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Relationship Between Eye Movements During Reading and Severity of Language Impairment in Persons with Aphasia

Sarah C. McWilliams
University of South Alabama, scm1521@jagmail.southalabama.edu

RELATIONSHIP BETWEEN EYE MOVEMENTS DURING READING AND SEVERITY OF LANGUAGE IMPAIRMENT IN PERSONS WITH APHASIA

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Sarah C. McWilliams
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TABLE OF CONTENTS

LIST OF TABLES

LIST OF ABBREVIATIONS

RCBA-2	*Reading Comprehension Battering for Aphasia- 2nd Edition*
PALPA	*Psycholinguistic Assessment of Language Processing for Aphasia*
TBI	Traumatic Brain Injury
WAB-R	*Western Aphasia Battery- Revised*
WAB-R AQ	*Western Aphasia Battery- Revised, Aphasia Quotient*

ABSTRACT

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Eye movements reflect cognitive-linguistic processing of neurotypical readers. Numerous reading related eye movement measures are associated with language processing, including saccades, fixations, word skipping, and regressions. Eye movements have also been used to examine language processing and reading in disordered populations including persons with aphasia. This study examined whether eye movement measures (i.e., fixation duration, gaze duration, total viewing time, skipping rate, saccade amplitude, regression path duration) obtained from connected text paragraph reading were associated with language severity (WAB-R) and reading comprehension skills (RCBA-2) in persons with various subtypes of aphasia as well as whether those same eye movement measures differed among persons with different subtypes of aphasia and neurotypical controls. Results indicated that regression path duration and word skipping reflected a significant difference between the control group and persons with aphasia. Additionally, there was a significant, strong, positive correlation between first fixation duration and severity of language impairment for persons with Broca's aphasia, indicating longer fixation duration is associated with less severe language impairment.

CHAPTER I

INTRODUCTION

Aphasia, typically caused by a stroke, is a disturbance in brain function which can impact any and/or all modalities of language, including the ability to speak, comprehend, read, and write (Brookshire, 2007). According to the National Aphasia Association (n.d.), the prevalence of aphasia, or the current number of individuals living with the disorder at this time, in the United States is two million individuals. The National Aphasia Association also reports the incidence, or number of individuals diagnosed per year, in the United States is 225,000 individuals. Aphasia is often characterized by the specific language processing deficits in areas of listening comprehension, repetition abilities, and fluency in spoken language that the individual experiences. The individual with aphasia is often then assigned a subtype, such as anomic aphasia, characterized by deficits in naming, Broca's aphasia, characterized by agrammatic speech with intact comprehension or Wernicke's, characterized by deficits in comprehension with fluent speech. Furthermore, it is common for concomitant disorders to occur with aphasia. One of the most common is alexia or acquired reading disorder. Language ability, including reading, in persons with aphasia is typically assessed with a standardized testing battery; however more recent studies have used eye movements obtained by eye tracking to provide a measure of language processing ability (Scahttka et al., 2010; Ablinger et al., 2014; Kim

& Lemke, 2016; DeDe, 2017; Smith et al. 2018). Importantly, few studies have examined the association between eye movements and language severity, including reading, in persons with aphasia.

Eye movement measures obtained from eye tracking, such as fixation duration (i.e., the amount of time eyes fixate on the text), saccadic amplitude (i.e., the number of times the eyes jump to a new area in the text), word skipping (i.e., how often the eyes skip over specific words in the text), and regressions (i.e., the eyes move backwards in the text) have been shown to reflect language processing in both the typical and neuro-atypical populations during reading and other tasks (Rayner & McConkie, 1976; Vitu et al., 1995; Klingehöfer & Conrad, 1984; Huck et al., 2017; Smith et al., 2018). Eye movements in unimpaired readers show specific patterns based on the contents of the text. For example, as text difficulty increases, fixation duration increases, saccade length decreases, and regression frequency increases (Rayner, 1998; Rayner & Pollastek, 2013). Furthermore, eye movement parameters like within word regressions (i.e., when the eye regress back to the beginning of a word) suggest difficulty processing a specific word, while regressions of more than 10 letter spaces in a text indicates difficulty comprehending a text (Rayner et al., 1996; Rayner, 2009). Current research indicates variability of eye movements among unimpaired readers is affected by oculomotor constraints and both cognitive and linguistic processing (Rayner 1998; Barnes, 2011; Rayner & Liversedge, 2011).

Eye tracking has been used to measure cognitive and linguistic processing during various tasks in neuro-atypical populations such as persons with dyslexia, Parkinson’s disease, traumatic brain injury, and aphasia (Eden et al., 1994; De Luca et al., 2002; Yu et al. 2016; Smith et al., 2018). Overall, eye movements have been shown to differentiate between neurotypical and neuro-atypical individuals across many cognitive-linguistic tasks (De Luca et al., 2002; Chan et al., 2005; Yu et al., 2006; Mani et al., 2018., Smith et al., 2018). Specifically, studies examining reading abilities in persons with aphasia have found longer fixation times than that of neurotypical individuals (Dede, 2017; Smith et al., 2018). While research using eye movements to examine aphasia and concomitant alexia is emerging, there is still a need to examine the eye movements of persons with aphasia and alexia relative to neurotypical individuals across a variety of cognitive-linguistic tasks.

