (RF+RC).

Participant Demographics		
	P3	P4
Demographics		
Age	73	63
Years post onset of stroke	3	6
Years of Education	20	14
WAB-R AQ	95.1	96.4
Aphasia Type	Anomic	Anomic
Reading Grade	12	9

Design

In both treatments, participant served as their own control in a double-blinded cross-over single-subject experimental design. The participants in both treatments received two phases of intensive reading therapy (2h/d x 5 days/week x 2 weeks = 20 hrs. per phase, with a 4 week washout between the two phases = 40 hrs. total; see Figure 2). Although the treatments were designed to be administered over 2 weeks, at times, the treatment period spanned one or two days beyond the 2 weeks due to statuary holidays, and/or scheduling conflicts. Each phase of therapy was coupled with either active (a-tDCS) or sham-tDCS (s-tDCS). The order of tDCS stimulation was randomized and counterbalanced across participants. All participants and experimenters delivering assessment/treatment were blinded to the tDCS condition. Behavioural and eyetracking assessments were employed before and immediately after each treatment phase. Assessment batteries and treatment were primarily delivered by the author of the study. The author's supervisor and another trained speech language pathology student also assisted with assessment and treatment when the study author had scheduling conflicts. Joint sessions between the study author, and the other experimenters were completed in the beginning to ensure treatment and assessment fidelity.

Figure 2. Treatment design denoting each phase, washout period and points of assessment.



Treatment

Transcranial direct current stimulation. Both treatments in the present study included treatment phases paired with active anodal-tDCS (a-tDCS) or sham-tDCS (s-tDCS). In both tDCS conditions, the anodal electrode was placed on the scalp over the occipitotemporal cortex (P3 on the International 10-20 Electroencephalography System), a neural region known to be involved in skilled reading (Price, 2012). The cathodal reference electrode was placed on the contralateral orbitofrontal cortex. A constant current stimulator from HDCstim (Newronika, Italy) delivered 1.5 mA for 20 mins per session via two 5cm x 7 cm sponge electrodes soaked with 8mL of normal (0.9%) saline in the a-tDCS condition. When the impedance was too high for stimulation to occur, an additional 2 mL of saline and 2 mL of conductive electroencephalography gel was added to the electrode to improve contact. Previous studies have demonstrated that sensations from tDCS decrease after the first minute of administration

(Paulus, 2003; Woods et al., 2016). Therefore, to maintain blinding in the control/sham condition (s-tDCS), the stimulator administered 1.5 mA of electrical stimulation, ramping up/down for one minute to ensure the participant experienced the same perceived sensations as a-tDCS.

Treatment 1: Reading fluency and phonological treatment approach (RF+PT).

Reading treatment. Each participant received individualized intensive reading therapy consisting of evidence-based treatments to remediate reading impairments. The multicomponent reading treatment protocol used in Treatment 1 was based on previous pilot research (Lee & Kim, 2017; Lee et al., 2017). Participants received reading fluency treatment combined with a phonological treatment approach.

Reading fluency treatment. One half of each treatment session followed Oral Reading for Language in Aphasia (ORLA; see Cherney 2004 for protocol) procedures using news articles from newsela.com adapted for the participant's reading grade (as determined by pre-treatment KETA-3 assessments). New passages were introduced after participants had completed the steps outlined in the treatment protocol (see Figure 4), rather than training to a criterion. ORLA involves repetitive oral reading of sentences and paragraphs, first in choral fashion and then independently. It is a text-based reading fluency approach that capitalizes on the structure of the text to facilitate lexical-semantic and top-down reading. The repetition of connected text allows for extensive modeling of the natural speech intonations and diverse grammatical structures that assist in increasing oral reading fluency and reading comprehension. Studies by other research groups, in addition to the pilot study, have demonstrated generalized language gains in addition to reading gains after ORLA (Beeson & Insalaco, 1998; Cherney, Merbitz, & Grip, 1986; Lee et al., 2017). Cherney and colleagues reasoned that the repetitive engagement of the auditory receptive domain and the oral expressive domain explained the generalized gains. ORLA is thought to improve oral reading fluency, which allows for more cognitive resources to devote to reading comprehension (Cherney, 2004). Homework involved MOR procedures (Moyer, 1979; Tuomainen & Laine, 1991) to promote reading rate and accuracy. Steps in MOR were distributed between home practice and oral reading within the session (see Figure 4 for outline of treatment protocol).

Phonological treatment. The other half of each treatment session consisted of an evidence-based phonological treatment sequence designed to improve sublexical reading skills (see Beeson, Rising, Kim, & Rapcsak, 2010 for protocol). Phonological awareness as well as letter-sound correspondences were systematically trained using a cueing hierarchy. Other phonemic training tasks (e.g., matching, identification, segmentation of initial and final sounds) were also integrated within the cueing hierarchy to increase phonemic awareness and proficiency in sublexical skills. Improving phonological awareness and orthographic conversion mechanisms provides an additional strategy for decoding and reading unfamiliar words.

tDCS Condition. tDCS order of stimulation was randomized and was coded by another researcher in the lab who had no other participation in the study. The study experimenters who were conducting assessments and delivering treatment, and the participants were blinded to the tDCS condition during the treatment and assessment sessions. P1 received s-tDCS in the first phase and a-tDCS in the second phase. P2 received a-tDCS in the first phase and s-tDCS in the second phase.

Treatment 2: Reading fluency and reading comprehension treatment (RF + RC).

Reading treatment. P3 and P4 both read with high proficiency, however demonstrated comprehension impairments of complex concepts and associations. These participants had less difficulty with sublexical reading and had relatively intact grapheme to phoneme abilities. Therefore, P3 and P4 received reading fluency treatment combined with direct reading comprehension treatment.

Reading fluency and reading comprehension. Reading fluency was targeted with MOR procedures (Moyer, 1979; Tuomainen & Laine, 1991) to promote reading rate and accuracy. Like Treatment 1, new passages were introduced after participants had completed the steps outlined in the treatment protocol (see Figure 5), rather than training to a criterion. These procedures were integrated with Attentive Reading Constraint Summarization-Written (ARCS-W) therapy (Obermeyer & Edmonds, 2018) and other general reading comprehension strategies (Cocks, Pritchard, Cornish, Johnson, & Cruice, 2013). The process of reading and then summarizing in ARCS-W promotes attention and comprehension because participants are required to process the text with the expectation of then generating a summary. ARCS-W also activates word-retrieval and the lexical-semantic pathway because participants are primed to use specific words present in the passages. Other evidence-based general reading comprehension strategies were used such as creating "mind maps" and underlining key words (Cocks et al., 2013). "Mind maps" involve physically drawing the connections and relationships between main ideas and sub-ideas. The strategies were designed to facilitate the organization and integration of information the participants had read to assist with their verbal and written summarizations. At times, other strategies were used, such as covering up text that was not part of the current focus.

tDCS condition. Treatment 2 utilized the same double blinding method as in Treatment 1. P2 received a-tDCS in the first phase and s-tDCS in the second phase. P3 received s-tDCS in the first phase and a-tDCS in the second phase.

Table 5. tDCS conditions for all participants in the present study.

Shaded rows (P1 and P2) participated in Treatment 1 (RF+PT). White rows (P3 and P4) participated in Treatment 2 (RF+RC).

Participant Demographics			
	Phase 1 tDCS	Phase 2 tDCS	Treatment Protocol
Participant			
P1	Sham	Active	(RF+PT) ORLA + MOR + Phonological Treatment Sequence
P2	Active	Sham	(RF+PT) ORLA + MOR + Phonological Treatment Sequence
P3	Active	Sham	(RF+RC) MOR + ARCS-W
P4	Sham	Active	(RF+RC) MOR + ARCS-W

Pre-treatment and Post-treatment Reading Assessment

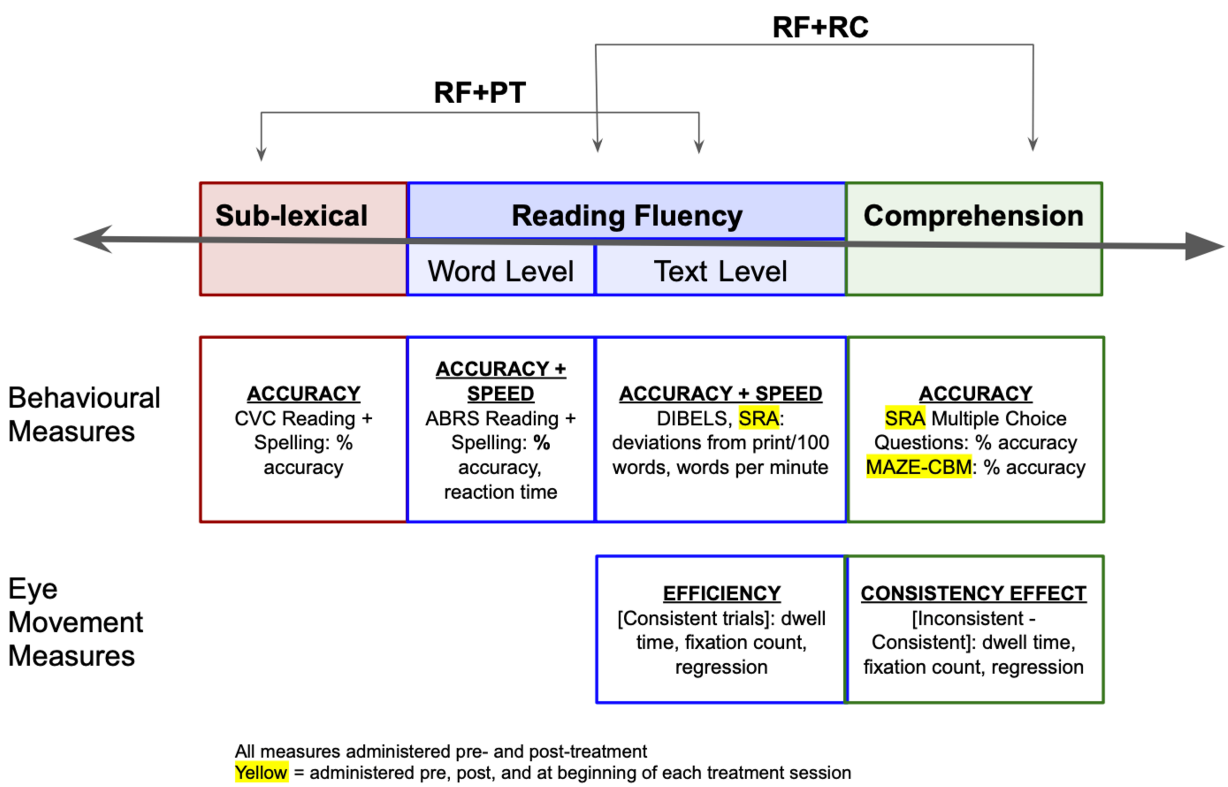
Reading can be roughly described as a continuum of language skills, as visualized in Figure 3. As discussed in the introduction, sublexical skills are required when encountering new or unfamiliar words. Over multiple exposures, words become stored in the lexicon and are read through the lexical-semantic route. Once individuals become more proficient with reading single words, they become better at reading connected text. Reading comprehension comes when individuals are accurate and fast enough at decoding the words to focus on understanding the meaning.

Multiple measures were utilized in the study to evaluate different participants' reading skills along the reading skills continuum: sublexical skills, reading fluency and reading comprehension abilities. Quantifying their skills in each of these sub-skills allows greater insight on treatment effects and how foundational skills contribute to the complex skill of understanding and comprehending the text.

Figure 3. Reading skills continuum and measures used in the present study.

Depiction of the reading skills continuum with associated behavioural measures. All measures were administered pre- and post-treatment. Yellow highlighted measure denotes measures that were administered pre- and post-treatment, and also at the start of each treatment session. Measures not highlighted represent measures that were only administered pre- and post-treatment.

CVC Reading + Spelling = Consonant vowel consonant nonword reading and spelling task; ABRS Reading + Spelling = Arizona Battery of Reading and Spelling; DIBELS = Dynamic Indicators of Basic Early Literacy Skills; SRA = Scientific Research Associates; MAZE-CBM = Curriculum-Based Measurements of Maze Reading



Establishing equivalent reading grade. As mentioned above, each participant's equivalent reading grade level was determined by their performance on the KETA-3 to characterize their reading abilities. The Letter and Word subtest was first administered to determine the starting point on the Reading Comprehension subtest. The scores on both subtests were then converted to the corresponding reading grade level. The reading grade level determined by the KETA-3 was also used to individualize some assessment batteries and treatment stimuli, which will be discussed in more detail.

All measures, aside from the assessments used to profile the participants (WAB-R and KETA-3), were administered before and after each treatment period to investigate if there were changes in performance after treatment. The same assessments were administered to all four participants. Select measures (see yellow highlighted measures in Figure 3) were also administered at the beginning of each treatment session to capture changes between sessions as the treatment progressed.

Sublexical skills. Sublexical skills were evaluated using consonant vowel consonant (CVC) nonwords where the orthography corresponded to common sound rules of English. Since nonwords are unknown word forms, individuals do not have pre-stored (i.e., memorized) forms they can access through the lexical-semantic route and must use the sublexical skills to complete nonword tasks. Both reading and spelling CVC nonwords utilizes sublexical skills, requiring grapheme to phoneme conversion abilities in the former, and phoneme to grapheme conversion abilities in the latter.

In the CVC nonword spelling task, the clinician orally dictated 20 CVC nonwords for the participants to spell out (e.g., “fadge” and “bope”). In the CVC nonword reading task, participants were given a different list of 20 CVC nonwords to read aloud. The accuracy of reading and spelling was determined as a measure of their sublexical skills abilities. Participants were given credit for each correct part of the CVC word (e.g., if the participant wrote "tadge" for "fadge" they were given 2 points out of 3, and if they said "fot" instead of "fadge" they were given 1 point out of 3).

Reading fluency. Reading fluency was measured at the single word and text level. Reading fluency requires decoding by accessing words through both sublexical and lexical-semantic reading routes with accuracy and speed, and is a precursory skill and predictor of reading comprehension (Eason et al., 2013). Thus, measures used in the present study quantify the accuracy and speed of participant's reading.

Reading fluency – single word level. The Arizona Battery for Reading and Spelling (ABRS; Beeson & Rising, 2010) was used to measure reading and spelling at the single word level. Although the primary measure of interest was reading fluency, evaluating spelling is also beneficial as spelling involves the same routes as reading and is another measure of lexical-semantic access. Both reading and spelling requires accessing stored word forms through the lexical-semantic route when words are known and familiar, and the sublexical route when the words are unknown (i.e., words that are not yet learned and/or forgotten). The ABRS consists of two lists of 40 real words balanced for frequency, length, regularity and imageability. At each assessment session, one list would be used for reading, and the other list would be used for spelling. The lists would then be switched for each of the pre/post assessment sessions to decrease potential practice effects. To evaluate spelling accuracy, the examiner orally dictated the ABRS words for participants to spell. To measure reading accuracy, participants read aloud 40 ABRS words that were presented one at a time on a screen using E-Prime (2.0) software. Reaction time from when the word was presented on the screen to when the participant started saying the word (as measured by a voice key) was also recorded as a measure of single word reading speed.

Reading fluency – text level. Text-level reading fluency was determined by oral reading accuracy (deviations/errors from print in 100 words; dfp/100w) and rate (words per minute; wpm) as participants read passages aloud. Higher oral reading accuracy is reflected by a lower dfp/100w, because less errors are made. Decreases in dfp/100w equate to improvements in reading accuracy. Passages of connected text from the validated and commercially available Dynamic Indicators of Basic Early Literacy Skills (DIBELS) and Scientific Research Associates (SRA; 2005) were used to evaluate text-level accuracy and rate of oral reading. During each assessment session (pre- and post-treatment) participants orally read an "easier" Grade 2 and a "challenging" Grade 8 untrained passages from DIBELS to capture their reading fluency at these two levels. In addition, participants orally read three untrained SRA passages from their grade level (reading grade as determined by the KETA-3) as a pre- and post-assessment measure. Each passage was around 100-150 words. One untrained SRA probe was also administered at the beginning of each treatment session to monitor progress from session to session.

Reading comprehension. Reading comprehension was evaluated offline and online. Untrained reading comprehension assessment tools were administered at the pre- and post-assessment sessions and also at the beginning of each treatment session to measure short term treatment gains and generalization.

Multiple choice questions from the Scientific Research Associates (SRA; 2005) were used as an offline measure of reading comprehension. Participants answered 7-8 multiple choice comprehension questions after orally reading untrained SRA passages mentioned prior.

Curriculum-Based Measurements of Maze Reading (MAZE-CBM; commercially available through AIMSweb.com) were also administered to assess online reading comprehension and the participants' ability to integrate content they had read. Maze Reading is a reliable and valid measure of reading comprehension in adults (Gellert & Elbro, 2013), and measures comprehension online; participants complete cloze sentence tasks as they read through the passage. In addition to measuring reading comprehension, cloze sentence reading tasks reflect the individual's reading fluency and are more sensitive to text integration abilities (Gellert & Elbro, 2013; Muijselaar, Kendeou, Jong, & Van, 2017).

In the MAZE-CBM passages, participants read passages of text where every 7th word (after the first sentence) they must select the correct word from three options integrated within the passages. During the evaluation process, participants are given 3 minutes to determine the choice that leads to the best consistency of information, depending on the context of what they are reading. The MAZE-CBM measures contextual integration, within the framework of reading comprehension.

Eye movement assessment. Lastly, participant's eye movements were recorded as they read paragraphs before and after each treatment phase to determine if treatment resulted in changes in their reading efficiency and comprehension. Typically, readers' eye movements patterns are different when they read connected text compared to single words. In connected text, instead of fixating on each individual word, readers have different eye movement patterns such as skipping small functor words (e.g., in, the, is), spending more time on content words and rereading portions that do not make sense (Rayner, 1998; Rayner et al., 2006). Since eye movements vary drastically between reading connected text and single words, results must be obtained from reading connected text directly. In the present study, paragraph stimuli were developed to assess eye movements while reading connected text. Details of the stimuli used are discussed in more detail below.

Participant's eye movement patterns were recorded as they read consistent passages and inconsistent passages. Typically, when skilled readers have difficulty comprehending (either because they missed information or because the text itself is unclear and/or has errors), they will spend more time reading, fixating longer on words, make more fixations and more regressions (Rayner, 1998; Rayner et al., 2006). The errors in inconsistent passages were designed to result in misunderstandings and breakdowns in comprehension, thus eliciting aberrant eye movement patterns. Differences in eye movement patterns between the two consistencies of passages were an inferred measure of comprehension, as it reflected the participant's ability to adjust their eye movements in response to detecting the inconsistency.

A total of 48 unique paragraphs were created by the research team. Each paragraph had a target antecedent and anaphor, and a consistent and inconsistent version (please see Appendix 1 for list of antecedents and anaphors) for a total of 96 paragraphs. Between the two versions, only the anaphor was different. In consistent paragraphs, the target antecedent and anaphor were congruent:

e.g., Matt was excited for lunch because he had packed himself a delicious **hamburger**. All morning long, he could not focus in class because he kept thinking about the delicious **hamburger** in his lunch box. He kept counting down the time till lunch.

In inconsistent conditions, the target antecedent and anaphor were incongruent:

e.g., Matt was excited for lunch because he had packed himself a delicious **hamburger**. All morning long, he could not focus in class because he kept thinking about the delicious **pizza** in his lunch box. He kept counting down the time till lunch.