Eye movements have the potential to assist researchers and practitioners in identifying specific language profiles and symptoms, such as the various aphasia or alexia subtypes. A study conducted by Smith and colleagues (2018) found differences in eye movement patterns among persons with varying types of aphasia. Individuals with anomic aphasia had a shorter saccadic amplitude relative to controls, while those with Wernicke's aphasia produced significantly shorter fixations relative to controls during the scene memorization task, suggesting this task may be a way to differentiate this subtype from other persons with aphasia. in which participants were required to memorize real world scenes, suggesting participants may Thus, eye movements have the potential to identify aphasia subtype; however, research in this area, particularly related to reading, is limited.

Eye movements have the potential to predict cognitive-linguistic processing difficulties and support the identification of subtypes of aphasia, which may be theoretically and clinically useful. However, research in this area is still in its infancy limiting our ability to generalize the results of the research. In short, more research is needed to determine whether eye movements during reading are different than neurotypical individuals, vary based on aphasia subtype, and can predict overall language impairment severity and reading comprehension ability. Based thereon, there are two overall aims of the current study. First, the current study sought to determine whether eye movement measures, such as fixation duration, gaze duration (i.e., summation of fixations before leaving a word), total viewing time (i.e., time spent viewing the passage), saccade amplitude, regression path duration, refixations (gaze count) obtained from connected text reading differ among persons with varying types of aphasia and neurotypical individuals. A secondary aim of this study was to examine whether eye movement measures can predict language processing severity and reading comprehension ability in persons with aphasia.

CHAPTER II

REVIEW OF LITERATURE

Aphasia and Concomitant Alexia

Aphasia is an acquired language disorder, typically caused by a stroke that can affect all modalities of language, including reading, writing, comprehension, and speaking (Brookshire, 2007). However, aphasia is most often characterized by the specific language processing deficits in areas of listening comprehension, repetition abilities, and fluency of speech. The individual with aphasia is often then assigned a subtype. Three of the most common types include: anomic, Broca's, or Wernicke's. Table 1 shows the different subtypes of aphasia and the accompanying symptoms the individual with aphasia often experiences. Although, it is important to note that most individuals do not fit perfectly into one subtype.

Table 1. Classification of Aphasia Subtypes
Modified from Murray and Clark (2015)

Aphasia Subtype	Predicted Site of Lesion	Comprehensi on	Fluency	Naming	Repetition
Broca's	Broca's area	Mild to moderately impaired	Nonfluent	Impaired	Similar to spontaneous speech
Wernicke's	Wernicke's area	Moderately to severely impaired	Fluent	Impaired	Similar to spontaneous speech
Global	Anterior and posterior left hemisphere	Moderately to severely impaired	Nonfluent	Impaired	Similar to spontaneous speech
Transcortical motor	Anterior or superior to Broca's area	Mild to moderately impaired	Nonfluent	Impaired	Less impaired than spontaneous speech
Transcortical Sensory	Posterior temporal lobe extending into the occipital lobe	Moderately to severely impaired	Fluent	Impaired	Less impaired than spontaneous speech
Transcortical Mixed	Anterior and posterior areas in the left hemisphere	Moderately to severely impaired	Nonfluent	Impaired	Less impaired than spontaneous speech
Conduction	Left arcuate fasciculus and/or supramarginal gyrus in the inferior parietal lobe	Mild to moderately impaired	Fluent	Impaired	More impaired than spontaneous speech
Anomic	Anywhere in the left hemisphere	Normal to mildly impaired	Fluent	Impaired	Similar to spontaneous speech

Models of linguistic processing can also be used to identify the underlying impairment causing deficits in a specific language modality. The model of linguistic processing (Kay et al.,1996) is one model that illustrates how both written and spoken language is thought to occur. As indicated by Kay and colleagues (1996) there are several components that function within the linguistic system to support each language modality. These include orthographic processing (i.e., conversion of phonemes into graphemes and graphemes into words), phonological processing (i.e., conversion of sounds into spoken language), lexical/semantic processing (i.e., conversion of words into meaning), and morphosyntactic processing (i.e., applying grammatical structure to linguistic input and output). All or some of these linguistic processes may be impaired in individuals with aphasia and impact their written and spoken language abilities to varying degrees. For example, a deficit in the orthographic system can impact someone's reading and writing ability either mildly or severely (Murray & Clark, 2015). Damage to the phonological system often leads to deficits in producing and understanding spoken language, while deficits in morphosyntactic processing alters the ability to apply and use grammatical structures either in spoken or written modalities (Murray & Clark, 2015). Lastly, understanding and producing content with meaning requires processing at the lexical-semantic level. Overall, impairment in lexical-semantic processing results in deficits in word finding (Murray & Clark, 2015).