Passages had an average of 37 words per paragraph. Average Flesch Reading Ease was 78.8 and average Flesch-Kincaid Grade Level was 5. The N-WATCH software (Davis, 2005), a psycholinguistic program developed to analyze words, was used to determine the frequency, imageability, age of acquisition and phonological and semantic neighbours of antecedents and the incongruent anaphors. Antecedents and the incongruent anaphors were matched, and their corresponding psycholinguistic features were compared using a *t*-test. Antecedents and anaphors used in the eyetracking stimuli were not statistically different (please see Appendix 2 for statistics).

The 96 paragraphs were divided into four sets of 24; one set was administered at each assessment session. Participants read 24 paragraphs in 16 point white Courier font against a black background on a computer screen while eye movement data was collected. Eye movement data during reading was gathered by the SR Research Eyelink 1000 with a desk-mounted camera. Head movement was stabilized by using a chin rest. Eye movement measures for each treatment condition included: total fixation duration (dwell time), total number of fixations, and number of regressions.

Treatment 1 (RF + PT) Procedures

Treatment probes. Please refer to yellow highlighted assessment measures in Figure 3 for all treatment probes administered. At the beginning of each treatment session, participants completed novel reading probes to measure treatment effect size and generalization. First, participants orally read untrained SRA passages and their reading rate (words per minute) and accuracy (deviations from print per 100 words) were determined. Then they completed multiple choice comprehension questions (% correct) based on the same SRA passage. Then, participants had 3 minutes to complete a MAZE-CBM passage.

Phonological treatment. The first half of the treatment session utilized probes, tasks and hierarchies described by the phonological treatment sequence (see Beeson, Rising, Kim, & Rapcsak, 2010 for protocol).

Reading fluency treatment. In the second half of the session, participants first orally read the previous session's trained passage, to establish the post-practice reading rate (words per minute) and accuracy (deviations from print per 100 words). Then, participants orally read the next novel passage that was going to be used for ORLA in the present session, to establish pre-practice reading rate and accuracy.

Figure 4. Outline of Treatment 1 steps in the present study and corresponding treatment protocols in ORLA (Cherney, 2010) and MOR (Tuomainen & Laine, 1991).

Treatment 1 (RF+PT)	Corresponding Steps from Published Treatment Protocols
1) Complete SRA probe	
2) Complete Maze reading probe	
3) Phonological Treatment (see Beeson, Rising, Kim, & Rapcsak, 2010 for protocol).	Phonological Treatment Sequence
4) Participant reads aloud previous passage practiced for homework/in previous session	MOR Step 3
5) Introduce new passage → Participant reads entire passage out loud	MOR Step 1
6) Clinician reads paragraph aloud to participant; clinician points to each word	ORLA Step 1
7) Clinician reads paragraph aloud to participant; both point to each word	ORLA Step 2
8) Clinician and participant read paragraph aloud together; both point to each word	ORLA Step 3
9) Clinician states a word for the participant to identify in paragraph	ORLA Step 4
10) Clinician points to a word in paragraph for the participant to read aloud	ORLA Step 5
11) Clinician and participant read aloud together again	ORLA Step 6
12) Repeat Steps 6) - 11) until whole passage is complete	
13) Homework: 1) Participant rereads the passage, three times	MOR Step 2

Treatment 2 (RF + RC) Procedures

Treatment probes. At the beginning of each treatment session, participants completed the same SRA and MAZE-CBM probes as Treatment 1.

Reading fluency and comprehension treatment. Prior to starting the reading fluency assessments (as outlined in Treatment 1), the participant and clinician reviewed the homework from the previous session. The clinician provided supportive and constructive feedback on the written summaries completed at home. After, the same procedures were completed as in Treatment 1 to gather the reading rate and accuracy data on trained and untrained passages. Please see Treatment 1 for additional details.

Please see Figure 5 for a detailed integrated treatment protocol used in this study. The present study closely followed the ARCS-W protocol outlined in Obermeyer & Edmonds, 2018. The ARCS-W (Obermeyer & Edmonds, 2018) is similar to the original ARCS treatment sequence (Rogalski & Edmonds, 2008; Rogalski, Edmonds, Daly, & Gardner, 2013) with repetitive reading and verbal summarizations within constraints of not using non-specific language (e.g., words like "thing, stuff"). However, the ARCS-W integrates written summarization. MOR procedures overlapped within some steps of ARCS-W (as outlined in Figure 5). Compared to the original ARCS-W protocol, this study incorporated more repetitive reading, as prescribed by MOR to target reading fluency. Compared to earlier studies of MOR (e.g., Beeson & Insalaco, 1998; Russo & Kim, 2010), no accuracy or time criterion was required before moving onto the next passage. The general reading strategies were also integrated after the key words were identified to solidify concepts and connections. Then the verbal summary was completed with the clinician, and the written summary was assigned for homework.

Figure 5. Outline of treatment steps in the present study and corresponding treatment protocols in ARCS-W (Obermeyer & Edmonds, 2018), MOR (Tuomainen & Laine, 1991), and a reading therapy program based on reading strategies (Cocks et al., 2013).

Treatment 2 (RF+RC)	Corresponding Steps from Published Treatment Protocols
1) Complete SRA probe	
2) Complete Maze reading probe	
3) Reads written summarizations to the clinician and checks for errors a. Clinician provides feedback regarding if constraints were followed and if important information was included (key words)	ARCS-W Step 6
4) Participant produces verbal summary of whole article	ARCS-W Step 8
5) Participant reads aloud previous passage practiced for homework/in previous session	MOR Step 3
6) Introduce new passage → Participant reads passage out loud	MOR Step 1
7) Participant reads one to three sentence segments twice, to themselves, for comprehension	ARCS-W Step 2
8) Participant identifies key words in the segment, by underlining, and writes them down a. Clinician writes down key words from the segment	ARCS-W Step 3 Reading strategy
9) Participant and clinician compare key words, discuss what is most important, and finalize list of key words a. Clinician compares key words and finalizes key word list with participant	ARCS-W Step 4
10) Participant creates mind map using key word to represent relationship of ideas a. Clinician provides support as needed	Reading strategy
11) Participant produces a verbal summary of the segment they read with the assistance of their key word list while following prescribed constraints (e.g., no nonspecific words, stay on topic, plus individual constraint) a. Clinician provides feedback regarding if constraints were followed and if important information was included (key words)	ARCS-W Step 5
12) Repeat steps 6-10 whole passage is summarized	
13) Homework: 1) Participant rereads the passage, three times 2) Participant summarizes segments or the whole article in writing (depending on progress through the article) a. Rate completeness of summary (e.g., 1 = not complete at all, 3= somewhat complete, and 5 = very complete	ARCS-W Step 7, 6/9, 10 MOR Step 2

Outcome Measures and Planned Analyses

Sublexical skills outcomes. Participants' pre- and post-treatment reading and spelling CVC nonwords scores were compared using McNemar's Chi Square test to determine if there was a significant change in correct and incorrect responses after treatment.

Reading fluency outcomes – word level. Pre- and post-treatment ABRS reading and spelling accuracy scores were also compared using McNemar's Chi Square. The latencies of single word reading on the ABRS before and after each treatment phase was compared using a 2 (stimulation: active, sham) x2 (time: pre, post) repeated measures ANOVA.

Reading fluency outcomes – text level. Reading rate and accuracy were measured on 2 types of text passages: untrained pre- and post-treatment measures (SRA, DIBELS), and also on within-phase improvement on trained news articles (newsela.com). In the latter case, each passage was assessed before and after ORLA and MOR procedures. Statistical tests were not completed on untrained measures due to the limited pre- and post-treatment data points (only 5 data points from SRA and DIBELS measures). Treatment effect sizes were used to assess generalization to novel passages (SRA, DIBELS), determined by calculating Cohen's *d* statistic (as described in Beeson & Robey, 2006). The *d* statistic was calculated by taking the difference between the mean of the reading rate (WPM) or accuracy (dfp/100w) pre-treatment and post-treatment, and then dividing by the standard deviation of the pre-treatment data points (e.g., *d* = (Post-Treatment WPM Mean – Pre-Treatment WPM Mean)/Standard deviation of Pre-Treatment WPM). Calculating treatment effect sizes factors in baseline variability and allows comparisons of treatment gains to be made across different units of measurements and types of data. The treatment effect sizes were then compared to benchmarks for small (2.6), medium (3.9) and large (5.8) effect sizes established for single-subject aphasia treatment studies (Robey, Schultz, Crawford, & Sinner, 1999). To calculate effect size, pre- and post-treatment reading rate and accuracy data points were taken from pre- and post-treatment assessment using the DIBELS and SRA passages. Within treatment reading rate and accuracy data points were taken from the SRA probes that were administered at the beginning of each treatment session. On passages used for daily oral reading practice, reading rate and accuracy for passages before and after training, and for each tDCS condition were compared using a 2 (stimulation: active, sham) x2 (time: pre, post) repeated measures ANOVA.

Reading comprehension outcomes. Treatment effect sizes (as described above) were calculated on MAZE-CBM accuracy scores, and the scores from the SRA multiple choice questions that were administered before and after treatment, as well as at the beginning of each treatment session.

Eye movement outcomes. As part of their pre- and post-assessments, participants' eye movements were also recorded as they read passages with consistent and inconsistent anaphors and antecedents. The raw data files were pre-processed using Eyelink Dataviewer software. The raw data was filtered based on values reported in (Huck et al., 2017). Fixations were manually shifted as necessary to compensate for calibration and/or drift correct issues that resulted in the fixations to be out of the interest areas. The dwell time, fixation count, and number of regressions were recorded for each trial and divided by each stimuli's pixel area presented on the screen. The measures were divided by the pixel area to account for different word lengths and varying number of words within trials. All the trials within each assessment period were then averaged.

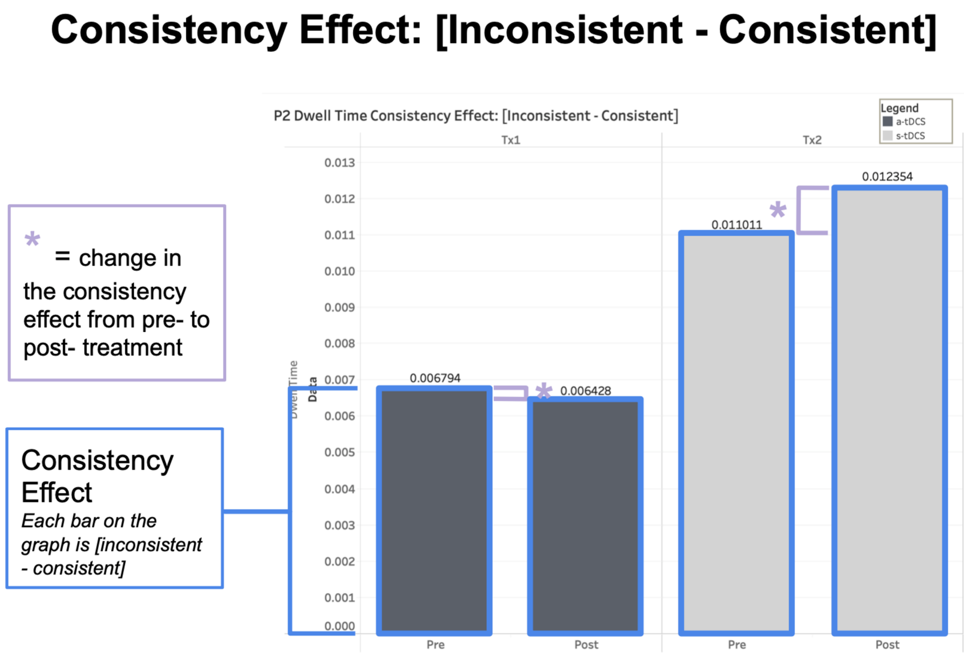
Two effects were investigated. In the present study, reading **efficiency** is defined as the ease of reading or reading fluency, characterized by the participant's overall dwell time, fixation count and number of regressions as they read *consistent* passages that did not have any incongruencies. A 2 (stimulation: active, sham) x2 (time: pre, post) repeated measures ANOVA, was used to determine if there was a significant difference in these measures after treatment and across tDCS conditions.

Inefficient readers, such as children first learning to read (i.e., laborious and not smooth reading), are known to make any combination of increased dwell time, more fixations, and more regressions (Rayner et al., 2006). Typically, after reading practice, an increase in efficiency would be expected in skilled readers. This increase could be described as a decrease in dwell time (i.e., the individual becomes faster and spends less time reading), a decrease in fixation count (i.e., the individual does not need to stop on as many words), and a decrease in regressions (i.e., the individual has to move back less to previously read text).

The second effect that was examined from the eye movement data was the **consistency effect.** The consistency effect is an inferred measure of the participant's comprehension; specifically, it quantifies their ability to discriminate and respond to inconsistent passages compared to consistent passages. In this study, the consistency effect is characterized by the *difference* in dwell time, fixation count and number of regressions participants make when reading *inconsistent* passages compared to *consistent* passages. With inconsistent passages, skilled readers spend more time reading (dwell time), stop more to focus on words (fixation count) and reread sentences more (regressions) to make sense of the conflicting content and to process and understand incongruency they've detected (Rayner et al., 2006). The presence of a consistency effect reflects comprehension as the reader has to process and understand the text before they can discriminate and modify their reading patterns for inconsistent passages. If there is no consistency effect, it means that the individual is making the same eye movement patterns when reading inconsistent passages as when they are reading consistent passages. The lack of difference in eye movements suggest that the reader has not comprehended the text and has not detected the conflicting content in the inconsistent passages. In general, a greater consistency effect (i.e., a greater difference in reading patterns between inconsistent and consistent passages) is expected after treatment, as readers should be better at discriminating and responding to inconsistent versus consistent passages. Thus, there should be a change in the consistency effect at post-treatment compared to pre-treatment (the "*" demonstrating a difference between consistency effects in Figure 6). However, treatment and reading practice could also result in a smaller consistency effect as the reader is more habituated and is less surprised by inconsistent passages. Thus, a treatment effect can be described as any change after treatment (i.e., both increases and decreases in the consistency effect).

To calculate the consistency effect, the average measures for each assessment period during the consistent trials were subtracted from the inconsistent trial (i.e., inconsistent passage eye movements – consistent passage eye movements). The consistency effect at each pre- and post-treatment assessment time point was then qualitatively compared for changes (i.e., comparing the two "*" between treatment phases in Figure 6).

Figure 6. Example of Graph Depicting Consistency Effect and Qualitative Comparisons



RESULTS

Treatment 1: Reading fluency treatment and Phonological Treatment Approach (RF+PT)

All participants received ten 1.5 hour treatment sessions over 2 weeks (around 15 hours) in each of their phases of treatment (total of 30 hours of direct treatment). At times, participants would have 1-3 day breaks in between treatment sessions due to weekends, statutory holidays or scheduling conflicts. Participants completed an additional 5-10 hours of home practice during each phase of treatment (average 30 minutes to 1 hour of home practice each day). In each phase, participants received around 2 hours of reading practice each day, totaling around 20 hours of reading practice over 2 weeks.

A summary of all participants' significant behavioural and eye movement results can be found in Table 14.

P1.

Behavioural outcomes. Based on P1's performance on the KETA-3 Letter and Word Subtest Score Letter and Word Subtest Score (75) and her Reading Comprehension Score (48), P1 was determined to be reading at a grade 5 level. See the table below (Table 6) for P1's performance on behavioural assessments before and after treatment in both treatment phases. See Table 7 for the statistical comparisons between P1's pre- and post-treatment assessment scores.

Table 6. Raw scores of P1's performance on assessment measures before and after treatments in both treatment phases.

P1 Pre-treatment and Post-treatment Behavioural Measures				
	Phase 1 s- tDCS		Phase 2 a-tDCS	
	Pre	Post	Pre	Post
Sublexical Skills				
CVC Nonword Spelling Accuracy (%)	42%	63%	57%	68%
CVC Nonword Reading Accuracy (%)	83%	83%	80%	82%
Reading Fluency – Word Level				
ABRS Reading Accuracy (%)	95%	93%	90%	93%
ABRS Reading Reaction Time (ms)	782.1	734.3	592.0	706.5
ABRS Spelling Accuracy (%)	83%	85%	83%	90%
Reading Fluency – Text Level				
Accuracy (deviations from print per 100 words)	4.6	4.7	4.7	3.6
Rate (Words per minute)	47.1	73.8	68.8	80.8
Reading Comprehension				
Multiple Choice Questions Accuracy (%)	71%	79%	71%	95%
MAZE-CBM Accuracy (%)	66%	81%	74%	87%

Sublexical skills. P1 made significant improvements in spelling CVC nonwords with treatment in both conditions (Phase 1: χ^2 (1) = 0.22, $p < .001$, Phase 2: χ^2 (1) = 0.12, $p = .02$).

However, there were no significant differences in CVC reading scores after treatment in either conditions. P1 was already performing at moderately high accuracy for CVC reading before treatment. Thus, there may have been less room for improvement as she may have already been close to her ceiling abilities.

Reading fluency – word level. Like CVC reading accuracy, P1 had high accuracy in spelling and reading single words (ABRS) before treatment. There were no significant improvements ABRS scores after treatment in either conditions. However, there were some significant differences in P1's reaction time when reading the ABRS words. There was a significant interaction between the tDCS phases and time (pre- and post-) measures ($F(1,15) = 7.352$, $p = .016$, $\eta p2 = .329$). Post hoc comparisons using paired t-tests with Bonferroni correction (0.05/2 = 0.025) indicated the pre-treatment mean reaction time did not significantly differ from post-treatment mean reaction time in the first treatment phase. However, in the second treatment phase, post-treatment mean reaction times were significantly higher than pre-treatment reaction times ($p = .018$), meaning P1 read single words slower after the second phase of treatment.

Reading fluency – text level. With treatment, P1 improved her rate when orally reading novel passages from DIBELS and SRA. After the first treatment phase with s-tDCS, her reading rate (WPM) gains were equivalent to a small effect size ($d = 2.91$). After the second treatment phase with a-tDCS, she had minimal gains in reading ($d = 1.23$). There was no change in P1's oral reading accuracy (dfp/100w) after either treatment phases.

Reading comprehension. P1's offline reading comprehension (as measured by answering multiple choice questions after reading novel SRA passages) improved slightly with treatment in both conditions (see Table 7). Treatment effect size during the a-tDCS condition ($d = 1.67$) was slightly larger compared to the effect size during s-tDCS ($d = .29$). However, treatment effect sizes were smaller than the threshold for a small treatment effect size as determined through other single-subject aphasia treatment studies (Robey et al., 1999).

P1's ability to integrate contextual information (as measured by the MAZE-CBM) improved more after the second phase of treatment with a-tDCS, with gains corresponding to a small effect ($d = 3.54$).