Alexia, an acquired reading disorder, commonly co-occurs with aphasia (Leff & Starrfelt, 2014). Based on the linguistic model, damage to the orthographic system may have the greatest impact on reading, while deficits in phonological, lexical-semantic, and morphosyntactic processing may also contribute to reading deficits depending on the reading task (e.g., single word reading, reading connected text, oral reading versus silent reading). There are three main subtypes of alexia that are most likely to co-occur with aphasia, surface, deep, and phonological, each with varying symptoms of reading impairment. When applied to the model of linguistic processing, surface alexia impairments may be located at the level of orthographic input lexicon, phonological output lexicon, or at the lexical-semantic level. Persons with surface alexia are able to read regularly spelled words (e.g., dog) and pseudowords (e.g., fird) but have difficulty reading irregularly spelled words that cannot be easily sounded out (e.g., yacht) (Cherney, 2004; Papathansiou & Coppens, 2022).

Persons with phonological and deep alexia have difficulty reading pseudowords; however, persons with phonological alexia typically have intact lexical-semantic processing (i.e., the ability to read words by sight without sounding out the individual sound) while persons with deep alexia do not (Cherney, 2004; Papathansiou & Coppens, 2022). Hallmark symptoms of deep alexia include impaired pseudoword reading, semantic errors (i.e., cat for dog), visual errors (e.g., quickly for quietly), and morphological errors during oral reading (heaviest for heavy). When alexia is associated with aphasia, there are often multiple levels of impairment and many patients do not fit within one specific subtype of alexia (Cherney, 2004).

Language ability, including reading, in persons with aphasia is typically assessed with a standardized testing battery or informal reading tasks. These assessments can be lengthy and lead to frustration and fatigue among persons with aphasia and concomitant alexia. However, more recent studies have used eye movements obtained by eye tracking to provide a measure of language processing ability (Schttaka et al., 2010; Ablinger et al., 2014; Kim & Lemke, 2016; DeDe, 2017; Smith et al., 2018). Few studies have examined the association between eye movements and language severity, including reading, in persons with aphasia, although a direct link between eye movements and cognitive-linguistic processing has been identified in neurotypical individuals as described below.

Eye Movements During Reading in Neurotypical Individuals

Eye movement measures obtained from eye tracking, such as fixation duration and saccade amplitude have been shown to reflect language processing in neurotypical individuals in many tasks such as listening comprehension using a visual word paradigm, but particularly during reading (Rayner & McConkie, 1976; Vitu et al., 1995; Klingehöfer & Conrad, 1984; Rayner & Liversedge, 2011; Rayner et al., 2012; Rayner & Pollastek, 2013). Reading is a highly complex skill, which requires the eyes to move in coordination with visuospatial attention, visuospatial processing, linguistic processing, and cognitive processing (Binder & Mohr, 1992; Reichle et al., 1998; Ben-Shachar et al., 2007; Rayner et al., 2012). The oculomotor system is responsible for programming eye movements during reading and is thought, in part, to be driven by the lexical complexity of the text (Rayner & McConkie, 1976; Rayner, 1998; Rayner & Liversedge, 201l). Thus, there is a documented association between eye movements and cognitive-linguistic processing in neurotypical individuals (Rayner, 1998; Rayner et al., 2012). When reading, the eyes do not simply travel from word to word, rather they move in fast ballistic motions (saccades), move backwards (regressions), skip words, or remain fixated on certain points (fixations). These movements measured by eye tracking can be used to further explain cognitive-linguistic processing during reading and have also been suggested to reflect the interaction between oculomotor and cognitive-linguistic processes in normal readers (Rayner, 1998; Rayner & Liversedge, 2011; Henderson & Luke, 2012; Luke & Henderson, 2013).

Between saccadic movements, the eyes remain fixated on particular points in the text in an approximate range from 100-500 milliseconds (Reichle et al., 1998; Rayner 1998). During fixations, new visual information is acquired and processed; thus, multiple factors such as word frequency, word predictability, and semantic relations between the fixated word and surrounding information will affect the length of time the eyes remain fixated on a given point (Rayner et al., 2005, 2012; Yan et al., 2006). For example, higher frequency words have been found to have shorter fixation times than those of a lower frequency (Inhoff & Rayner, 1986). In addition, as a text becomes more difficult to process, either due to word characteristics such as length or frequency, fixation times will increase, further indicating that the lexical features of the word are correlated with the duration of a fixation (Rayner & Fischer, 1996).

While most content words are fixated, function words (e.g., “to”, “is”) are typically skipped (Rayner, 1998). The average saccade length ranges from 7-9 letter spaces, however there is considerable variability outside of this range (Rayner et al., 2012). The main goal of a saccade is to focus on a new area for processing (Vitu, 2011). As the eyes skip from fixation point to fixation point, visual processing is largely suppressed during the saccade (Wolverton & Zola, 1983). During the time between, when the decision is made to move from one fixation point to the time when a saccade is initiated, this is known as saccade latency or fixation duration and is considerably affected by the visual stimulus (Bell et al., 2006; Gilchrist, 2011). The main factors affecting the selection of the next saccadic target is the time it takes to process the information at the current fixation point and the processing of information outside of the fovea (i.e., the area of the retina where visual acuity is the highest) to determine the next fixation point (Gilchrist, 2011). The latency time is an important component in initiating a saccade as it involves decision processing and the utilization of fine motor planning and execution (Gilchrist, 2011).