Table 7. Comparison of P1's performance on assessment measures before and after treatments in both treatment phases

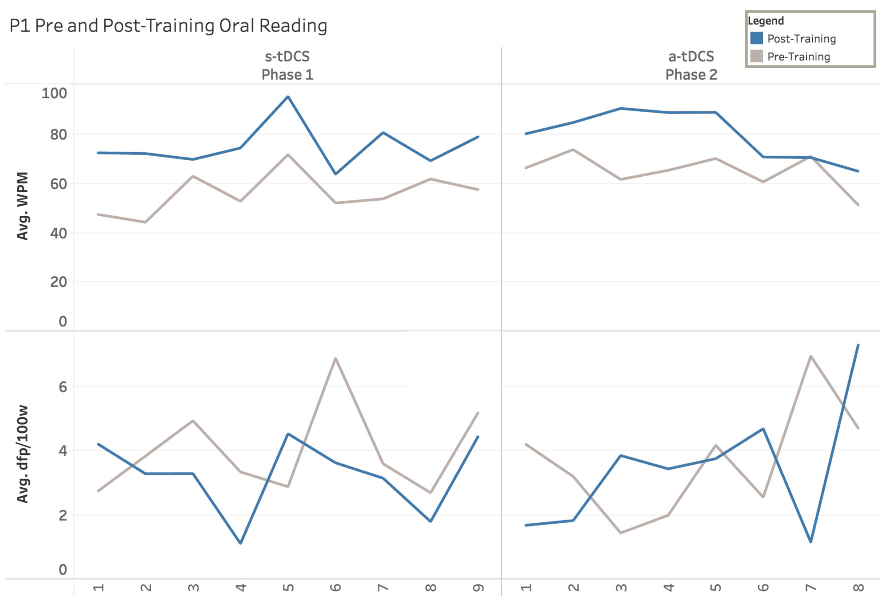
P1 Pre- and post-treatment Behavioural Measure Changes		
	Phase 1 s- tDCS	Phase 2 a-tDCS
Sublexical Skills		
CVC Nonword Spelling Accuracy *(p)*	<.001*	0.04*
CVC Nonwords Reading Accuracy *(p)*	n.s.	n.s.
Reading Fluency – Word Level		
ABRS Reading Accuracy *(p)*	n.s.	n.s.
ABRS Reading Reaction Time *(p)*	Interaction effect: .016	
ABRS Spelling Accuracy *(p)*	n.s.	n.s.
Reading Fluency – Text Level		
Accuracy – Deviations from print per 100 words *(d)*	0.05	-1.00
Rate - Words per minute *(d)*	2.91*	1.23
Reading Comprehension		
Multiple Choice Questions *(d)*	0.29	1.67
MAZE-CBM *(d)*	0.59	3.54*

* = treatment effect size corresponding to small effect size ($d > 2.6$); or scores significantly different pre- and post- (alpha = .05)
n.s. = not significant ($p > .05$)

Trained reading passages. Reading fluency was measured on passages used for RF+PT. Measures were taken on passages before and after ORLA and MOR, as described in the methods section. P1's reading rate on passages increased with practice as there was a significant main effect of reading practice (pre- and post-; $F(1,6) = 83.979$, $p < .001$). However, there was no interaction effect between the treatment (pre- and post-) and the tDCS condition. There were no significant differences in reading accuracy (dfp/100w) before and after reading practice.

Figure 7. P1's Pre- and Post-Training Reading Rate (WPM) and Reading Accuracy (dfp/100words) on Trained Passages.

Higher WPM represents faster reading rate. Lower dfp/100w represents better reading accuracy.



Eye movement outcomes.

Efficiency. The efficiency effect captures the participant's changing ability to read regular passages with ease and fluency.

Please refer to Table 14 for a summary of all eye movement results for all participants. Figures 8, 9, and 10 show P1's efficiency as measured by dwell time, fixation count and regressions, respectively. There were no significant differences in dwell time and fixation count for each treatment phase, but there was a significant interaction effect between the number of regressions P1 was making and the treatment phase ($F(1,11) = 39.557$, $p < .001$). Post hoc comparisons using paired t-tests with Bonferroni correction (0.05/2 = 0.025) indicated P1 made significantly less regressions after the first treatment paired with s-tDCS ($p = .003$), but there were no changes in regressions after second treatment paired with a-tDCS. P1's average dwell time and number of fixations did not change across assessment periods.

P1's eye movements can be somewhat linked to her behavioural outcomes. Please refer to Table 14 for a summary of both pre- and post-treatment behavioural and eye movement outcomes. The first treatment phase with s-tDCS led to a change in reading fluency as she made less regressions when reading regular passages. This change in eye movement was accompanied by an increase in oral reading rate. The second treatment phase with a-tDCS led to more regressions with a decreased reading rate. For P1, changes in her reading rate appear to be inversely related to the number of regressions she made.

Figure 8. P1 <u>Dwell Time</u> Efficiency Effect.

No significant change in <u>dwell time</u> in consistent passages across assessment sessions.

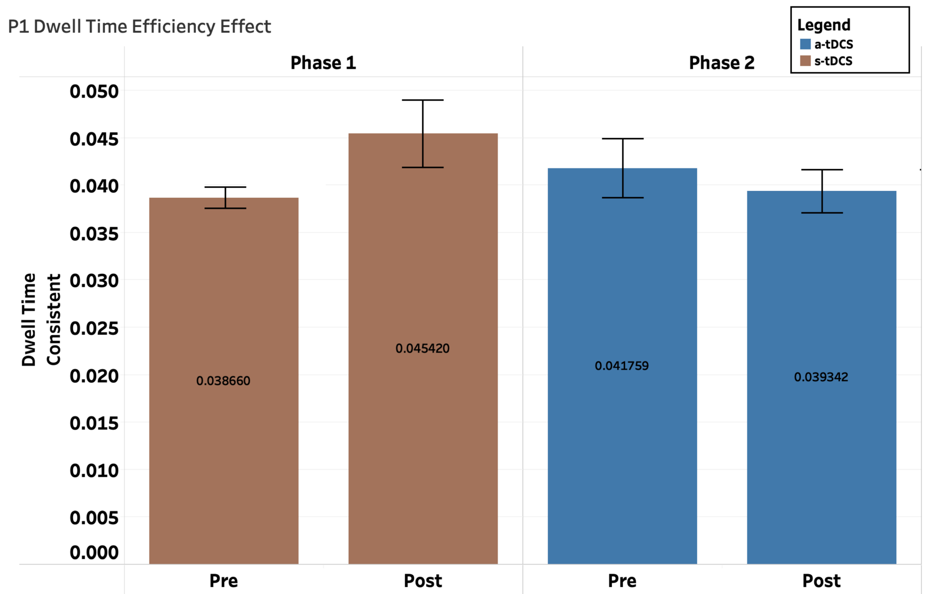


Figure 9. P1 <u>Fixation Count</u> Efficiency Effect.

No significant change in <u>fixation count</u> in consistent passages across assessment sessions.

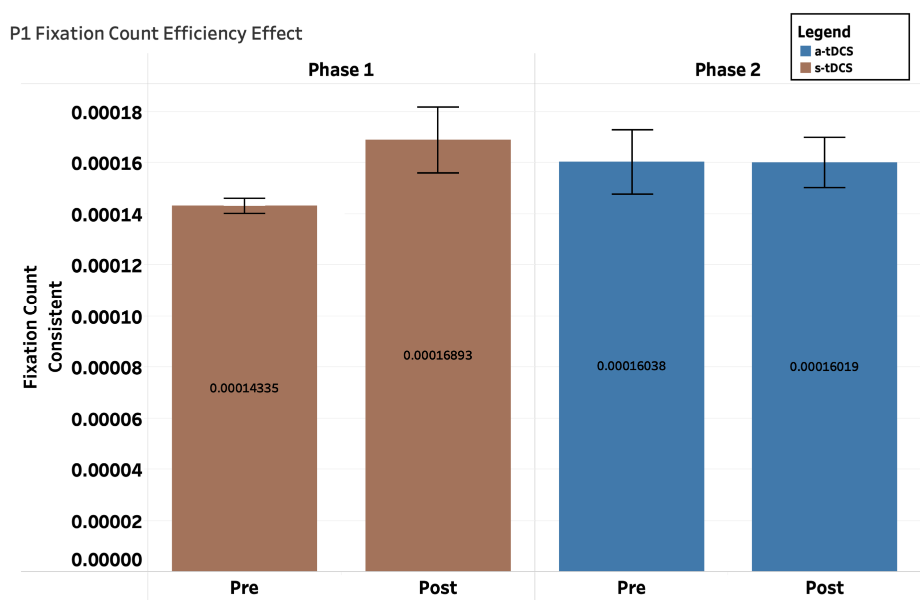
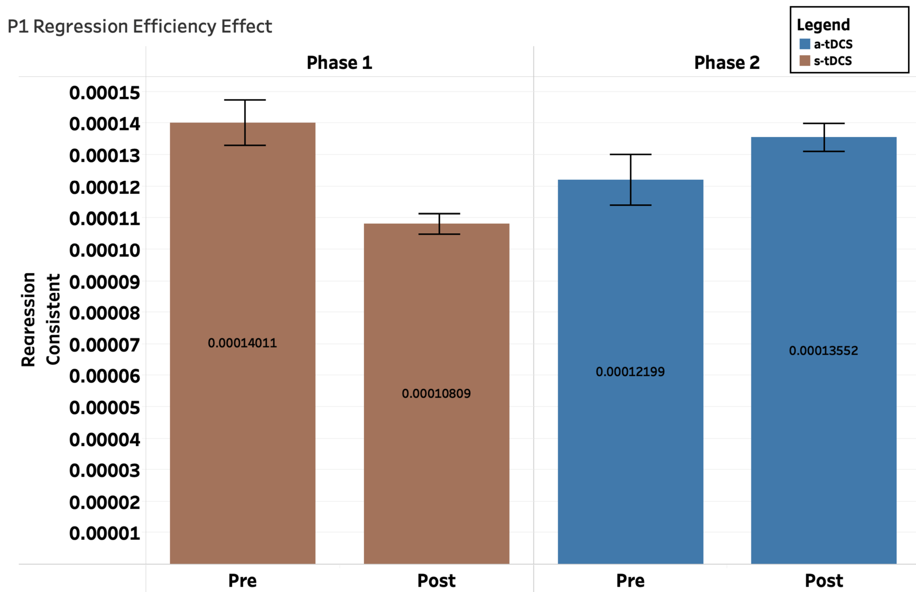


Figure 10. P1 <u>Regression</u> Efficiency Effect.

Significant interaction effect in P1's <u>regression</u> efficiency effect. P1 made less <u>regressions</u> after the first treatment paired with s-tDCS, but there were no changes in <u>regressions</u> after second treatment paired with a-tDCS.



Consistency effect. The consistency effect is an inferred measure of comprehension. It reflects the participant's response to comprehension breakdowns and misunderstandings elicited by inconsistent passages (as compared to their typical reading patterns with passages that have no inconsistencies).

Table 14 includes a general summary of the eye movement results for all participants with respects to the changes in the consistency effect. The following Figures 11, 12 and 13 show the consistency effect of P1's <u>dwell time</u>, <u>fixation count</u> and <u>regressions</u>, respectively. In summary, the greatest change between pre- and post-treatment consistency effect in <u>fixation count</u> and <u>regressions</u> were seen after the first treatment phase with s-tDCS. The greatest change between pre- and post-treatment consistency effect with <u>dwell time</u> was after the second phase of treatment with a-tDCS.

The following discusses the relationship between pre- and post-treatment changes in more detail. Prior to treatment in the first phase ("Pre" columns in Figures 11, 12 and 13), P1 already demonstrated a consistency effect, as she had longer dwell times, was making more fixations, and less regressions during inconsistent trials compared to consistent trials. P1 demonstrated an *increase* in the consistency effect after the first phase treatment with s-tDCS in all three measures of dwell time (Figure 11), number of fixations (Figure 12), and regressions (Figure 13). This meant that after treatment with s-tDCS ("Post" columns in the Figures (Figures 11, 12 and 13), there were greater differences between P1's dwell time, fixation count and regressions in the inconsistent condition compared to the consistent condition. In comparison to the second phase of treatment, the first phase of treatment resulted in larger changes in pre- versus post-treatment consistency effects in fixation count and regressions.

After the second phase of treatment with a-tDCS, there was a *decrease* in consistency effect in all three measures. Smaller consistency effect (i.e., smaller differences between the two consistencies) means that P1 read consistent and inconsistent passages more similarly after the second phase of treatment. Compared to the first phase of treatment, the second phase of treatment resulted in larger change in the consistency effect of dwell time, even though there was a change in the consistency effect of fixation count as well. The consistency effect in the number of regressions was minimal both before and after treatment.

In the first phase of treatment s-tDCS, P1 did not have significant gains in comprehension even though there were larger changes in P1's fixation count and regressions. In the second phase of treatment with a-tDCS, there were significant gains in comprehension. In this case, larger post-treatment changes in dwell time may reflect improved comprehension.

Figure 11. P1 <u>Dwell Time</u> Consistency Effect.

There were changes in consistency effect of <u>dwell time</u> after treatment in both phases. However, there is a greater change in consistency effect of <u>dwell time</u> after the second phase of treatment with a-tDCS.

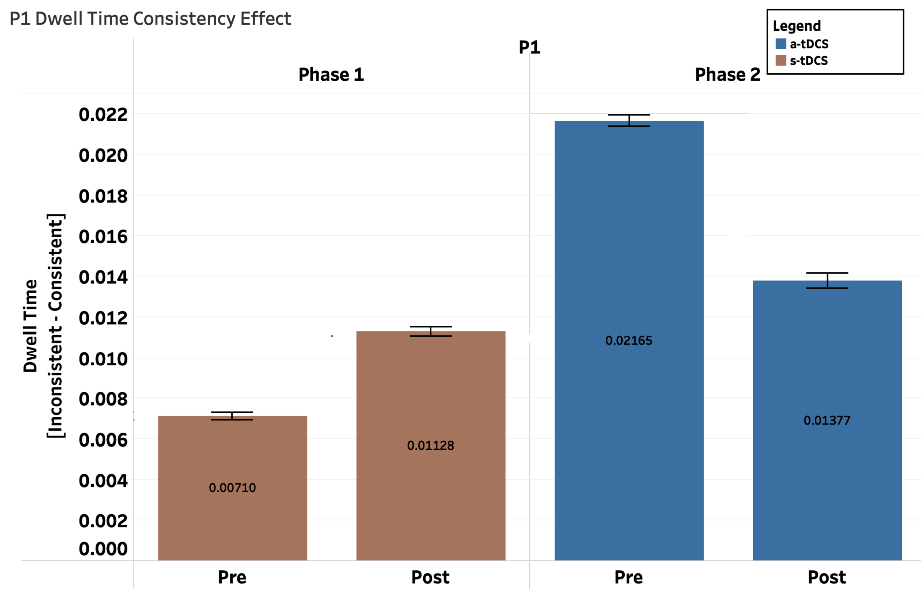


Figure 12. P1 <u>Fixation Count</u> Consistency Effect.

There were changes in consistency effect of <u>fixation count</u> after treatment in both phases. However, there is a greater change in consistency effect of <u>fixation count</u> after the first phase of treatment with s-tDCS.

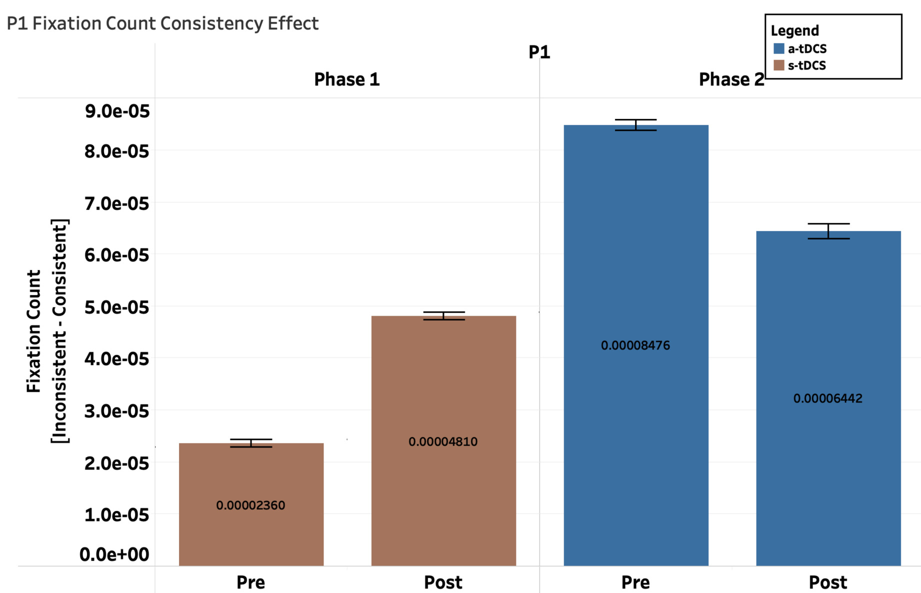
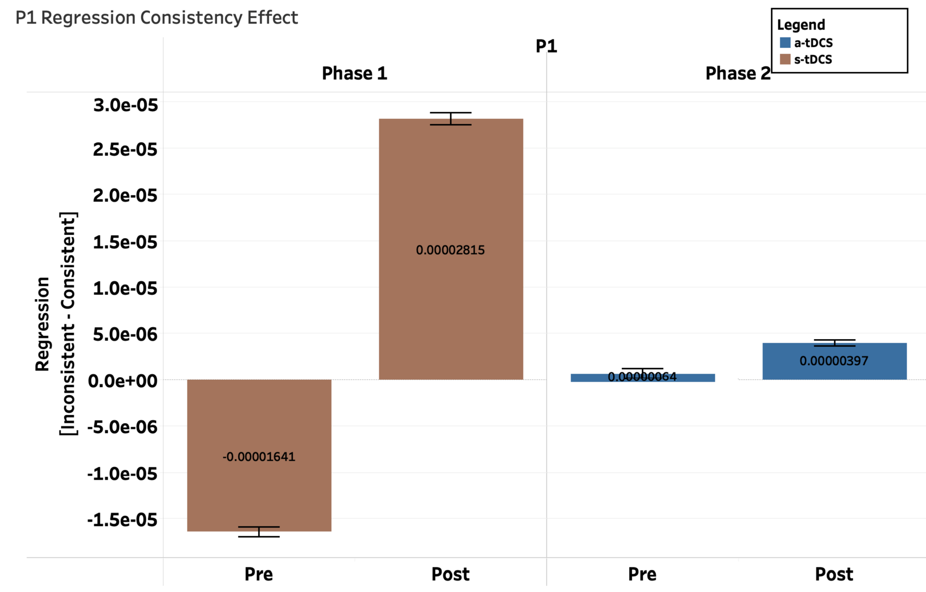


Figure 13. P1 Regression Consistency Effect.

There was a change in consistency effect of regression after the first phase of treatment with s-tDCS. Minimal consistency effect and change in consistency effect noted after the second phase of treatment with a-tDCS.



P1 Summary. P1 received RF+PT with s-tDCS in the first treatment phase, and a-tDCS in the second treatment phase. P1 made gains in sublexical spelling skills after both phases of treatment. Single-word and text-level reading rate also improved with treatment. Although her text-level reading rate did not significantly increase after the second treatment phase (a-tDCS), P1 maintained reading rate gains from the first treatment phase (s-tDCS). Reading comprehension improvements were observed after the second phase of treatment (a-tDCS).

When reading consistent passages, P1's regressions decreased after the first treatment phase, and remained constant after the second treatment phase, consistent with behavioural observations of improved reading fluency (faster rate).

The first treatment phase resulted in larger changes between pre- and post-treatment consistency effect in fixation count and regressions, but insignificant gains in reading comprehension. In the second treatment phase, there were larger changes in the consistency effect for dwell time, which was accompanied by significant gains in reading comprehension.

P2.

Behavioural outcomes. The KETA-3 was administered in the initial assessment session to determine the grade level that would be used for assessment and treatment. Based on his Letter and Word Subtest Score (65) and his Reading Comprehension Score (73), P2 was determined to be reading at a grade 10 level. See the table below (Table 8) for P2's performance on behavioural assessments before and after treatment in both treatment phases.

Table 8. Raw scores of P2's performance on assessment measures before and after treatments in both treatment phases.

P2 Pre-treatment and Post-treatment Behavioural Measures				
	Phase 1 a-tDCS		Phase 2 s-tDCS	
	Pre	Post	Pre	Post
Sublexical Skills				
CVC Nonword Spelling Accuracy (%)	77%	65%	82%	75%
CVC Nonwords Reading Accuracy (%)	72%	82%	77%	73%
Reading Fluency – Word Level				
ABRS Reading Accuracy (%)	88%	95%	100%	90%
ABRS Reading Reaction Time (ms)	496.6	536.0	530.7	607.8
ABRS Spelling Accuracy (%)	70%	60%	55%	53%
Reading Fluency – Text Level				
Accuracy (deviations from print per 100 words)	11.6	8.5	11.1	10.3
Rate (Words per minute)	94.8	98.9	96.1	101.7
Reading Comprehension				
Multiple Choice Questions Accuracy (%)	83%	88%	79%	71%
MAZE-CBM Accuracy (%)	65%	87%	88%	90%

Sublexical skills. In general, treatment appeared to decrease P2's ability to spell CVC nonwords accurately. In the first phase of treatment with a-tDCS, his ability to spell CVC nonwords significantly decreased after therapy ($\chi2(1) = 0.12$, $p = .02$). However, at the same time, he improved in his ability to read CVC nonwords ($\chi2(1) = 0.1$, $p = .03$). The changes in the second phase of treatment in P2's ability to spell and read CVC nonwords were not significant.

Reading fluency – word level. After treatment in both conditions, it took P2 more time to read single real words aloud ($F(1,18) = 46.787$, $p < .001$, $\eta p2 = .722$), however, the condition of stimulation did not impact the amount of changes. There were no significant changes in P2's ability to spell or read single real words.

Reading fluency – text level. P2 did not make significant gains in reading rate and accuracy on passages he read aloud or the accuracy of reading single words in either phases.

Reading comprehension. P2 did not make significant gains in reading comprehension, in either phases, as determined by answering multiple choice questions after reading paragraphs or when completing MAZE-CBM probes.

Table 9. Comparison of P2's performance on assessment measures before and after treatments in both treatment phases.

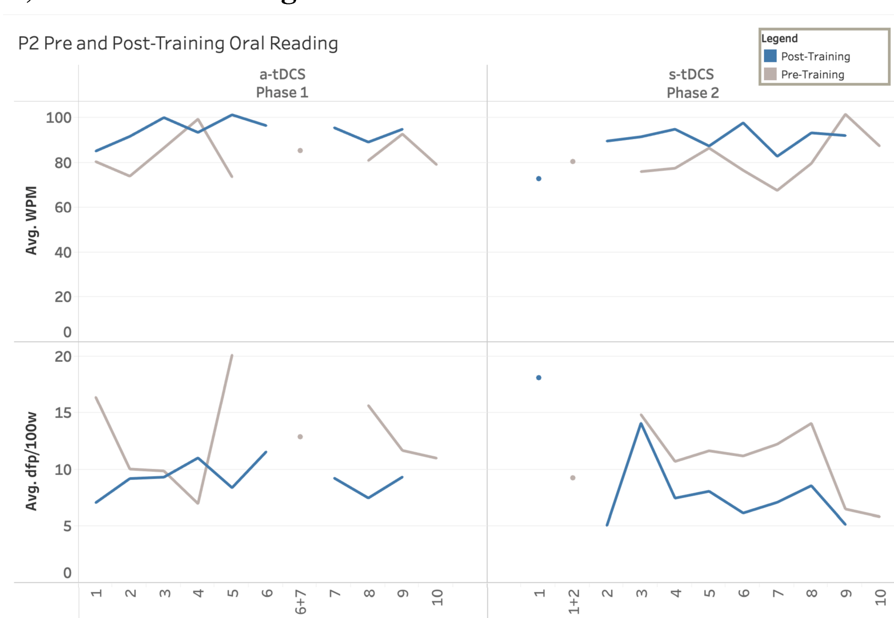
P2 Pre- and post-treatment Behavioural Measure Changes		
	Phase 1 a- tDCS	Phase 2 s-tDCS
Sublexical Skills		
CVC Nonword Spelling Accuracy *(p)*	0.02*	n.s.
CVC Nonwords Reading Accuracy *(p)*	0.03*	n.s.
Reading Fluency – Word Level		
ABRS Reading Accuracy *(p)*	n.s.	n.s.
ABRS Reading Reaction Time *(p)*	Treatment effect <.001*	
ABRS Spelling Accuracy *(p)*	n.s.	n.s.
Reading Fluency – Text Level		
Accuracy – Deviations from print per 100 words *(d)*	-0.52	-0.29

Rate - Words per minute *(d)*	0.38	0.37
Reading Comprehension		
Multiple Choice Questions *(d)*	0.29	-1.15
MAZE-CBM *(d)*	1.62	1.66

* = treatment effect size corresponding to small effect size (*d* > 2.6); or scores significantly different pre- and post- (alpha = .05)
n.s. = not significant (*p* > .05)

Trained reading passages. P2's reading rate on trained passages improved with practice ($F(1,3) = 164.760$, $p < .001$), similarly between the two phases. The condition of stimulation did not result in significantly different amounts of improvement.

Figure 14. P2's Pre- and Post-Training Reading Rate (WPM) and Reading Accuracy (dfp/100words) on Trained Passages.



Eye movement outcomes.

Efficiency. In this measure of reading fluency/reading ease with consistent passages, there was a main effect of P2's dwell time. P2's dwell time increased with both phases of treatment with both tDCS conditions ($F(1,11) = 15.870$, $p = .002$). An increase in dwell time after treatment represents a decrease in reading efficiency as he required more time to read consistent passages. P2's <u>fixation count</u> and <u>regressions</u> before and after receiving treatment were not significantly different, and the type of tDCS did not affect these measures either.

Figure 15. P2 <u>Dwell Time</u> Efficiency Effect.

Significant change in <u>dwell time</u> when reading consistent passages after treatment in both phases.

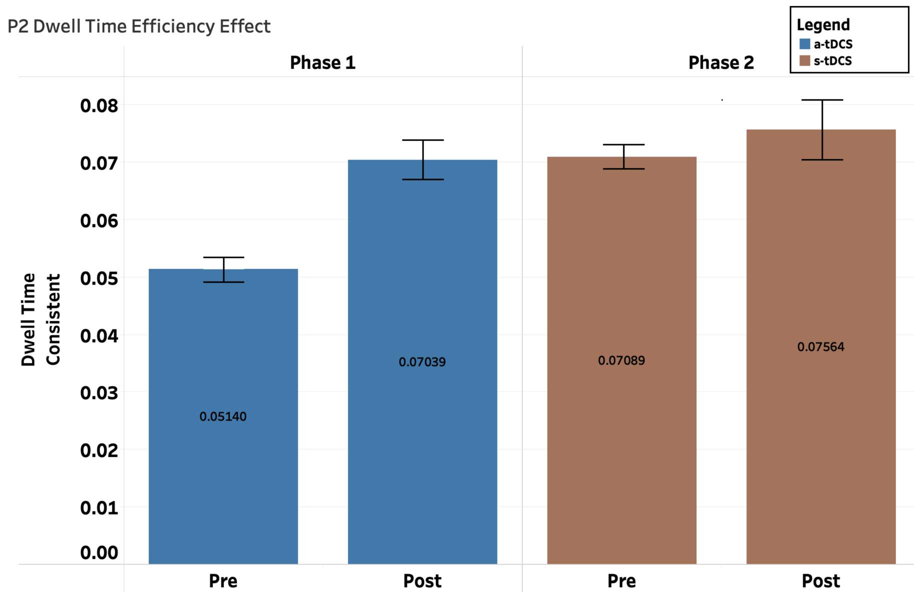


Figure 16. P2 Fixation Count Efficiency Effect.

No significant changes in fixation count when reading consistent passages after treatment in either phases.

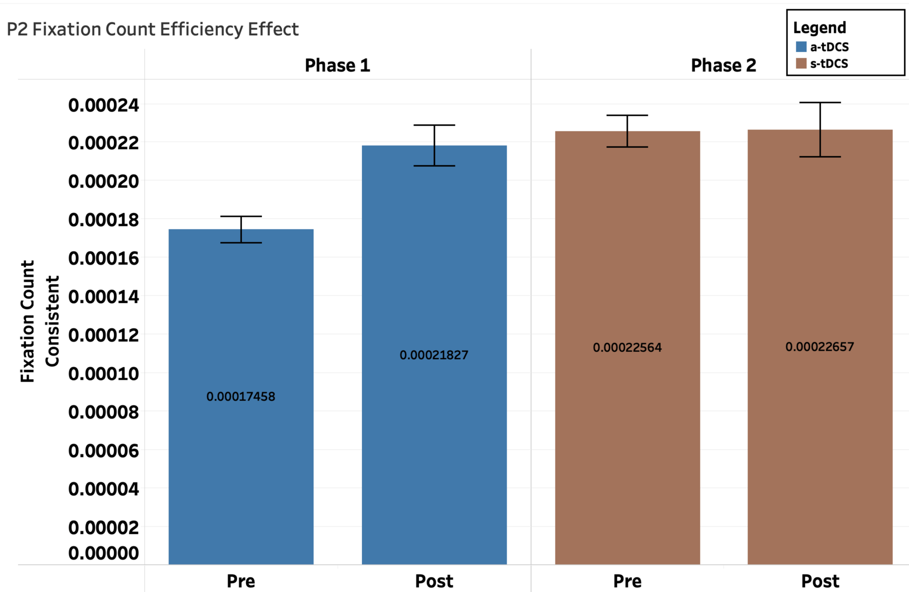
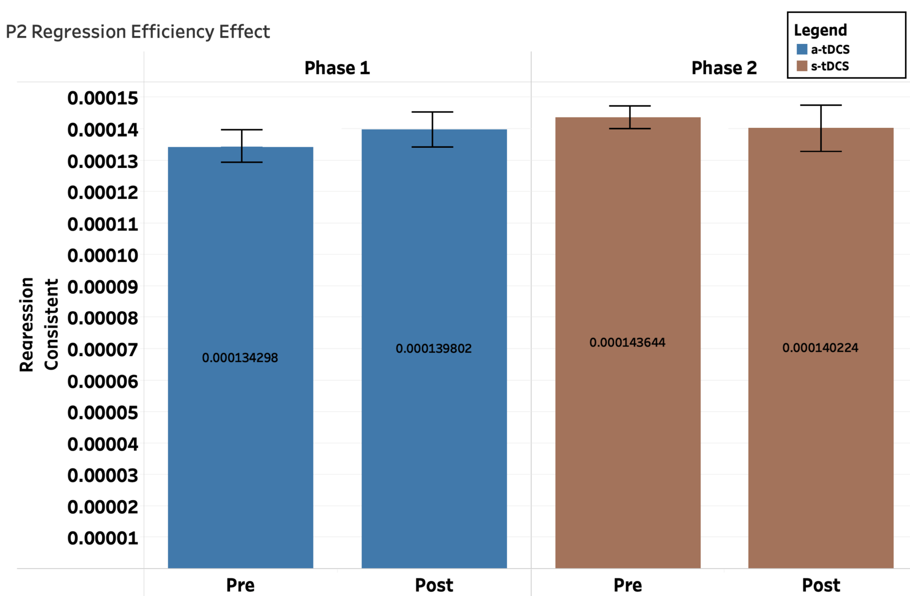


Figure 17. P2 Regression Efficiency Effect

No significant changes in regressions when reading consistent passages after treatment in either phases.



Consistency effect. In this inferred measure of reading comprehension, differences between the reading patterns in the inconsistent and consistent passages are examined. Most notably, there was a change in the fixation count consistency effect after the first phase of treatment with a-tDCS. Aside from that change, there were minimal changes in the consistency effect for other measures in both treatment phases.

There was a greater change in the consistency effect of P2's fixation count after the first phase of treatment with a-tDCS. After treatment, he was making more fixations with consistent passages, rather than more fixations with inconsistent passages as expected. Regardless of the direction of the consistency effect, the difference suggests that P2 was responding differently to the two types of passages after treatment with a-tDCS in the first phase. After the second phase of treatment with s-tDCS, the fixation count consistency effect remained the same.

There were minimal changes in P2's dwell time consistency effect after both phases of treatment. Dwell time increased when reading consistent passages in both phases, but there was no change in the consistency effect for the dwell time measure. This means that his dwell time for inconsistent and consistent passages increased similarly after treatment. P2 did not have a noticeable regression consistency effect and had minimal changes with treatment in both conditions.

Figure 18. P2 <u>Dwell Time</u> Consistency Effect

Minimal changes in <u>dwell time</u> consistency effect observed after both phases of treatment.

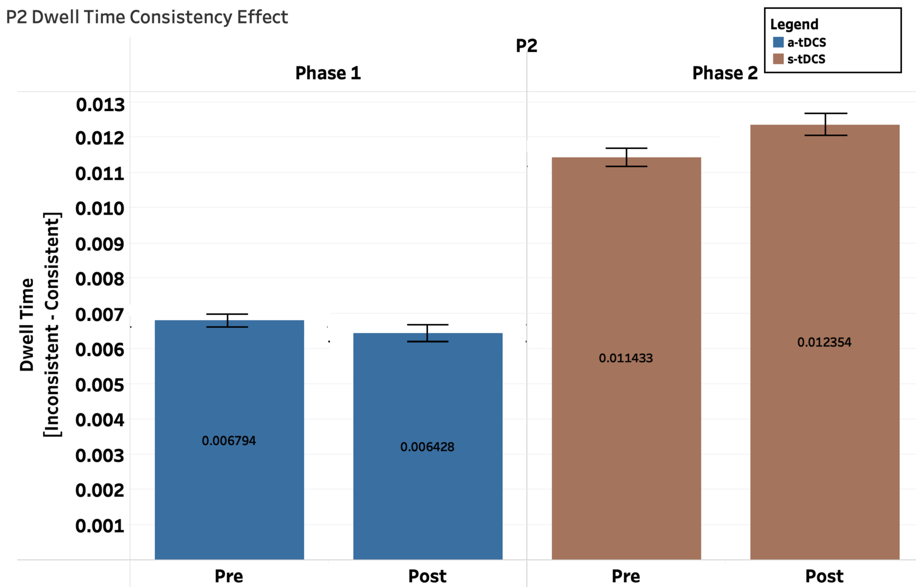


Figure 19. P2 <u>Fixation Count</u> Consistency Effect.

Greater change in <u>fixation count</u> consistency effect noted after the first treatment phase with a-tDCS. Minimal changes in <u>fixation count</u> consistency effect after second phase of treatment with s-tDCS.

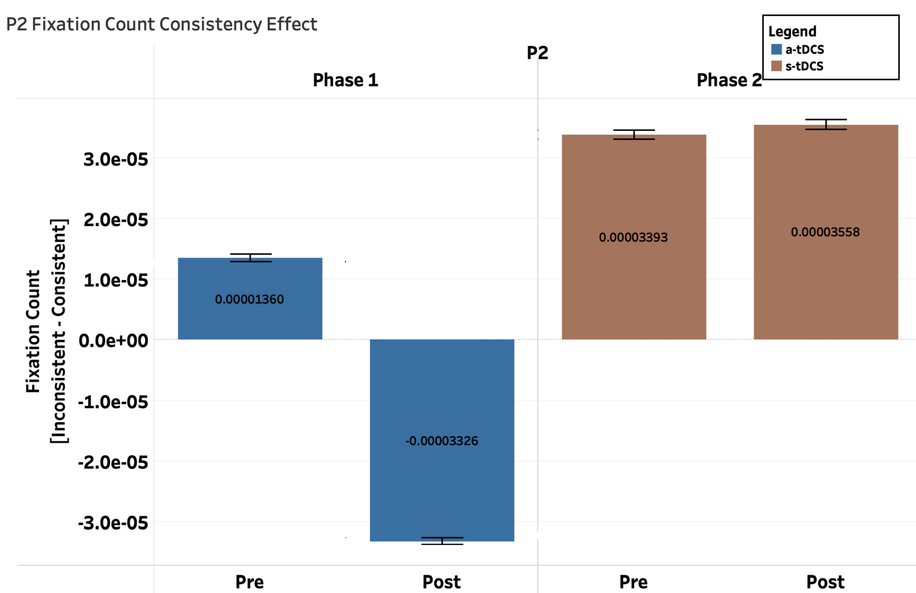
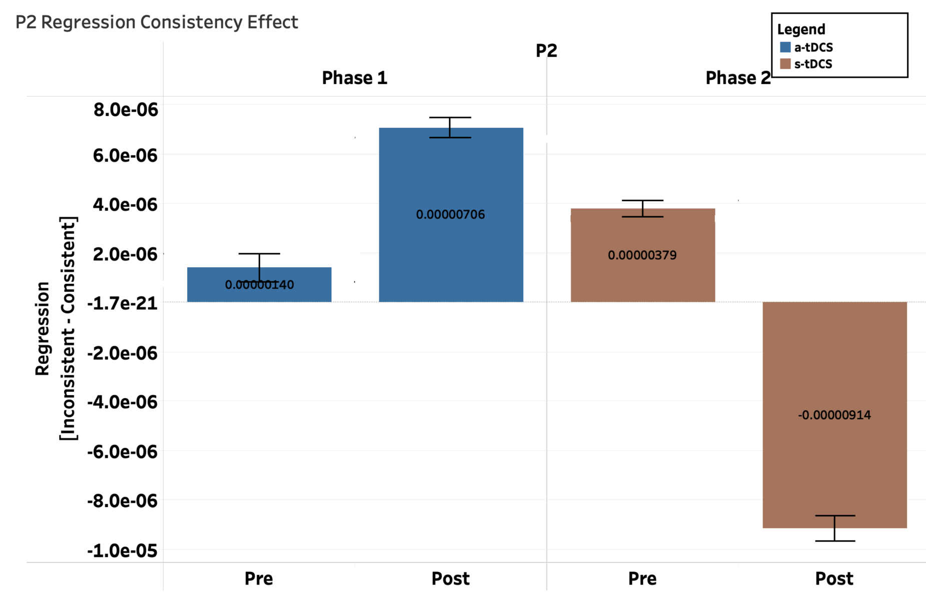


Figure 20. P2 Regression Consistency Effect.

Minimal regression consistency effect noted in both phases of treatment. Minimal changes in regression consistency effect observed after both phases of treatment. Please note scale in figure.



P2 Summary. P2 received RF+PT with a-tDCS in the first treatment phase, and s-tDCS in the second treatment phase. Overall, there were minimal behavioural and eye movement changes.

P2 had reduced sublexical skills throughout both phases of treatment. There were only changes in P2's sublexical skills in the first treatment phase; P2's sublexical reading skills increased and sublexical spelling skills decreased. With treatment in both phases, P2 became slower at reading single words, but there were no changes in his text-level reading rate, accuracy or reading comprehension.

When reading consistent passages, P2's dwell time increased after both treatment phases. The only change in his consistency effect was in fixation count after the first phase of treatment.

Treatment 2: Reading Fluency and Reading Comprehension Treatment (RF + RC)

Participants received the same treatment dosage as described in Treatment 1. The changes in behavioural and eye movement outcomes summary can be found in Table 14.

P3.

Behavioural outcomes. The KETA-3 was administered in the initial assessment session to determine the grade level that would be used for assessment and treatment. Based on his Letter and Word Subtest Score (98) and his Reading Comprehension Score (78), P2 was determined to be reading at a grade 12 level.

Table 10. Raw scores of P3's performance on assessment measures before and after treatments in both treatment phases.

P3 Pre-treatment and Post-treatment Behavioural Measures				
	Phase 1 a- tDCS		Phase 2 s-tDCS	
	Pre	Post	Pre	Post
Sublexical Skills				
CVC Nonword Spelling Accuracy (%)	72%	78%	82%	87%
CVC Nonwords Reading Accuracy (%)	93%	97%	95%	93%
Reading Fluency – Word Level				
ABRS Reading Accuracy (%)	100%	100%	93%	100%
ABRS Reading Reaction Time (ms)	482.2	485.7	524.47	506.53
ABRS Spelling Accuracy (%)	100%	100%	93%	100%
Reading Fluency – Text Level				
Accuracy (deviations from print per 100 words)	.9	1.3	1.2	1.4
Rate (Words per minute)	166.9	169.6	165.9	173.2
Reading Comprehension				
Multiple Choice Questions Accuracy (%)	83%	58%	77%	79%
MAZE-CBM Accuracy (%)	59%	86%	86%	81%

Sublexical skills. There were minimal changes in P3's ability to read and spell nonwords with treatment in both conditions.