At the same time, the eyes do not consistently jump forward in the text and often move backwards as well. This is known as a regression or a regressive saccade. As the difficulty of a text increases, the frequency of regressions also increases (Rayner 1998). Skilled readers typically regress to a previous word, however, within word regressions suggest difficulty processing the current word and longer regressions indicate difficulty comprehending the text (Murray & Kennedy, 1998; Rayner, 2009).

Word skipping has also been shown to reflect language processing during reading. As word length increases, the likelihood of skipping a word significantly decreases (Vitu et al.,1995). Skilled readers tend to skip more words, particularly function words, compared to less skilled readers; however, if a word is skipped without fully being processed, the eyes will regress and then re-fixate to process the word (Brysbaert & Vitu, 2005). Both the ability to skip words based on word length and regress in the text when the incorrect word is skipped, further indicates the relationship between eye movements and language processing (Brysbaert & Vitu, 2005).

Overall, the decisions of when and where to move the eyes are considered to be largely separate from one another (Rayner, 1998; Rayner et al., 2012). When to move the eyes is determined by both the difficulty of the text as well as on going linguistic processing

(Rayner, 1998; Reichle et al., 2003). While in comparison, where to move the eyes is determined by the text to the right of the fixation (O'Regan, 1980; Gilchrist, 2011).

Eye Movements During Reading in Neuro-atypical Individuals

With the established association that eye movements are associated with language processing during reading, eye movements have also been used to examine language processing in neuro-atypical populations, such as dyslexia, Parkinson's disease, traumatic brain injury (TBI), and aphasia. In a study where persons with dyslexia read short words, long words, and pseudowords, the number of saccades was 30% higher than that of those in the control group when reading long words and pseudowords (De Luca et al., 2002). Previous studies examining eye movements during reading in children with dyslexia found that their eye movements were far less stable than those of unimpaired children (i.e., poor fixation control; Eden et al., 1994). Children with dyslexia have also been found to have more frequent and longer fixation times suggesting greater difficulty processing the text (Hutzler & Wimmer, 2004). In addition to dyslexia, eye movements have been used to study other neurogenic disorders such as traumatic brain injury, aphasia, and Parkinson's disease. A case study conducted by Yu et al. (2016) examined eye movement measures during reading in one man with Parkinson's disease which indicated increased saccades and a smaller saccade amplitude suggesting less information is being acquired with each fixation. In addition, a meta-analysis conducted by Mani, et al., (2018) found that persons with mild to severe TBI also exhibit specific saccadic eye movements (i.e., anti-saccades and memory guided saccades) that differ from neurotypical individuals, thus suggesting possible cognitive deficits due to the high oculomotor function needed to maintain control for these movements. Several studies have also examined the eye movements of persons with acquired alexia. These studies are discussed below.

Eye Movements during Reading in Persons with Aphasia and Concomitant Alexia

Individuals with aphasia and concomitant alexia are known to have damage to brain regions involved in linguistic processing; however, it is important to note alexia can also be observed separately from aphasia. As there is growing evidence that suggests using eye tracking may provide reliable evidence of language impairment, it is likely that persons with aphasia and concomitant alexia would show atypical eye movements relative to neurotypical individuals. Further, eye movements should correspond to the severity of language impairment, particularly in reading, although this has not yet been thoroughly.

While atypical eye movement patterns in persons with aphasia and concomitant alexia is likely, the research in this area is emerging and there is still much to be understood about the eye movements of persons with aphasia and alexia during reading (but see Klingelhöfer & Conrad, 1984; Thompson & Choy, 2009; Dickey & Thompson, 2009; Schattka et al., 2010; Kim & Lemke, 2016; Dede, 2017; Smith et al., 2018). Current literature suggests persons with aphasia have far lower word skipping rates and longer rereading times (Dede, 2017). Word frequency has been shown to play a role in whether persons with aphasia regress further back in a sentence than neurotypical individuals. Huck and colleagues (2017) indicated that persons with aphasia did not fixate on low-frequency words, rather they may have regressed to an earlier place in the sentence without fixating on the low frequency words, suggesting a deficit in lexical processing. Furthermore, persons with aphasia have been found to produce shorter fixations and smaller saccades in comparison to neurotypical individuals during reading tasks due to possible deficits in the ability to comprehend the text (Smith et al., 2018). Through the use of single word reading times and local fixation patterns, Schattka and colleagues (2010) were able to distinguish between individuals with surface and phonological-deep acquired alexia. Those with surface alexia showed eye movement patterns similar to neurotypical individuals when fixating on a word (i.e., their eyes landed towards the center of the word), which was common throughout for individuals with lexical errors. Those with phonological-deep alexia had significantly higher re-reading times as well as a landing position further away from the center of the word. In addition, a case study conducted by Kim and Lemke (2016) examined eye movements during before and after reading treatment in one individual with acquired alexia and found that initial fixation shifted closer to the center of a word following treatment suggesting the possible benefit of using eye movement measures for monitoring reading treatment progress in persons with aphasia. In comparison, Smith et al. (2018) suggested that eye movements in persons with aphasia may return to a more normal pattern throughout the recovery process; however, oculomotor control may never function as it did prior to the stroke. Lastly, a recent scoping review of the current research analyzing reading comprehension in persons with aphasia determined that eye tracking is a valuable tool for analyzing language processing in persons with aphasia; however, the eye movement measures should be chosen carefully based on the research question (Sharma et al., 2021).

Purpose of the Present Investigation

Language impairment that impacts reading ability is common in persons with aphasia and concomitant alexia. Eye movement measures obtained from eye tracking, such as fixation duration and saccade amplitude have been shown to reflect language processing in neurotypical and neuro-atypical individuals (Rayner & McConkie, 1976; Vitu et al., 1995; Klingehöfer & Conrad, 1984; Ablinger et al., 2014; Smith et al., 2018). Thus, eye movements have the potential to predict cognitive-linguistic processing difficulties and identify subtypes of aphasia, which may be theoretically and clinically useful. For example, eye movements can potentially be used as an assessment tool to measure severity of reading impairment as well as a way to measure treatment progress. However, research in this area is still emerging, limiting our ability to generalize the results of the research. Therefore, the current study aimed to examine whether eye movement measures obtained from connected text reading, specifically fixation duration, gaze duration, total viewing time, saccade amplitude, skipping rate, proportion of regressive saccades, and refixations (gaze count), differ among persons with aphasia compared to an age-matched control group, and explored whether differences emerged among persons with varying aphasia subtypes. A secondary aim was to examine whether eye movement measures are associated with language impairment severity and reading comprehension skills. The current study seeks to answer the following specific research questions.

Research Questions and Hypotheses

1. Do eye movement measures obtained from connected text reading, specifically fixation duration, gaze duration, total viewing time, skipping rate, saccade amplitude, regression path duration differ among persons with anomic, Broca's, and conduction/Wernicke's aphasia and an age-matched control group?

Hypothesis: Based on Sharma et al., (2022), Huck et al., (2017), and Compared to a neurotypical age-matched control group, it was expected that individuals with aphasia would have longer fixation duration, higher gaze duration, longer total viewing time, more refixations, shorter saccade amplitudes, higher proportion of regressive saccades, and lower rate of skipping. It was expected that persons with anomic aphasia would not differ significantly from controls across eye movement measures as their language deficits are mild in nature. It was expected that persons with Broca's and conduction/Wernicke's aphasia would differ from the control group and from persons with anomic aphasia, and persons with Broca's aphasia would show eye movement patterns indicative of greater language impairment (e.g., the longest fixation duration, lowest skipping rate).

2. What is the association between eye movement measures obtained from connected text reading, specifically fixation duration, gaze duration, total viewing time, saccade amplitude, skipping rate, proportion of regressive saccades, and refixations (gaze count), and connected text reading comprehension using the Reading Comprehension Battery of Aphasia, 2nd Edition(RCBA-2) and language severity, using

the Western Aphasia Battery- Revised (WAB-R) for persons with anomic, Broca's, and conduction/Wernicke's aphasia?

Hypothesis: Overall, it was expected that there would be a strong negative association between gaze duration, fixation duration, regressions, refixations, word skipping and connected text reading ability and language processing severity (e.g., poorer reading comprehension and language severity) would be associated with longer fixations, more refixations and shorter saccade amplitudes. It was expected that there would be a stronger positive association between saccade amplitude, and reading comprehension and language severity. Persons with anomic aphasia would show less association between eye movement measures and connected text reading ability and language severity due to possible ceiling performance on reading measures, while persons with conduction/Wernicke's aphasia would show moderate associations between eye movement measures and connected text reading ability and language severity. Lastly, persons with Broca's aphasia would show the strongest associations between eye movement measures and connected text reading and language severity due to poorer scores on the reading and language assessments. Based on overall language severity, persons with Broca's aphasia would have a longer fixation duration, shorter saccade amplitudes, more regressions and fewer words skips which would be associated with poorer language and reading ability.

CHAPTER III

METHODS

Eye movement and assessment data for the current study was previously collected and has been, in part, reported in Smith and colleagues (2018). Below is a description of the participants, assessments, and eye tracking protocol that was used to collect the eye movement data to be used to answer the current study's research questions. The current study focused on data preparation and analysis specific to the research questions asked in the current study, as the eye tracking protocol and assessments had already been administered.