Reading fluency – word level. P3 read single words consistently at 100% across each assessment time. There were no main effects of treatment (pre/post-treatment) on reaction times of reading single real words, however, there was a significant interaction effect ($F(1,29) = 5.373$, $p = .028$, $\eta p2 = .156$). Post hoc comparisons using paired *t*-tests with Bonferroni correction ($0.05/2 = 0.025$) indicated the pre-treatment mean reaction time did not significantly differ from post-treatment mean reaction time in the first treatment phase. However, in the second treatment phase, P3 read single words faster after ($p = .021$). In the first treatment phase, P3 spelled single words consistently at 100% in both pre- and post-treatment assessments. In the second phase, P3 had a lower pre-treatment spelling accuracy, which significantly improved to 100% after treatment ($\chi 2(1) = 0.463$, $p < .001$).

Reading fluency – text level. There were little changes with therapy in both conditions, on P3's reading rate and accuracy when orally reading novel passages.

Reading comprehension. P3 made the greatest gains in MAZE-CBM reading comprehension scores with treatment with a-tDCS in the first phase, demonstrating increased abilities to integrate information online. With a-tDCS, P3's improvements corresponded to a large treatment effect size (6.88) for maze reading scores, however, there was a small treatment effect decrease in multiple choice questions accuracy (-3.88). P3's changes in the s-tDCS conditions were insignificant.

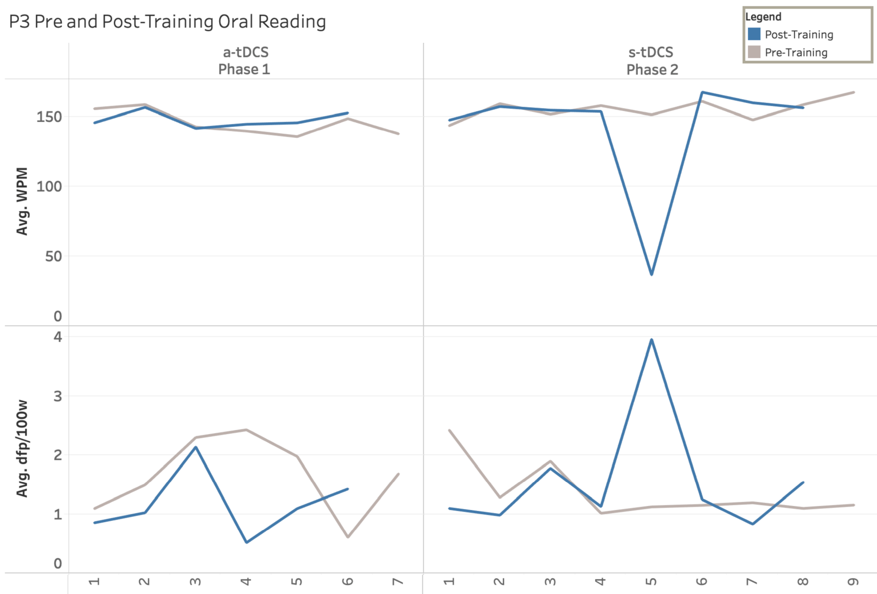
Table 11. Comparison of P3's performance on assessment measures before and after treatments in both treatment phases.

P3 Comparison of Pre to Post Outcome Measures		
	Phase 1 a- tDCS	Phase 2 s-tDCS
Sublexical Skills		
CVC Nonword Spelling Accuracy *(p)*	n.s.	n.s.
CVC Nonwords Reading Accuracy *(p)*	n.s.	n.s.
Reading Fluency – Word Level		
ABRS Reading Accuracy *(p)*	n.s.	n.s.
ABRS Reading Reaction Time *(p)*	Interaction effect <.028	
ABRS Spelling Accuracy *(p)*	n.s.	<.001*
Reading Fluency – Text Level		
Accuracy – Deviations from print per 100 words *(d)*	0.59	0.35
Rate - Words per minute *(d)*	0.16	0.49
Reading Comprehension		
Multiple Choice Questions *(d)*	-3.88*	-0.78
MAZE-CBM *(d)*	6.88*	0.08

* = treatment effect size corresponding to small effect size ($d > 2.6$)
n.s. = not significant ($p > 0.05$)

Trained reading passages. There were no changes in reading rate ($F(1,4) = .044$, $p = .845$), or accuracy ($F(1,4) = 2.077$, $p = .223$), with practice when orally reading passages.

Figure 21. P3's Pre- and Post-Training Reading Rate (WPM) and Reading Accuracy (dfp/100words) on Trained Passages.



Eye movement outcomes.

Efficiency. There were no changes in efficiency as dwell time, fixation count and regression remained the same after treatment in both phases. This suggests that there were no changes in P3's reading fluency and ease after either treatment.

Figure 22. P3 <u>Dwell Time</u> Efficiency Effect.

No significant changes in <u>dwell time</u> when reading consistent passages after treatment in either phases.

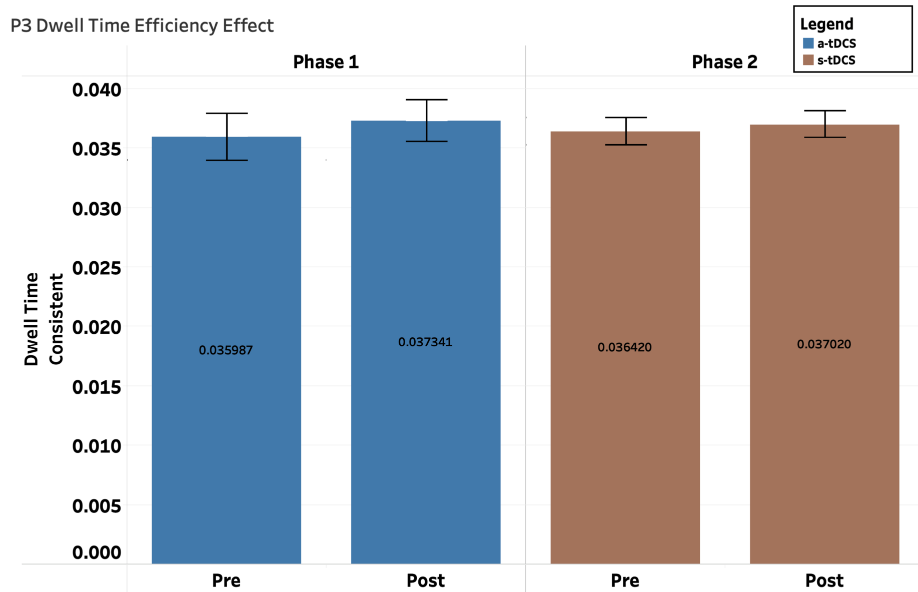


Figure 23. P3 <u>Fixation Count</u> Efficiency Effect.

No significant changes in <u>fixation count</u> when reading consistent passages after treatment in either phases.

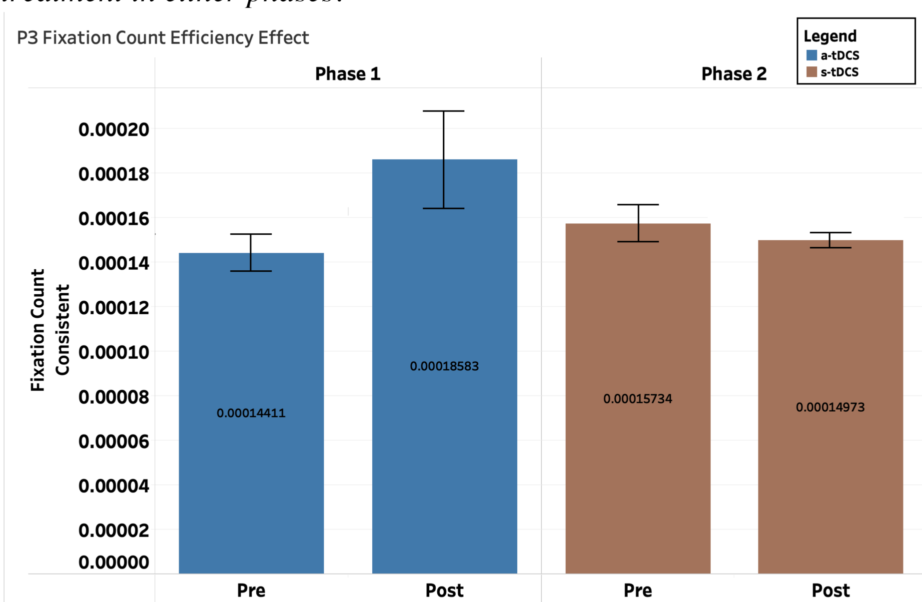
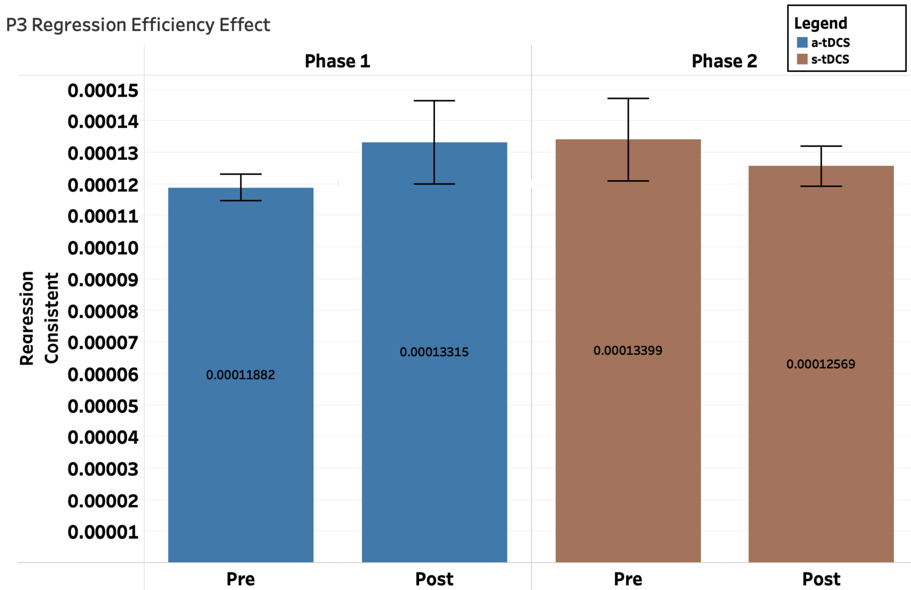


Figure 24. P3 Regression Efficiency Effect.

No significant changes in regressions when reading consistent passages after treatment in either phases.



Consistency effect. There was a greater change in dwell time and fixation count consistency effects after the first phase of treatment with a-tDCS. The second phase of treatment with s-tDCS resulted in a greater change in the regression consistency effect.

Prior to receiving treatment in the first phase with a-tDCS, there was no consistency effect in any of the three measures; P3 read inconsistent and consistent passages very similarly (as seen in the "Pre" treatment column under "Phase 1" in Figures 25, 26 and 27). After the first phase of treatment, there were changes in the consistency effect in all three measures. P3's dwell time and fixation count consistency effect increased after the first phase of treatment. He had longer dwell times and made many more fixations when reading inconsistent passages. At the same time, after the first treatment with a-tDCS, the regression consistency effect decreased and became a negative consistency effect; after treatment, he made more regressions when reading consistent passages compared to inconsistent passages regressions. Regardless of the direction of the consistency effect, treatment resulted in more differences between how P3 was reading inconsistent and consistent passages.

In the second phase of treatment with s-tDCS, there continued to be consistency effects in all three measures. However, there were minimal changes in the dwell time and fixation count consistency effect after treatment. Treatment with s-tDCS did not appear to change the difference in dwell time and fixation counts made between inconsistent and consistent passages. Before the second phase of treatment, the regression consistency effect was negative (i.e., P3 was making more regressions when reading consistent passages compared to inconsistent). There were large positive changes in the regression consistency effect after treatment, resulting in an overall smaller regression consistency effect.

Figure 25. P3 Dwell Time Consistency Effect.

Greater changes in dwell time consistency effect after treatment in the first phase with a-tDCS. Minimal changes noted after the second phase with s-tDCS.

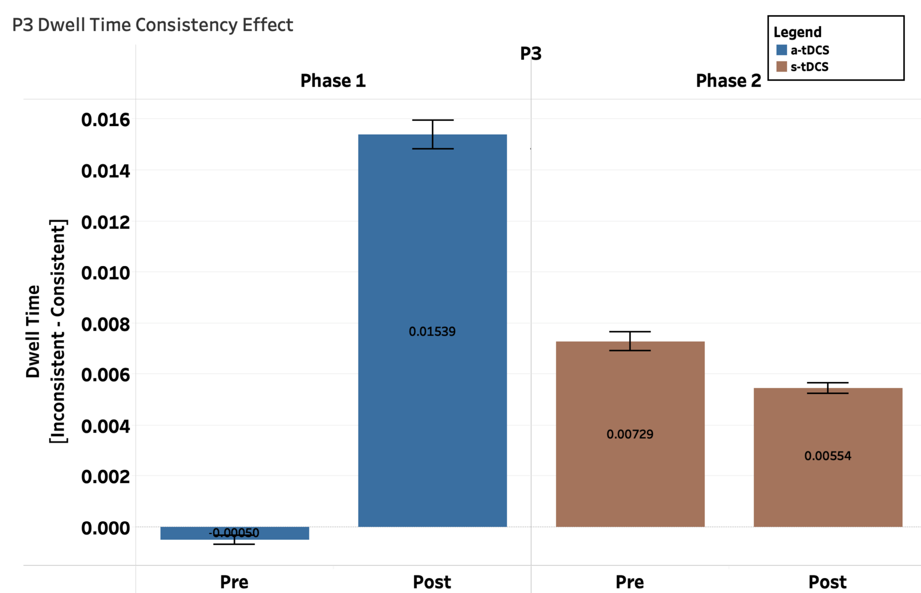


Figure 26. P3 Fixation Count Consistency Effect.

Greater changes in fixation count consistency effect after treatment in the first phase with a-tDCS. Minimal changes noted after the second phase with s-tDCS.

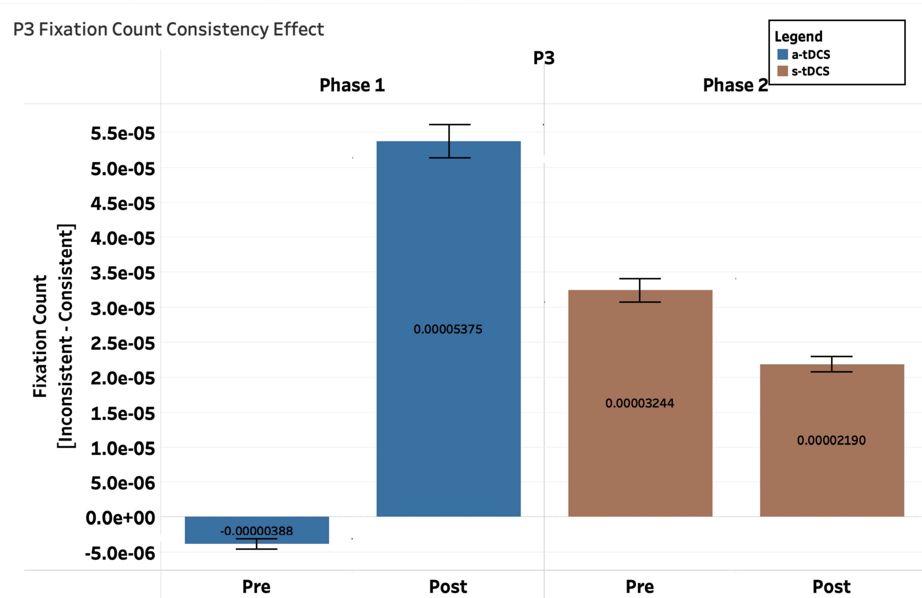
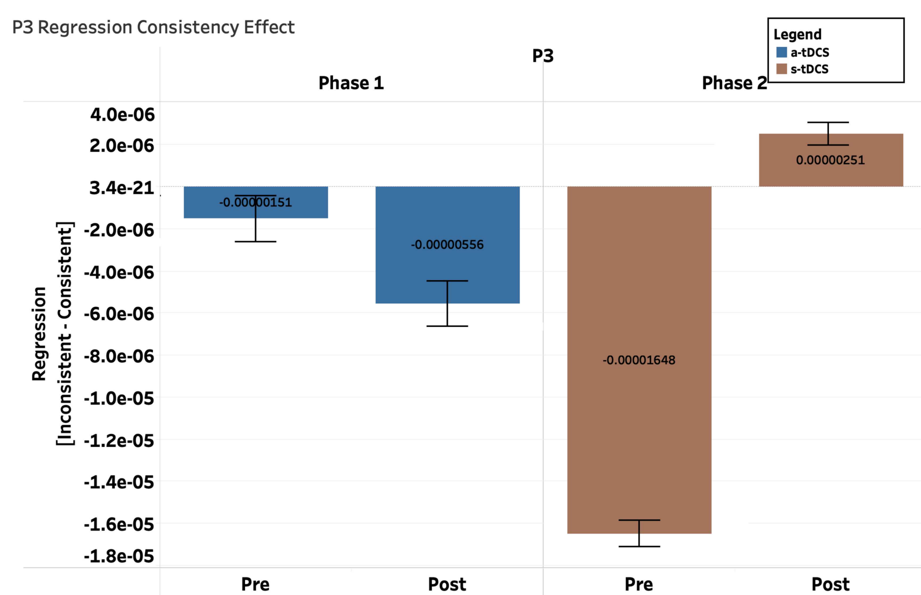


Figure 27. P3 Regression Consistency Effect.

Changes noted in regression consistency effect after both phases of treatment. Greater changes in regression consistency effect after treatment in the second phase with s-tDCS.



P3 Summary. P3 received RF+RC with a-tDCS in the first treatment phase, and s-tDCS in the second treatment phase. P3 was already performing with high accuracy on multiple measures, prior to treatment. After the second phase of treatment, he became faster at reading single words. His text-level reading rate and accuracy remained constant.

Greater changes in the dwell time and fixation count consistency effect after the first phase of treatment with a-tDCS, were accompanied by significant gains in online reading comprehension. In the second treatment phase with s-tDCS, there was a larger change in the regression consistency effect, however minimal gains in reading comprehension.

P4.

Behavioural outcomes. The KETA-3 was administered in the initial assessment session to determine the grade level that would be used for assessment and treatment. Based on his Letter and Word Subtest Score (74) and his Reading Comprehension Score (70), P4 was determined to be reading at a grade 9 level.

Table 12. Raw scores of P4's performance on assessment measures before and after treatments in both treatment phases.

P4 Pre-treatment and Post-treatment Behavioural Measures				
	Phase 1 s- tDCS		Phase 2 a-tDCS	
	Pre	Post	Pre	Post
Sublexical Skills				
CVC Nonword Spelling Accuracy (%)	75%	80%	75%	85%
CVC Nonwords Reading Accuracy (%)	97%	97%	97%	95%
Reading Fluency – Word Level				
ABRS Reading Accuracy (%)	100%	93%	98%	100%
ABRS Reading Reaction Time (ms)	646.25	603.9	583.9	732.4
ABRS Spelling Accuracy (%)	90%	93%	85%	88%
Reading Fluency – Text Level				

Accuracy (deviations from print per 100 words)	2.0	2.1	1.2	1.9
Rate (Words per minute)	116.8	101.5	109.1	113.8
Reading Comprehension				
Multiple Choice Questions Accuracy (%)	75%	75%	75%	67%
MAZE-CBM Accuracy (%)	91%	99%	95%	100%

Sublexical skills. P4 was consistently reading CVC nonwords at a high accuracy over the four assessment time periods. In the a-tDCS condition, P4 improved in his ability to spell CVC nonwords ($\chi 2(1) = 0.1$, $p = .03$), however, this improvement was not seen in the s-tDCS condition.