. Participants

Twenty-four individuals with aphasia (8 with Broca's aphasia, 8 with anomic aphasia, 8 with either conduction or Wernicke's aphasia) and 24 age-matched control participants were recruited. All participants gave signed informed consent for study inclusion and the University of South Carolina Institutional Review Board approved the study.

All participants with aphasia suffered a left hemisphere stroke and had no history of neurological and speech-language or reading disorders prior to their stroke based on self-report. All participants were right-handed and were in the chronic phase of recovery (i.e., a minimum of six months post onset). As part of a larger eye-tracking paradigm, participants completed a connected text-reading task while their eye-movements were recorded. Presence of aphasia and reading deficits were assessed using the Western Aphasia Battery-Revised (*M* = 70.7, *SD* = 18.78; WAB-R; Kertesz, 2007), the Reading Comprehension Battery for Aphasia-2 (*M*= 81.17 , *SD* = 15.72; RCBA-2; LaPointe & Horner, 1984) and the Psycholinguistic Assessments of Language Processing in Aphasia (PALPA; Kay et al., 1996): Scores are indicated out of 100, with a score of 100 indicating no language impairment.. Demographic information and assessment scores for persons with aphasia is shown in Table 2. Each participant with aphasia completed a visual case history and screening of the visual system, with the exception of one participant who chose to discontinue study participation for personal reasons. This participant's eye movement data, however, is included in the analyses. The visual screening determined that each person with aphasia's visual acuity was adequate for study participation with binocular near vision measured at 20/25 or better.

Table 2. Demographic Information for Persons with Aphasia

Participant	Gender	Age	Ed Level (years)	Months Post-Onset	WAB-R AQ	RCBA-2 Score
Anomic						
1	M	67	12	76	93.2	93
2	M	59	10	137	83.2	77
3	F	61	12	212	86.2	81
4	F	79	18	37	90.5	93
5	M	57	12	47	91.1	68
6	F	38	18	108	98.5	97
7	F	45	16	63	82.1	96
8	M	49	18	34	87.5	94
Mean (SD)	-	56.9 (12.9)	14.5 (3.3)	89.3 (61.1)	89.0 (5.4)	87.4 (10.7)
Broca's						
9	M	56	18	74	72.7	86
10	M	53	16	58	57.5	74
11	F	54	14	117	74.8	82
12	F	70	14	26	67.2	87
13	M	52	18	113	65.1	79
14	M	67	16	151	72.6	84
15	M	57	16	98	59.4	92
16	F	51	14	148	43.4	75
Mean (SD)	-	57.5 (7.1)	15.8 (1.7)	98.1 (43.5)	64.1 (10.5)	82.4 (6.2)
Conduction						
17	M	65	16	15	82.9	93
18	M	66	12	17	45.2	29
19	M	61	16	32	90.1	94
Wernicke's						
20	M	74	16	37	73.5	83
21	F	58	14	47	49.3	52
22	M	67	14	43	52.7	88
23	M	62	18	63	31.2	NT
24	F	73	16	70	46.9	70
**Mean (SD)*	-	65.8 (5.6)	15.3 (1.8)	40.5 (19.7)	60.0 (20.7)	72.7 (24.3)

Notes: NT indicates the participant was not tested on this assessment; Ed Level indicates education level; AQ indicates aphasia quotient; WAB-R AQ and RCBA-2 scores are out of 100; * indicates the *Mean (SD)* for persons with Conduction and Wernicke's aphasia.

Apparatus

Eye movements were recorded using an SR Research Eyelink 1000 eye tracker (spatial resolution: 0.01°) sampling at 1000 Hz. Chin and head rests were used to minimize head movements. Participants sat 90 cm away from a 20-inch monitor with a refresh rate of 140 Hz. The experiment was created using the Experiment Builder software package (SR Research Experiment Builder).

Stimuli

The text-reading stimuli consisted of 35 texts, ranging from 40 to 60 words in length, at approximately an 8th grade reading level and were from the same repository as the stimuli used in Henderson and Luke (2014).

Procedure

Participants viewed all stimuli with both eyes, although eye movements were recorded from only one. When possible, the right eye was recorded, unless there was difficulty calibrating or there was a significant medical history involving the right eye (e.g., cataract surgery). For the group of individuals with aphasia, the right eye was recorded for 16 individuals and the left eye for eight. For the age-matched control group, the right eye was recorded for 23 individuals and the left eye for one. The stimuli presentation order within condition were the same for all participants. The larger eye tracking protocol also included a scene memorization, pseudo-reading, and scene search task. Scene memorization was completed first, followed by pseudo-reading, scene search, and finally text-reading. Each task was completed in one block for a total of four blocks.