Reading fluency – word level. P4 was also consistently reading real single words with high accuracy over the four assessment time periods. His accuracy in spelling real words did not change in either phases after treatment. His reaction time for reading real single words changed with therapy ($F(1,19) = 7.598$, $p = .013$, $\eta p2 = .286$), and there was an interaction effect ($F(1,19) = 24.240$, $p < .001$, $\eta p2 = .561$). Post hoc comparisons using paired *t*-tests with Bonferroni correction (0.05/2 = 0.025) indicated the pre-treatment mean reaction time did not significantly differ from post-treatment mean reaction time in the first treatment phase. However, in the second treatment phase, post-treatment mean reaction times increased, significantly differing from pre-treatment reaction times ($p < .001$).

Reading fluency – text level. P4 also did not make gains in reading rate or accuracy with novel passages in either phase.

Reading comprehension. P4's multiple choice comprehension of novel passages did not improve with treatment in either condition. However, there was a small treatment effect (2.9) on his reading comprehension on the MAZE-CBM task in the s-tDCS condition. While he did make gains in maze reading in the a-tDCS condition (achieving 100% in post-treatment assessments), the treatment effect size was less than the threshold for a small effect size (Robey et al., 1999).

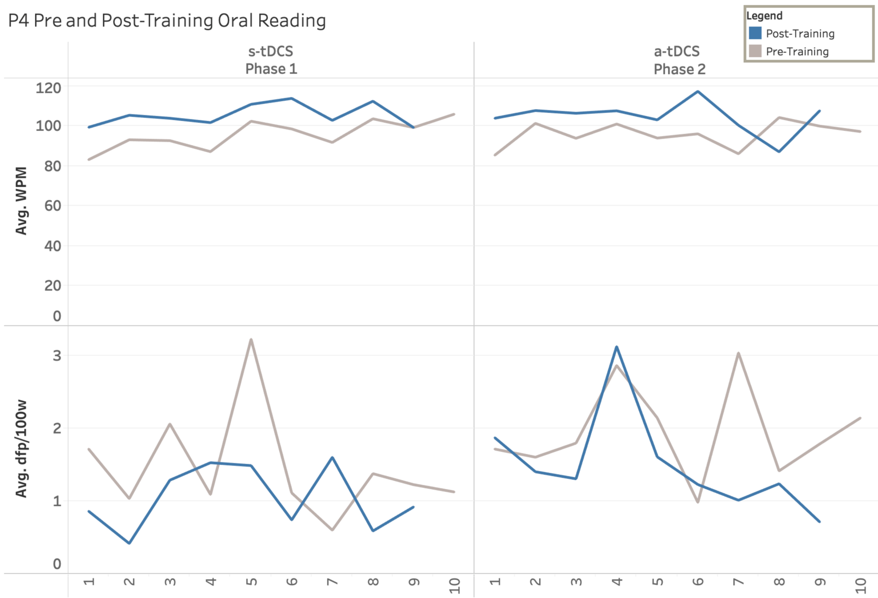
Table 13. Comparison of P4's performance on assessment measures before and after treatments in both treatment phases.

P4 Comparison of Pre to Post Outcome Measures		
	Phase 1 s-tDCS	Phase 2 a-tDCS
Sublexical Skills		
CVC Nonword Spelling Accuracy *(p)*	n.s.	0.03
CVC Nonwords Reading Accuracy *(p)*	n.s.	n.s.
Reading Fluency – Word Level		
ABRS Reading Accuracy *(p)*	n.s.	n.s.
ABRS Reading Reaction Time *(p)*	Treatment effect .013 Interaction effect <.001	
ABRS Spelling Accuracy *(p)*	n.s.	n.s.
Reading Fluency – Text Level		
Accuracy – Deviations from print per 100 words *(d)*	0.09	0.86
Rate - Words per minute *(d)*	-0.76	0.17
Reading Comprehension		
Multiple Choice Questions *(d)*	0	-0.38
MAZE-CBM *(d)*	2.9*	1.14

* = treatment effect size corresponding to small effect size (*d* > 2.6)
n.s. = not significant (*p* > 0.05)

Trained reading passages. In both phases, P4 read his trained passages faster ($F(1,6) = 46.569$, $p < .001$) with more accuracy ($F(1,5) = 22.631$, $p = .005$) after practicing.

Figure 28. P4's Pre- and Post-Training Reading Rate (WPM) and Reading Accuracy (dfp/100words) on Trained Passages.



Eye movement outcomes.

Efficiency. Treatment resulted in changes of efficiency when reading consistent passages, as there were main effects of treatment with dwell time ($F(1,11) = 6.835$, $p = .024$) and fixation count ($F(1,11) = 15.641$, $p = .002$). There was also an interaction effect for all measures: dwell time ($F(1,11) = 18.173$, $p = .001$), fixation count ($F(1,11) = 20.124$, $p = .001$) and regressions ($F(1, 11) = 6.876$, $p = .024$) efficiency effect.

Post hoc comparisons using paired *t*-tests with Bonferroni correction (0.05/2 = 0.025) indicated that dwell time and fixation count did not significantly differ before and after treatment in the first treatment phase (s-tDCS). However, following the second treatment phase (a-tDCS), P4's dwell time decreased ($p = .001$) and he made significantly fewer fixations ($p < .001$).

Number of regressions did not significantly differ before and after treatment in either phase. P4 read with more efficiency after the second phase of treatment with a-tDCS.

Figure 29. P4 Dwell Time Efficiency Effect.

No change in Dwell time after the first phase of treatment with s-tDCS and significantly decreased after the second phase of treatment with a-tDCS.

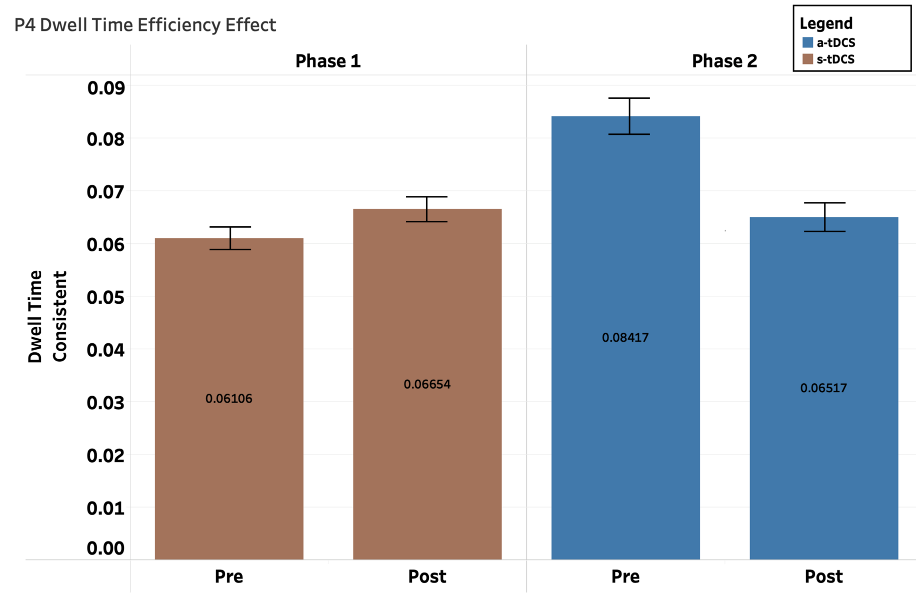


Figure 30. P4 Fixation Count Efficiency Effect.

No change in fixation counts after the first phase of treatment with s-tDCS and significantly decreased after the second phase of treatment with a-tDCS.

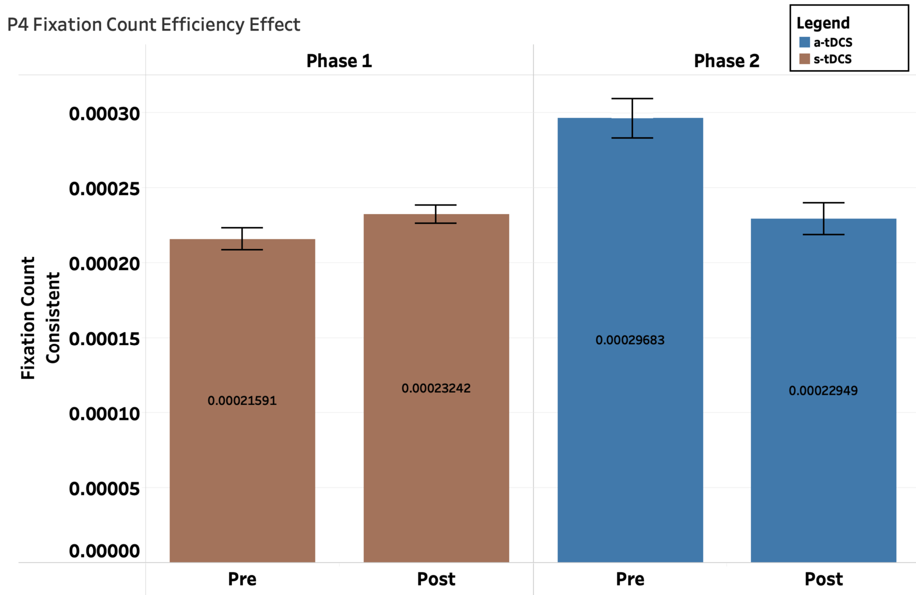
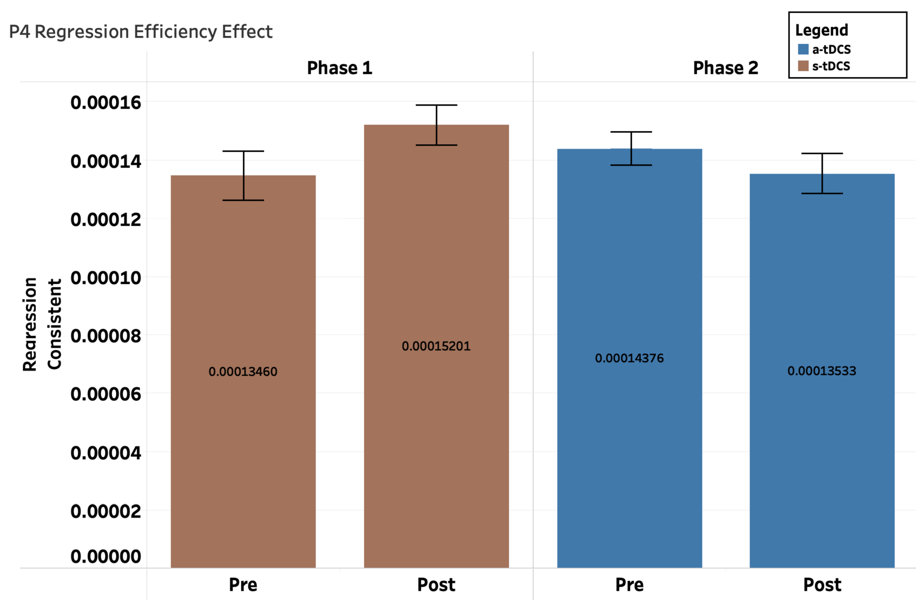


Figure 31. P4 Regression Efficiency Effect.

No difference in pre- and post-treatment regressions after both treatment phases.



Consistency effect. In P4, there were greater changes in the dwell time, fixation count and regression consistency effect after the second phase of treatment paired with a-tDCS.

Both before and after the first phase of treatment with s-tDCS, there were minimal dwell time or fixation count consistency effects observed. There was a change in the regression consistency effect after the first phase of treatment. Specifically, after treatment P4 made more regressions when reading consistent compared to inconsistent passages, resulting in a more negative regression consistency effect. However, there was a greater change in the regression consistency effect after the second phase of treatment.

In the second phase of treatment with a-tDCS, P4 demonstrated a dwell time and fixation consistency effect before treatment. There was no regression consistency effect before treatment. After a-tDCS in the second phase, there was an increase in the dwell time, fixation count and regression consistency effect.

Figure 32. P4 Dwell Time Consistency Effect.

Minimal dwell time consistency effect observed before and after the first phase of treatment with s-tDCS. Greater change in dwell time consistency effect after the second phase of treatment with a-tDCS.

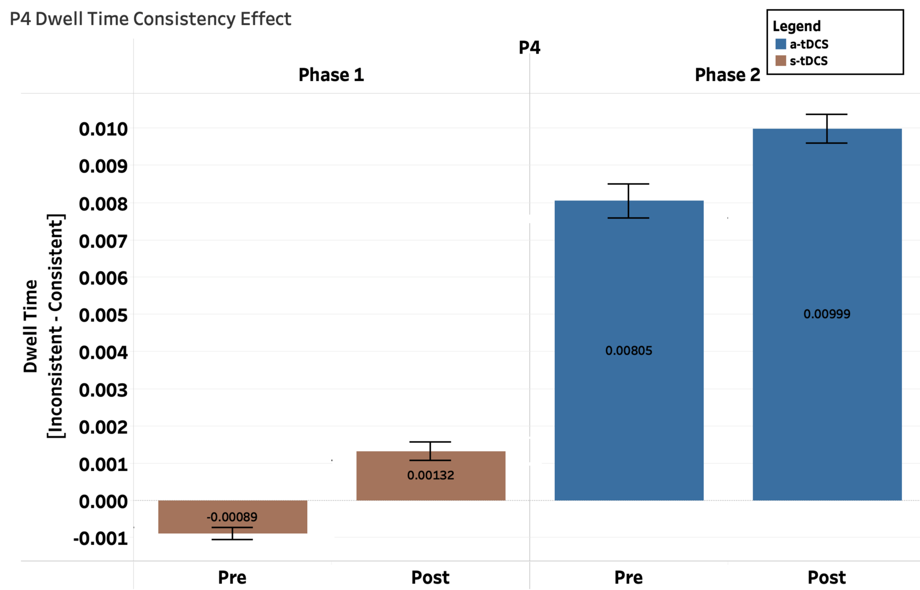


Figure 33. P4 Fixation Count Consistency Effect.

Minimal fixation count consistency effect observed before and after the first phase of treatment with s-tDCS. Greater change in fixation count consistency effect after the second phase of treatment with a-tDCS.

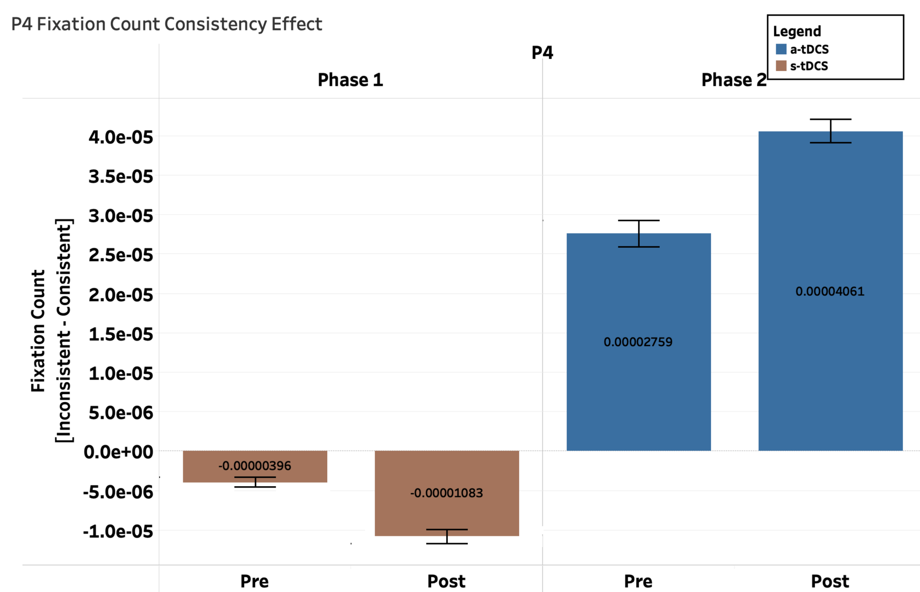
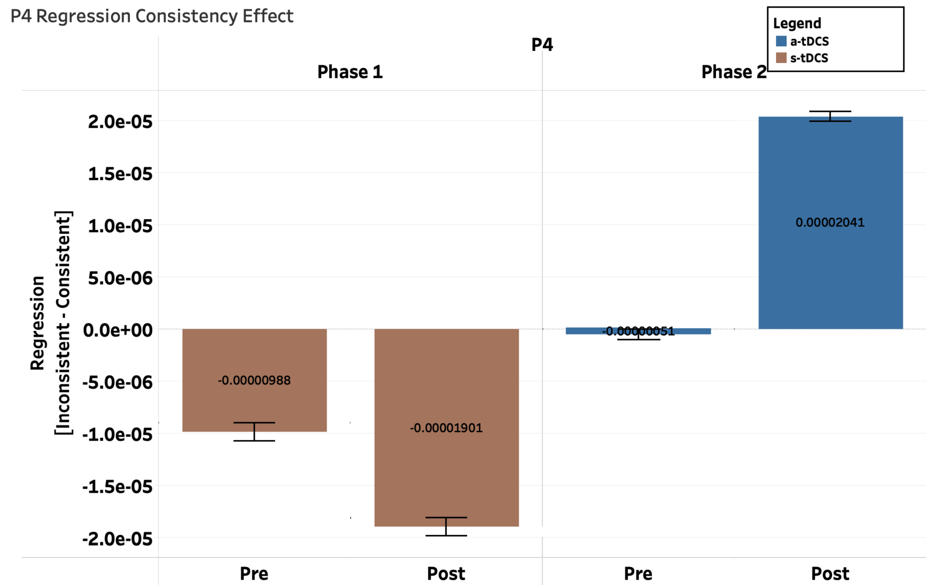


Figure 34. P4 Regression Consistency Effect.

Greater change in regression consistency effect after the second phase of treatment with a-tDCS.



P4 Summary. P4 received RF+RC with s-tDCS in the first phase of treatment, and a-tDCS in the second phase of treatment. P4 made more behavioural gains in the first treatment phase with s-tDCS, however, had more eye movement changes after the second treatment phase with a-tDCS.

P4's sublexical spelling improved after the second phase of treatment. He read single words slower after the second phase of treatment. His text-level reading rate and accuracy remained constant.

When reading consistent passages, there were decreases in dwell time and fixation count after the second phase. There were minimal changes in the consistency effects after the first phase of treatment, however, there were significant gains in reading comprehension. There were greater changes in the consistency effect of all three of the eye movement measures after the second phase of treatment paired with a-tDCS. However, these changes in eye movements did not coincide with gains in reading comprehension.

Table 14 provides a summary of behavioural and eye-movement outcomes for all four participants.