With the exception of two changes to the experimental paradigm due to methodological oversight (described below), each trial in each task began with a dot presented on the screen that participants fixated; then, they pressed the spacebar to begin the trial. This allowed the participant to initiate the start of the trial and allowed the eye tracker to capture any drift that may have occurred since the last calibration sequence. The dot was placed in the upper left corner, approximately at the start of the paragraph, for the reading task. If the eye tracker detected an accurate and stable fixation, the stimulus was presented, if not, the process was repeated with the option to recalibrate as needed. The participant viewed each stimulus for 12 seconds before it was removed from the screen. In all cases, the next trial began by presenting another dot and repeating the same procedure. Instructions for each task were provided before each task in multiple modalities (i.e., verbal and written cues), in addition to examples and demonstrations of each task, as needed. Text-reading task instructions directed participants to silently read the paragraphs of text.

To gain more information, two changes were made to the experimental paradigm approximately halfway through data collection. The changes were isolated to the reading tasks. The first change was the addition of yes/no and multiple-choice reading comprehension questions to the text-reading task, thus, a portion of the participants (i.e., 15 persons with aphasia, 11 age-matched control participants) completed reading comprehension questions between each text-reading trial. Control participants answered questions with 85% accuracy, and persons with aphasia with 62% accuracy. The second change allowed these same participants to end the text--reading trials when they finished reading, rather than viewing each stimulus for 12 seconds before it was removed from the screen. To match the eye movement data for the reading tasks more closely before and after the paradigm change, only eye movement data prior to when participants started to re-read the text will be included in the analyses described below, limiting the analyzed data to the initial reading of the paragraph. As reported in Smith et al. (2018), no significant differences emerged between the groups before and after the change for mean fixation duration or mean saccade amplitude, suggesting that the addition of the comprehension questions and change in allotted reading time did not meaningfully alter the mean duration, mean amplitude, variability in duration of the reading fixations or variability in the amplitude of the reading saccades.

Data Preparation

Although the raw eye movement data was collected as part of a previous study, significant preparation occurred to prepare the data for the analyses described below. Table 3 describes each eye movement measure used for the analyses. Select measures were chosen from Barnes et al. (2017) who examined reading ability and eye movements during a connected text oral reading task in adults enrolled in a basic education program and from Sharma et al. (2021) who examined eye tracking measures for studying aphasia in a systematic scoping review. First fixation duration, gaze duration, total view time, and word skipping were used from Barnes et al. (2017) and saccade amplitude, average first fixation duration, and regression path duration were used from Sharma et al. (2021).

Table 3. Eye movement measures based on Barnes et al. (2017) and Sharma et al. (2021)

Eye movement measure	Definition
First Fixation Duration	Average time of the first fixation on each word
Gaze Duration	Summation of all fixation durations before leaving the word
Total Viewing Time	Summation of all gaze durations for a word
Total Number of Words Skipped	Total number of words skipped
Saccade amplitude	Distance in character spaces the eyes move between fixations for progressive rightward moving saccades
Average First Fixation Duration	The average of the first fixation on a target region.
Regression Path Duration	The total duration of all fixations that occur after the first fixation of a regression.

The following steps were taken to prepare the eye movement data for the analyses:

1. Using DataViewer, eye movements were drift corrected for each trial (35 trials) and participants (24 persons with aphasia, 24 control participants).
2. Determined how to calculate each eye movement measure. Eye movement measure calculations were determined using the FAQs page and support forum on SR Research Supqport for extracting eye movement data.

3. Reviewed variables (e.g., first fixation, saccade amplitude) in each report based on the eye movement measures used (i.e., fixation duration, gaze duration, total viewing time, skipping rate, saccade amplitude, regression path duration) and determined which variables were best suited for calculation.
4. For each report that was exported, determined which eye movement variables needed to be included based on the eye movement measure definition in order to calculate each eye movement measure. Exported the appropriate reports and variables to Excel.
5. Determined how to calculate first pass reading (i.e., summation of all eye movements through the first time reading through the passage excluding any attempts to reread the passage) and apply the formula to the data in each Excel file.
6. Using the knowledge learned in step 2, applied any formulas required to calculate each reading measure in Excel.
7. Created pivot table in excel for eye movement measure to indicate the mean and standard deviation for all trials and each participant.
8. Calculated the mean value across all trials of the connected-text task for each participant and reading measure.

CHAPTER IV

RESULTS

Descriptive statistics including means and standard deviations for each participant group and eye movement measure are shown in Table 4. Individual participant data is shown in Appendix B. Overall, participant group means for each eye movement measure were within close proximity of one another for most measures. For persons with aphasia, the average saccade amplitude for all participant groups deviated from the mean the least among all subtypes, while regression path duration and sum of words skipped showed the widest range of measurements. Persons with anomic aphasia had the furthest deviation from the mean across all measures for any subtype for regression path duration (M=516.9, SD= 265.3) and sum of words skipped (M=887.1, SD=237.1).