Table 14. Summary Table of Pre- to Post-Treatment Changes in Behavioural Outcomes and Eye Movement Outcomes for All Participants in Both Treatments

--- = no change between pre- and post-treatment; **↑** *= statistically significant increase from pre- to post-treatment;* ↑ *= non-statistically significant increase from pre- to post-treatment;* **↓** *= statistically significant decrease from pre- to post-treatment;* ↓ *= non-statistically significant decrease from pre- to post-treatment;* ▵ *= smaller change from pre- to post-treatment;* △ *= larger change from pre- to post-treatment; grey shading denotes treatment phases with a-tDCS*

Pre to Post-treatment Changes in Behavioural and Eye Movement Outcomes								
	Treatment 1				Treatment 2			
	P1		P2		P3		P4	
	Phase 1	Phase 2	Phase 1	Phase 2	Phase 1	Phase 2	Phase 1	Phase 2
Sublexical Skills								
CVC Nonword Spelling Accuracy *(p)*	**↑**	**↑**	**↓**	---	---	---	---	**↑**
CVC Nonwords Reading Accuracy *(p)*	---	---	**↑**	---	---	---	---	---
Reading Fluency – Word Level								
ABRS Reading Accuracy *(p)*	---	---	---	---	---	---	---	---
ABRS Reading Reaction Time *(p)*	---	**↑**	**↑**	**↑**	---	**↓**	---	**↑**
ABRS Spelling Accuracy *(p)*	---	---	---	---	---	**↑**	---	---
Reading Fluency – Text Level								
Accuracy – Deviations from print per 100 words *(d)*	↑	↓	↓	↓	↑	↑	↑	↑
Rate - Words per minute *(d)*	**↑**	↑	↑	↑	↑	↑	↓	↑
Reading Comprehension								
Multiple Choice Questions *(d)*	↑	↑	↑	↓	**↓**	↓	---	↓

MAZE-CBM *(d)*	↑	↑	↑	↑	↑↑	↓	↑	↑
Eye Movement – Efficiency								
Dwell time	---	---	↑	↑	---	---	---	↓
Fixation count	---	---	---	---	---	---	---	↓
Regressions	↓	---	---	---	---	---	---	---
Eye Movement – Consistency								
Dwell time	△	△	---	---	△	---	---	△
Fixation count	△	△	△	---	△	---	---	△
Regressions	△	---	---	---	△	△	---	△

Discussion

In the present study, four individuals with alexia received reading treatment combined with non-invasive brain stimulation. Two individuals with mild-moderate alexia received treatment aimed at improving sublexical skills and reading fluency (RF+PT treatment), and the other two individuals with mild alexia received treatment aimed at improving reading fluency and comprehension (RF+RC treatment). All participants received two phases of treatment, counterbalanced across pairs: one phase with a-tDCS and the other phase with s-tDCS. Various assessment tools were utilized to measure the participants' abilities along the continuum of reading skills (please refer to Figure 3). Assessments were administered before and after each treatment phase to determine if treatment resulted in reading gains, and if the treatment combined with the a-tDCS resulted in augmented gains.

Treatment 1: Reading Fluency + Phonological Treatment (RF+PT)

P1 and P2 had lower reading abilities and more impaired sublexical skills compared to the other two participants. The behaviour and eye movement results after treatment provide support for the reading skills continuum and the relationship between sublexical skills and reading fluency as requisite skills for reading comprehension (Cherney, 2004; Eason et al., 2013; Gough & Tumner, 1986).

P1. The presence of behavioural gains and corresponding eye movement changes in both treatment phases provides evidence that a reading approach combining reading fluency and phonological skills treatment can be effective in remediating reading impairments and can also affect the reader's underlying reading mechanism.

P1's sublexical skills were impaired before treatment, but improved after both treatment phases, suggesting that RF+PT treatment is effective in targeting sublexical skills. P1 demonstrated incremental gains across the reading skills continuum depicted in Figure 3. Namely, after the first phase of treatment, her sublexical skills and reading fluency improved. After the second phase she demonstrated continued improvements in sublexical skills, maintained her gains in reading fluency from the first phase and also improved her reading comprehension. These changes in P1's reading abilities across the two conditions demonstrate the theoretical basis of the reading skills continuum; when sublexical decoding skills are strong, it allows for increased reading fluency, which in turn promotes reading comprehension (Cherney, 2004; Eason et al., 2013).

Using a phonological treatment approach combined with a reading fluency approach appeared to be effective in targeting P1's reading fluency and reading comprehension.

Considering the behavioural gains with changes in eye movements may provide insight towards the underlying mechanism contributing reading improvements or persisting deficits (Rayner et al., 2006). After the first phase of RF+PT with s-tDCS, P1 had greater reading efficiency with decreased regressions, and a larger change in number of fixations and regressions when reading consistent versus inconsistent paragraphs, accompanied by faster behavioural text reading. Although there were many eye movement changes and reading rate changes, there were insignificant reading comprehension gains.

In the second phase of treatment with a-tDCS, there was a larger difference in the duration of fixations (dwell time) she made when reading consistent versus inconsistent passages. These changes in eye movements after the second phase of treatment were combined with slower single word reading, limited gains in reading rate but significant gains in reading comprehension. These results seem to suggest that mechanistically, spending a longer time fixating on words may have resulted in increased reading comprehension. These changes may have been facilitated by the addition of a-tDCS in the second treatment phase or may simply have been due to the additive effects of an additional treatment dose.

These results suggest that in a participant with mild-moderate aphasia and alexia, treatment that increases sublexical reading skills facilitates improvements in reading fluency, as seen in P1 after both phases of RF+PT treatment. When the same treatment (RF+PT) is combined with a-tDCS, there are significant improvements in reading comprehension which may come at a cost of decreased reading speed, as seen in P1 after the second phase of treatment. Whether this was truly a result of the stimulation or a result of a treatment order effect bears replication with additional participants.

P2. P2's lack of behavioural gains can potentially be attributed to a client profile that may not be suitable for RF+PT. P2 provides an example of an individual who had impaired sublexical skills and who also did not experience reading fluency or comprehension gains. P2's pattern of results also corroborates the existence of the reading skills continuum, that impaired sublexical skills may prevent gains in reading skills further along the continuum. Interestingly, P2 had better sublexical skills than P1 before treatment, but still experienced limited behavioural gains. According the reading skills continuum, P2 would have been expected to achieve greater reading fluency and reading comprehension gains because of his less impaired sublexical skills. Potentially, P2's impaired sublexical skills remained an unsurmountable barrier for his reading fluency and comprehension to improve. Although P1 had more impaired sublexical skills before treatment, her sublexical spelling was responsive to RF+PT after both treatment phases and she was able to generally maintain the gains. Conversely, P2's sublexical skills had mostly insignificant decreases after treatment in both phases. Individuals like P2, who have impaired sublexical skills that are not responsive to treatment, may have limited reading fluency and comprehension gains with an RF+PT protocol. In addition to confirming that sublexical skills are necessary for reading fluency and comprehension (Cherney, 2004; Eason et al., 2013), P2's profile and corresponding minimal treatment gains contribute additional information to the reading skills continuum and its impact on reading ability. Beyond requiring sufficient sublexical skills, *improving* sublexical skills may be required for reading fluency and phonological based approaches to have an effect on reading fluency and comprehension.

Of the minimal changes in P2's eye movements, the most changes were seen when treatment was paired with a-tDCS. However, the differences did not appear to be significant enough to influence the reading mechanisms underlying increases in reading fluency or comprehension. tDCS is known to be task-dependent, modulating what is ongoing during the time of stimulation (Galletta et al., 2016). Thus, the lack of underlying changes in eye movements with treatment alone (without stimulation) could mean that there was minimal existing change for the active stimulation to further augment when it was applied. This provides further evidence that a-tDCS is only effective in augmenting the treatment effects of an individual who was already responding and making gains from the treatment itself.

Effects of RF+PT treatment and tDCS with mild-moderate alexia. The different treatment effects P1 and P2 experienced provides insight into most suitable participant profiles for this treatment approach, and how a-tDCS can be applied.

Generalizability of text-based alexia treatments. If one were to think about stimuli they read as part of their activities of daily living, (e.g., emails, text messages, articles, disclaimers, pamphlets, store and traffic signs, menus) the majority of what is read is not single words but connected text. Therefore, it is essential for alexia treatments to have functional translations in generalizing to connected text. Otherwise, if gains are limited to the treatment environment or to single words, the treatment will not result in changes in the PWA's quality of life. However, generalization to novel stimuli has been a consistent challenge in alexia treatments, particularly with single word reading treatment approaches (Cherney, 2004). A recent study showed that even with a-tDCS, improvements with a single word treatment approach was limited to trained single word stimuli, with no gains in connected text (Woodhead et al., 2018).

In Treatment 1, ORLA and MOR were used to train reading fluency. P1 had generalized reading fluency gains to novel passages (SRA and DIBELS used in pre- and post-testing) and had reading comprehension gains even though the protocol did not target comprehension directly. These results corroborate the increased generalizability of text-based treatment approaches to novel stimuli, as well as the facilitative nature of training reading fluency on reading comprehension (Cherney, 2004, 2010; Russo & Kim, 2010).

Treatment intensity. P1 underwent a similar treatment protocol to the case study in the Brown et al., (2016) study. There are considerable differences between the two studies, but treatment intensity was a distinctive difference. The individual in the Brown et al., (2016) study received one to three, one-hour sessions per week totaling 40 hours over months. P1 received a more intensive treatment, with 2 hours of reading practice a day totaling 20 hours over 2 weeks. Although both PWA received highly comparable treatments, P1 demonstrated greater treatment effect sizes for reading fluency in the first treatment phase and reading comprehension in the second treatment phase. The participant in the Brown et al., (2016) study only had notable gains in sublexical skills, with informal gains in reading fluency and comprehension. When solely comparing the outcomes of similar treatment protocols with different intensities, a more intensive multimodal reading treatment may be more efficacious for higher level reading skills such as text-level reading fluency and reading comprehension in individuals with mild-moderate alexia.

Effects of multicomponent reading treatment and individualization of RF+PT. A multicomponent reading fluency with phonological treatment approach combined with a-tDCS may be most effective for an individual who: 1) has mild-moderate aphasia; and 2) is demonstrating response to treatment with improving sublexical skills. There is currently little information on how alexia treatment can be individualized to the client's ability profile (Leff & Benrmann, 2008), thus the present study provides pertinent information on the suitability of RF+PT for different client profiles and how RF+PT can be individualized.

Many alexia treatments to date target one component of the reading skills continuum. The pilot study presented at the beginning of the study and Brown and colleges were some of the first groups to explore the text-level reading treatment effects of combining multiple reading treatment approaches (Brown et al., 2016; Lee et al., 2017). Results of the present study corroborates the benefit of targeting multiple reading skills in a multicomponent treatment protocol to increase sublexical and reading comprehension abilities (Brown et al., 2016). The present study presents additional evidence that a multicomponent reading treatment should first be directed towards weak requisite skills in the individual's reading profile. In Brown et al's., (2016) case study, PA from the pilot study, and P1 from the present study, increases in sublexical skills occurred along with informal gains in functional reading (Brown et al., 2016), and significant gains in reading comprehension (Lee et al., 2017). However, P2 and PB had impaired and non-responsive sublexical skills and did not experience gains in reading fluency and comprehension. This demonstrates that targeting skills further along the continuum may be futile as preliminary skills are a precondition for latter skills (Cherney, 2004; Gough & Tumner, 1986). Treatment effects of the multicomponent RF+PT show that it may not be suitable for all clients to receive the established protocol of first targeting sublexical skills and then reading fluency in the second half. In a multicomponent reading treatment such as RF+PT, it may be a more efficient use of treatment resources to first focus on establishing changing/improving sublexical skills before shifting the treatment focus to include reading fluency and comprehension. For individuals not demonstrating improving sublexical skills, consideration can be given to prioritize gains in phonological skills before focusing on reading tasks.

Treatment 2: Reading Fluency and Reading Comprehension Treatment (RF+RC)

P3 and P4 had higher reading abilities, relatively intact sublexical skills and single word reading and spelling. They had limited gains in these areas, but relatively high accuracy before receiving treatment, which could mean that they were already performing close to their ceiling in these 'lower level' reading skills. It also provides more support for the reading skills continuum. P3 and P4 were examples of individuals who had higher and stable sublexical and reading fluency skills and were able to make gains in reading comprehension after RF+RC treatment. Potentially their prerequisite and foundational skills of decoding and reading fluency were sufficiently automated prior to treatment, allowing them to direct ample cognitive resources to reading comprehension and its improvement.

P3. P3 provides another example of treatment with a-tDCS leading to minimal changes in single word reading, minimal gains in reading rate of connected text, but increases in reading comprehension (similar to P1). P3's consistent single word and text-level reading fluency across both treatment phases, suggests that RF+RC with and without active tDCS, is not effective at increasing reading rate with individuals with mild alexia, who are already close to their ceiling reading rate. Comprehension gains were only noted after the first phase with a-tDCS, which could indicate a-tDCS's effect in augmenting gains or could represent a treatment order effect.

In the first phase with a-tDCS, there were significant reading comprehension gains coinciding with changes in the dwell time and fixation count consistency effect. In the second phase with s-tDCS, there was a lack of reading comprehension gains with a larger change in the regression consistency effect. P3's gains after the first phase of treatment provides evidence that an RF+RC approach with a-tDCS is effective for promoting behavioural gains and corresponding changes in the underlying reading mechanism observed in eye movements. Increases in reading comprehension could be correlated with shifts in reading pattern to account for changes in dwell time and fixation count consistency effects. That is, when encountering comprehension breakdowns, fixating longer and making more fixations could potentially reflect improved contextual integration skills. Taken together with P1's results, both individuals exhibited changes in the length of time they were fixating on consistent versus inconsistent words, suggesting this change in dwell time paired with a-tDCS could be the common factor underlying increased reading comprehension.

P4. Similar to other participants, P4 became slower to read single words with a-tDCS in the second phase. However, unlike P1 and P3, comprehension gains were not noted after the second treatment phase with a-tDCS; they were only noted after the first phase with s-tDCS. In P4, most behavioural gains occurred after the first phase of treatment. Combined with the results of P3, it suggests that the most treatment gains followed the first 20 hours of treatment. With individuals with mild alexia receiving RF+RC, a-tDCS does not appear to augment treatment gains beyond what is achieved in the first 20 hours of treatment.

Examining P4's treatment outcomes provides greater insight on the relationship between eye movements and reading comprehension. After the first phase of treatment with s-tDCS, he had reading comprehension gains, and limited consistency effect changes. After the second phase of treatment with a-tDCS, there was insignificant changes in reading comprehension, but many changes in consistency effects and efficiency measures. This provides an example of the paradoxical effect seen in studies examining eye movements following treatment (Ablinger, Huber, Schattka, & Radach, 2013; Kim & Lemke, 2016), where there are behavioural gains but minimal changes in eye movements, and vice versa. P1 and P3's results suggest that changes in dwell time consistency effect reflect the reading mechanism associated with reading comprehension gains. However, when this is interpreted with P4's results, it appears that changes in the regression consistency effect may limit or reflect a lack of reading comprehension improvement, even when there is change in dwell time consistency effect. Potentially, if an individual can slow down their reading rate (i.e., increase dwell time) and/or skip over less words (i.e., make more fixations), without changing how many times they moved back to previously read text (i.e., no change in regressions), these may be all that is needed to increase reading comprehension.

In the present study, the presence of a regression consistency effect is a minute measure in the large battery of outcome measures. However, a minimal change in regression consistency effect is the most consistent factor present in phases, across all participants, who demonstrated gains in reading comprehension. These associations drawn between eye movement measures and behavioural gains are preliminary attempts to understand the mechanisms underlying treatment induced reading gains.

RF+RC treatment for mild alexia. These two participants further exemplify the reading skills continuum, and the necessity of established sublexical skills and reading fluency to make further gains in reading comprehension (Cherney, 2004; Eason et al., 2013; Gough & Tumner, 1986). In both participants, reading gains were demonstrated on the MAZE-CBM task, suggesting an RF+RC approach may facilitate decoding and context integration skills.

Efficacy of RF+RC approach. Though more treatment studies on multicomponent reading treatments are emerging, there has yet to be a reading fluency treatment combined with a protocol that targets reading comprehension directly. The Brown et al., (2016) study discussed previously involved phonological and reading fluency approaches, however, did not incorporate aspects that were intended to remediate reading comprehension. Since the present RF+RC is a novel multicomponent treatment, there is a need to determine if there is a value in combining existing ARCS and reading strategy based treatments with reading fluency approaches.

To build upon the discussions in Treatment 1 around the generalizability of treatment outcomes on untrained stimuli, Treatment 2 show that using an RF+RC also results in reading comprehension gains with untrained text-level passages. Since the RF+RC protocol is derived from a combination of MOR (Moyer, 1979), ARCS-W (Obermeyer & Edmonds, 2018) and reading strategy based treatment (Cocks et al., 2013), gains can be attributed to the combination of the three treatment approaches. Comparing results from the present study with each of the three treatment studies may provide value in delineating the observed treatment effects.

MOR has been investigated by multiple researchers and has been consistently shown to result in increases in decoding, reading fluency, comprehension (Beeson & Insalaco, 1998; Cherney, 2004; Kim & Lemke, 2016; Russo & Kim, 2010), and even lexical-semantic working memory (Mayer & Murray, 2002). P3 and P4 in the present study did not experience gains in text-level reading fluency, however replicated gains in reading comprehension. The generalizability of MOR is not conclusive (Purdy et al., 2018), however, as mentioned earlier, in the present study all the pre- and post-treatment assessment batteries were completed with untrained stimuli, providing evidence of generalization.

It is difficult to compare treatment effects of the present study with the majority of ARCS and ARCS-W treatment literature because they used spoken and written discourse and single word confrontation naming outcome measures (Obermeyer & Edmonds, 2018; Rogalski & Edmonds, 2008; Rogalski et al., 2013). Webster et al., (2013) conducted a treatment study comparing ARCS and other text-based reading treatments. They used reading comprehension and fluency as outcome measures, which makes it the most comparable to the present study. Although the present study was based around the ARCS-W protocol, the only major difference between the two is the integration of written summarizations. The participant in Webster et al., (2013)'s study experienced insignificant reading fluency and comprehension gains, after treatment.

After receiving a strategy based reading approach, the individual in Cocks et al., (2013)'s study experienced significant gains in reading fluency, comprehension and in emotional factors such as confidence and pleasure. However, the study was designed for and implemented with an individual with mild alexia associated with cognitive impairments (Cocks et al., 2013). The difference in profile limits the ability to draw comparisons with the present study.

Although there were many different factors between the studies (e.g., severity of aphasia, type of alexia, type of outcome measures), all of the three treatment approaches on their own may result in some generalizable gains in reading fluency and/or comprehension. In the present study, only reading comprehension gains were observed, suggesting that combining multiple approaches within the same treatment session may result in limited gains in reading fluency. However, further exploration on the benefits of a multicomponent reading treatment involving direct reading comprehension remediation is warranted.

Treatment intensity. Treatment 2 adds additional insight into determining the appropriate treatment dosage for people with mild alexia. From the results of the present study, individuals with high reading abilities may only benefit from the first dosage (i.e., 20 hours over two weeks) of intensive treatment with MOR and ARCS to increase their abilities to integrate contextual information. There were minimal behavioural gains in the second treatment phase for both participants irrespective of the tDCS condition. Thus, beyond the 20 hours, more treatment within 1.5 months after the first dosage may not be effective in improving reading outcomes.

In addition, the present study had the most intensive dosage of behavioural treatment compared to similar studies of acquired alexia. Participants in many of the studies described above only received 1 hour of treatment per week once a week (e.g., Cocks et al., 2013; Kim & Lemke, 2016), or 1-1.5 hours twice a week (e.g., Obermeyer & Edmonds, 2018; Webster et al., 2013). Participants received more than two hours of treatment per week, a threshold that has been attributed to increased treatment gain (Bhogal et al., 2003; Robey, 1998). However, participants in Treatment 2 did not demonstrate augmented gains beyond what has been noted in the extant literature for each approach. This suggests that an intensive reading treatment may not be necessary for individuals with mild alexia. Furthermore, it provides supportive evidence for an opposing hypothesis that distributed practice treatment delivery may be more effective

(Dignam et al., 2016), compared to the present study's massed practice intensive treatment schedule.

Individuals with mild alexia receiving an RF+RC approach may not need an intensive treatment schedule for more than 20 hours. Having a more distributed treatment schedule, with less than 20 sessions, may be easier for the client and their clinician, but lead to comparable behavioural gains. Optimizing the treatment approach and delivery for the individual's unique abilities is essential for efficacious treatments (Leff & Benrmann, 2008).

Effects of a-tDCS on Multimodal Reading Treatment Outcomes

To date, there are only two studies involving tDCS and text-based reading treatments. Cherney et al., (2013), has explored tDCS with ORLA in an individual with severe mixed non-fluent aphasia (WAB-R AQ = 27.1/100). There were small gains of general language function, oral reading of trained and untrained sentences after ORLA with a-tDCS. However, the study did not have control condition. Lacey et al., (2014) investigated tDCS with MOR in an individual with pure alexia. When MOR was delivered with tDCS, the participant achieved gains in reading rates after fewer treatment sessions. However, pure alexia is a peripheral alexia with impairments in perception, and has a different etiology compared to the central alexias (impairments in sublexical and lexical processing) discussed in the present study (Papathanasiou & Coppens, 2017). The extant literature does not inform the effects of tDCS on reading treatments for individuals with mild to moderate central alexia. Thus, the present study provides valuable information on the applicability of tDCS on alexia treatments.

Contrary to studies by Cherney et al., (2013) and Lacey et al., (2014) there were limited effects of a-tDCS in augmenting gains in text-level reading fluency when tDCS was paired with ORLA and MOR in both RF+PT and RF+RC. In the present study, a-tDCS appears to generally augment existing gains in behavioural and eye movement measures. In all of the participants, treatment phases with a-tDCS led to decreased (P1, P2, P4) or no change (P3) in single word reading speed. In two of these participants (P1, P3), the decreased/constant single word reading speed was combined with increases in reading comprehension. Potentially, a-tDCS slowed single word reading speed and/or limited reading rate with connected text but promote reading comprehension. However, there is not a clear pattern as to the effects of a-tDCS on reading comprehension, as two of the four participants did not experience greater gains in reading comprehension with a-tDCS.

Although there generally appears to be slightly more improvements when treatment is paired with a-tDCS, P2 made minimal gains in both treatment phases. As discussed earlier, these results may provide further support that tDCS modulates ongoing behaviours or augmenting behavioural gains that were already preexisting (Galletta et al., 2016).

The relationship between a-tDCS and eye movements is exploratory. From the eye movement perspective, a-tDCS leads to more changes in the dwell time and fixation count consistency effect. Greater changes in dwell time and fixation count consistency effect reflects gains in reading comprehension at times. However, a *lack* of larger changes in regression consistency effect is a more consistent reflection of improvements in reading comprehension. Potentially, a-tDCS could promote greater changes in dwell time and fixation count consistency effect that facilitates reading comprehension, when regression consistency effect is not also present.

Many tDCS and aphasia treatment studies apply similar dosages of tDCS (20-30 minutes of 1-2 mA for 5-15 sessions), with varying dosages of behavioural intervention (Galletta et al., 2016; Hamilton, Chrysikou, & Coslett, 2011; Woods et al., 2016). The most efficacious combination of tDCS and behavioural dose has not yet been determined. Due to the lack of understanding of tDCS's effects on behavioural treatment, there is a general assumption that a "typical" dose of tDCS can potentially augment outcomes of any behavioural treatment (Galletta et al., 2016). The results of the present study contributes valuable information on the effects of a "typical" dosage of tDCS (20 minutes of 1.5 mA for 20 sessions), in combination with concurrent behavioural treatment for mild-moderate and mild alexia. For individuals with mild alexia, it appeared that the tDCS dose was not as imperative as the behavioural treatment dose. Regardless of active stimulation, both P3 and P4 demonstrated increased gains after the first 20 hours of intensive RF+RC treatment. The results from the present study suggest that the "typical dose" of tDCS may be ineffective in augmenting treatment outcomes for individuals with mild alexia undergoing RF+RC treatment.

The present study on the effects of tDCS on reading treatment is a Phase I/II study (Robey, 2004). A-tDCS was explored in combination with reading fluency and phonological or reading comprehension approaches. Although there are mixed results on the specific behaviours and mechanisms that a-tDCS influences, the lack of adverse events in the present study and in other tDCS studies (Bikson et al., 2016; Woods et al., 2016), combined with the ease of application renders tDCS a feasible complement to behavioural interventions. Further research to delineate the relationship between eye movements and behavioural changes, and well as the impact of tDCS on behavioural reading measures and eye movement outcomes is warranted.

Use of Eyetracking Methodology

Eye movements were used in the present study as a fine-grained measure of reading abilities. To date, there have been limited investigations of treatment-induced eye movements in PWA. There is general understanding that eye movements of PWA differ compared to healthy skilled readers, and that there can be shifts in PWA's eye movements after therapy (Ablinger, Huber, et al., 2014; Ablinger et al., 2013; Ablinger, Von Heyden, et al., 2014; Chesneau, Joanette, & Ska, 2007; Kim & Lemke, 2016). When compared to eye movements before treatment, the present study demonstrates that reading treatment can shift eye movement patterns. This general observation is commensurate with the literature. However, it is difficult to delineate the effects of reading treatment on the participants' reading strategy with the present study's methodology and stimuli. Though there have been some attempts to draw comparisons and relationships between behavioural and eye movement changes, conclusions remain preliminary.

Some studies that have compared eye movements to controls have noted a paradoxical effect, where there are behavioural gains in reading rate after treatment, but increased differences from the "typical" eye movement patterns of control participants (Ablinger et al., 2013; Kim & Lemke, 2016). In the present study, eye movements were not collected from control participants, but instead were compared within participants before and after treatment. In treatment phases where P1 (second phase with a-tDCS) and P4 (first treatment phase with s-tDCS) experienced reading comprehension gains, there were less eye movement changes compared to the other treatment phase. The decreased eye movement changes in treatment phases corresponding to increases in reading comprehension may provide another instance of the paradoxical effect mentioned earlier.

Other studies using eyetracking have utilized the initial landing position of fixations to hypothesize the readers' reading strategy (Ablinger, Huber, et al., 2014; Kim & Lemke, 2016). The present study utilized more global measures of dwell time, fixation count, and regressions which limits the ability to ascertain the participants' reading strategy. However, the changes in eye movements after reading treatment showed when there were post-treatment changes in the regression consistency effect, there were no significant gains in reading comprehension. This simple relationship was not mutually exclusive, as there were treatment phases where there were no reading comprehension gains even though there were no changes in regression consistency effect. Reading comprehension gains were also generally accompanied by greater changes in the dwell time and/or fixation count consistency effect, without changes in regression consistency effect. Although the specific reading strategy cannot be determined based on these global measures, the effect of a change in regression consistency effect suggests that its presence could indicate a maladaptive treatment-induced reading strategy.

The relationship between eye movements and reading treatment continues to be equivocal. Eye movements can be understood as a reflection of comprehension processes and mechanism of a reader's difficulty (Rayner et al., 2006), however, eye movements have also been directly targeted as an approach to reading treatment (Ablinger, Von Heyden, et al., 2014).

The eye movement portion of the present study was exploratory, and conclusions are speculative. However, relying solely on behavioural outcome measures when completing reading treatment research has limitations in that they do not provide insight into the underlying mechanisms of reading recovery. Scores on behavioural assessment measures do not pinpoint the origin of difficulties when reading connected text. Researchers and clinicians can only extrapolate the difficulties individuals face by utilizing a range of assessment tasks to assess different skills (e.g., the continuum of reading skill assessments used in the present study described in Figure 3). For example, participants' impairment in sublexical skills based on poor performance on sublexical single word tasks (e.g., CVC nonword tasks) does not necessarily reflect an equally poor ability to use sublexical reading strategies in connected text. Thus, there continues to be a need for an assessment tool which investigates the reading strategy and mechanism during connected text reading. There is still a need for more investigations with eyetracking methodology's application for aphasia treatment research. More understanding on the specific measures which best reflect reading strategies and are most sensitive to treatment-induced reading changes is needed. However, the results of the present study continue to corroborate the benefit of using eye movements to understand the mechanism of reading treatment.

Limitations

As with many studies, the present study had limitations that should be acknowledged. This was a treatment study with a limited clinical population. The extensive inclusion and exclusion criteria, as well as the time commitment required, significantly reduced the number of potential participants. The limited participants in the study resulted in less replication for each treatment as well as for the tDCS conditions.

There is high variability between individuals with stroke-induced brain injury. Multiple factors such as age, gender, time since stroke and location, size, and type of stroke adds layers of variability in treatment response between participants who could have had similar behaviour and skill profiles before treatment. Although measures were taken to recruit participants with similar language abilities and to screen for baseline abilities, there were still individual differences that may have affected outcomes. Other personal factors such as attitude, motivation, and life experience also contributed to variability between the participants and their response to rehabilitation (Doogan, Dignam, Copland, & Leff, 2018). As well, within individuals with stroke-induced aphasia, high variability is common in their performance from session to session (Duncan, Schmah, & Small, 2016).

The present study used a single subject cross over design to account for interpersonal variability. In this way, each participant would serve as their own control, which theoretically would allow interpretations of the tDCS effects. However, single subject designs limit the generalizability to other individuals with alexia. As well, attempts to draw conclusions and generalizations between the heterogenous participant profiles may have led to an attenuation of treatment gains. The challenge of generalizability in aphasia treatment research is common, as there is high heterogeneity in this clinical population as well as the treatment approaches (Fama & Turkeltaub, 2014). Although measures were taken, using a crossover design resulted in unavoidable treatment order and carry over effects. In the present study, two participants received each treatment as an attempt to avoid a treatment order effect from using a cross over design. A washout period in between the two phases was also used to decrease potential treatment and tDCS carry over effects. As a result of the limited participants and replications in the present study, treatment order and carry over effects cannot be completely ruled out.

Conducting a time intensive research study with human participants also led to scheduling conflicts. The author of the study was the primary individual administering the assessment and treatment protocol. However, when there were scheduling conflicts, treatment was delivered by the author's supervisor or another trained Speech Language Pathology student. Although, training and precautions were taken to ensure treatment fidelity, there were unavoidable nuances in how each experimenter delivered treatment and interacted with the participants. There was variability in the length of each participant's treatment phase even though everyone received the same number of sessions. Treatment periods varied 1-2 days from the proposed week due to statuary holidays, scheduling conflicts and/or illnesses.

As reading is a complicated process involving a continuum of skill, multiple measures were used to characterize the participants' reading abilities. Using multiple measures could result in increased type I error. Also, there may have been practice effects with assessment tools. The ABRS and CVC nonword reading and spelling assessments may have been more susceptible to practice effects, as participants were given the same stimuli at each assessment session. In all the other measures, participants received different stimuli at each assessment session.

There were treatment sessions where the impedance became too elevated for the tDCS to make a proper conduction. In those sessions, additional saline and conductive gel used for electroencephalography had to be used to improve conduction for the tDCS to function. The increased impedance (i.e., lack of contact and conduction for the stimulation to be successful) was most likely due to the dry climate, the thickness of the participant's hair, or the electrochemistry of their skin. Although measures were taken to control the saline and gel used, the process still introduced variability across the participants.

Future Directions

The present study had limited replications of treatment conditions, conducting another study with the same treatment protocol with more PWA would provide more definitive results, refine conclusions and decrease the influence of treatment order and carry over effects. Similar to many other aphasia treatment studies, a single subject design was used (Leff & Benrmann, 2008). Enrolling more PWA with similar participant profiles would also provide more delineation for the participant profile that would be best suited for each treatment approach. Doing so, along with more systematic replications, would contribute to current understanding on how individual factors can predict responses to specific treatments.

The majority of aphasia treatment literature focuses on treatment gains without accounting for intraindividual variability. A recent study by Duncan and colleges demonstrated higher intraindividual variability as a predictor for greater improvements after speech repetition treatment (Duncan et al., 2016). Investigating intraindividual variability in addition to treatment outcomes could better elucidate the important predictors for treatment gains.

The literature examining eye movements following reading treatment for PWA is limited. There is little consensus on what the appropriate measures are that best represent the changes in eye movements expected. Currently, the present study only examined participants' dwell time, fixation count, and regressions. Exploring other eyetracking measures could provide more fine-grained information on cognitive processing and mechanisms of reading before and after treatment. As well, improving eyetracking stimuli by creating more specific and balanced passages could increase sensitivity of eyetracking to the treatment effects.

The present study demonstrated that active tDCS can facilitate greater treatment effects. Given the ease and safety of tDCS, it is a viable adjunct to treatment research. More research with behavioural aphasia treatments and tDCS would better delineate the effects of tDCS on treatment effects. In the present study, tDCS stimulation was applied at the beginning of each treatment phase. Since the effects of tDCS are understood to be activity dependent (Galletta et al., 2016), there may be value in selectively stimulating portions of a multimodal reading treatment session. Future investigations could explore applying tDCS during specific tasks targeting the skill of interest (e.g., portion of the session targeting sublexical skills versus reading comprehension). Selectively stimulating could hone the effects of tDCS on the individual's area of impairment.

The present study did not collect maintenance measures due to the participants' and experimenters' time restraints and it would have extended the present project beyond feasibilities of time. Another interesting extension would be to investigate treatment maintenance after behavioural intervention with tDCS. Vestito and colleges, found that significant treatment gains, in word naming, were maintained 16 weeks after treatment concluded (Vestito, Rosellini, Mantero, & Bandini, 2014). Better understanding of the temporal effects of tDCS on treatment gains will allow more precise treatment dosage and frequency recommendations.

Conclusion

In conclusion, the present study provides insight for future reading treatment titration. The current field has yet to delineate how specific individual parameters may affect response to treatment (Doogan et al., 2018). The present study provides valuable information on how individual client factors may affect the effectiveness of particular treatment approaches. Although promising, the state of the literature on the potential of tDCS to augment treatment outcomes remains inconclusive (Crosson et al., 2019; Galletta et al., 2016). Results from the present study can potentially inform the suitability and response to a multimodal reading treatment and a-tDCS for particular client profiles.

For individuals with mild-moderate alexia, establishing strong sublexical skills is a prerequisite to further gains in reading fluency and reading comprehension. An RF+PT protocol with a-tDCS is effective for individuals with mild-moderate alexia and who have relatively intact/improving sublexical skills.

For individuals with mild alexia, an RF+RC protocol can promote increased contextual integration and decoding. In the present study, the majority of treatment gains were seen in the first 20 hours of treatment. Thus, extended periods of intensive treatment for individuals with mild alexia may not be warranted.

A-tDCS may be most effective when combined with treatment for an individual with mild-moderate aphasia, who is demonstrating response to treatment and has improving sublexical skills. Individuals who do not have sufficient or improving sublexical skills do not benefit from reading treatment targeting fluency, and thus may require the establishment of strong sublexical skills first. Individuals with mild alexia may only need short periods of intensive treatment to make gains and may not experience augmented gains from tDCS.

A-tDCS may have impact on eye movements involved with reading fluency which in turn influences the individual's reading comprehension. Specifically, in this study, a-tDCS led to decreased reading rate, or reduced gains in reading rate, but promoted increased contextual integration and ability to decode. A-tDCS also appeared to affect reading patterns, in how individuals responded to a passage that is not consistently coherent. Individuals whose dwell time and fixation count were modified by a-tDCS, but whose regressions remained constant, appeared to experience significant gains in their contextual integration reading comprehension.

Understanding treatment effects and the optimal client profile for each treatment approach, is essential to maximize treatment gains and healthcare resources.

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Appendix

I. List of Antecedents and Anaphors used for Eyetracking Stimuli.

Sentence number	Antecedent	Anaphor
1 Congruent	textbook	textbook
1 Incongruent	textbook	magazine
2 Congruent	guitar	guitar
2 Incongruent	guitar	drums
3 Congruent	roses	roses
3 Incongruent	roses	daisies
4 Congruent	canoe	canoe
4 Incongruent	canoe	kayak
5 Congruent	comedy	comedy
5 Incongruent	comedy	action
6 Congruent	plane	plane
6 Incongruent	plane	train
7 Congruent	coffee	coffee
7 Incongruent	coffee	juice
8 Congruent	carrot	carrot
8 Incongruent	carrot	celery
9 Congruent	elephant	elephants
9 Incongruent	elephant	giraffes
10 Congruent	sister	sister
10 Incongruent	sister	brother
11 Congruent	truck	truck
11 Incongruent	truck	van
12 Congruent	shoes	shoes
12 Incongruent	shoes	socks
13 Congruent	puppy	puppy
13 Incongruent	puppy	kitty
14 Congruent	lettuce	lettuce
14 Incongruent	lettuce	beans
15 Congruent	bicycle	bicycle
15 Incongruent	bicycle	scooter
16 Congruent	zebra	zebra
16 Incongruent	zebra	monkey
17 Congruent	Italy	Italy
17 Incongruent	Italy	France
18 Congruent	swing	swing
18 Incongruent	swing	slide
19 Congruent	Flowers	Flowers
19 Incongruent	Flowers	Candies
20 Congruent	propane	propane
20 Incongruent	propane	charcoal
21 Congruent	garage	garage
21 Incongruent	garage	shed
22 Congruent	toaster	toaster
22 Incongruent	toaster	blender

23 Congruent	lake	lake
23 Incongruent	lake	river
24 Congruent	poodle	poodle
24 Incongruent	poodle	sheltie
25 Congruent	trees	trees
25 Incongruent	trees	flowers
26 Congruent	hamburger	hamburger
26 Incongruent	hamburger	pizza
27 Congruent	leg	leg
27 Incongruent	leg	arm
28 Congruent	teacher	teacher
28 Incongruent	teacher	doctor
29 Congruent	coffee	coffee
29 Incongruent	coffee	tea
30 Congruent	daughter	daughter
30 Incongruent	daughter	son
31 Congruent	table	table
31 Incongruent	table	chair
32 Congruent	soldier	soldier
32 Incongruent	soldier	marine
33 Congruent	salt	salt
33 Incongruent	salt	pepper
34 Congruent	candle	candle
34 Incongruent	candle	lamp
35 Congruent	closet	closet
35 Incongruent	closet	attic
36 Congruent	feathers	feathers
36 Incongruent	feathers	fur
37 Congruent	sweater	sweater
37 Incongruent	sweater	jacket
38 Congruent	squares	squares
38 Incongruent	squares	circles
39 Congruent	Paris	Paris
39 Incongruent	Paris	Texas
40 Congruent	unity	unity
40 Incongruent	unity	contrast
41 Congruent	forest	forest
41 Incongruent	forest	valley
42 Congruent	danger	danger
42 Incongruent	danger	tension
43 Congruent	driver	driver
43 Incongruent	driver	speaker
44 Congruent	mystery	mystery
44 Incongruent	mystery	comedy
45 Congruent	poets	poets
45 Incongruent	poets	dancers
46 Congruent	title	title
46 Incongruent	title	chapter
47 Congruent	stories	stories
47 Incongruent	stories	songs
48 Congruent	content	content

48 Incongruent	content	advice

II. Comparison of psychometric properties of antecedents and anaphors

	t-test for Equality of Means				
Measure	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference
Written and Spoken Frequency (CELEX_An)	0.472	0.493	0.249	190	0.804
Written Frequency (CELEX_W_An)	0.508	0.477	0.263	190	0.793
Number of Letters (LEN_L_An)	0.955	0.33	-0.74	190	0.46
Orthographic Neighbourhood size (N_An)	0.494	0.483	0.412	190	0.681
Phonological Neighbourhood size (PN_An)	2.383	0.124	0.9	177	0.369
Age of Acquisition (AOA_2_An)	0.03	0.862	0.077	190	0.939
Imageability (IMG_An)	0.34	0.56	-0.918	190	0.36