Table 4. Descriptive Statistics for Aphasia Subtypes and Controls

	Simple Fixation Duration (ms)	Regression Path Duration (ms)	Total Duration (ms)	Gaze Duration (ms)	Sum of Words Skipped	Average Saccade Amp. (deg °)	First Fixation Duration (ms)
Whole Group (*n*=24)							
PWA	236.1 (44.6)	488.8 (189.9)	194.1 (11.1)	287.9 (75.3)	894.9 (216.4)	4.7 (0.6)	212.2 (52.9)
Controls	232.0 (35.2)	359.8 (64.0)	191.6 (12.1)	274.1 (46.5)	732.2 (136.8)	4.9 (0.7)	218 (43.6)
Broca's (*n*=8)							
PWA	249.1 (46.4)	439.9 (100.1)	194.1 (14.1)	309.6 (74.7)	868.0 (142.3)	4.7 (0.7)	213.8 (62.5)
Controls	220.2 (34.0)	333.0 (22.7)	189.7 (15.7)	263.7 (47.0)	691.1 (72.1)	4.9 (0.6)	193.8 (32.8)
Anomic (*n*=8)							
PWA	225.0 (33.5)	516.9 (265.3)	198.4 (9.9)	294.22 (56.81)	887.1 (237.1)	4.6 (0.5)	206.1 (51.2)
Controls	234.1 (45.5)	364.2 (71.5)	194.6 (7.7)	272.19 (57.20)	724.9 (152.7)	5.0 (0.6)	217.9 (36.4)
Wernicke's/conduction (*n*=8)							
PWA	234.3 (54.1)	509.5 (184.2)	189.9 (8.3)	301.27 (98.40)	929.5 (274.1)	4.8 (0.6)	216.7 (50.8)
Controls	241.8 (24.0)	382.1 (80.1)	190.4 (12.6)	286.5 (36.2)	780.5 (168.1)	5.0 (0.9)	242.2 (50.2)

The first research question asked whether the eye movement measures, fixation duration, gaze duration, total viewing time, skipping rate, saccade amplitude, and regression path duration differ among persons with anomic, Broca's, and Wernicke's/conduction aphasia as well as when compared to an age matched control group. Linear mixed effects models were run using JASP 0.16.1 (2022) to compare eye movement measures from the mean of fixation duration, regression path duration, total duration, gaze duration, and saccade amplitude across these participant groups. A separate model was run for each eye movement measure. The details of each model are shown in Appendix A. Eye movement measure was the dependent variable. Participant group (i.e., persons with aphasia vs. controls), aphasia subtype (i.e., anomic, Broca's, Wernicke's/conduction), and time (i.e., pre- vs. post- protocol changes) were the fixed effects. Participant was a random effect. Trial number was entered as a random effect, but the model was unable to converge, so it was removed from the model. An analysis of variance (ANOVA) was run separately for the sum of word skipping as the trial data was categorial (i.e., the word was skipped or not), not continuous which is required for the linear mixed effects model. Participant group, aphasia subtype, and time were entered as fixed factors into the ANOVA.

For the linear mixed effects models, there were no significant main effects of participant group (i.e., control vs. persons with aphasia), aphasia subtype (i.e., anomic, Broca's, Wernicke's/conduction), or time (i.e., before and after the change in the experiment protocol) for any of the eye movement measures (all $p > .11$), except participant group for regressive path duration ($p = .04$). This main effect indicates that the whole group of persons with aphasia ($M = 438.40$, $SD = 562.19$), collapsed over subtype, had a longer regressive path duration than the whole control group (*M* = 350.91, *SD* = 373.86). Additionally, there were no significant interactions between participant group, aphasia subtype, or time (all $p >. 24$). The ANOVA for word skipping revealed one significant main effect for participant group (F (1, 36) = 5.50, p =.03) indicating persons with aphasia skipped significantly more words (*M* = 894.88, *SD* = 216.41) than control participants (*M* = 732.17, *SD* = 136.75). All other main effects and interactions were not significant (all $p > .70$).

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The second research question asked what the relationship was between eye movement measures (e.g., fixation duration, regression path duration), language severity (WAB-R AQ scores) and reading comprehension ability (RCBA-2 scores). Because most skewness and kurtosis values fell beyond the range of -1 and +1, across all eye movement measures for each subtype group, Spearman's correlation was used to investigate this question. A separate Spearman's correlation was used to examine the associations of eye movement measures and WAB—R AQ and RCBA-2 scores for each aphasia subtype and the group of persons with aphasia as a whole. A summary of the results is presented in

Table 5. For the whole group of persons with aphasia, there was a weak, significant, positive correlation between language severity and total duration (r = .34, p = .05), suggesting a longer duration is associated with less language impairment. There were also two weak significant negative correlations between regression path duration, sum of words skipped (r = -.36, p = .05) and reading comprehension (r = -.42, p = .02) suggesting more words skipped and a larger regression path duration is associated with poorer reading comprehension. Although significant, these associations are weak suggesting other variables may be influencing the correlation such as the complexity of the text. For persons with Broca's aphasia, there was a strong, significant, positive correlation between the average of the first fixation duration and language severity (r = .74, p = .02). This association indicates that a longer first fixation duration is associated with less language impairment as measured by the WAB-R AQ. Other eye movement measures showed moderate associations between variables, despite not being statistically significant. Specifically, for persons with Broca's aphasia, there was a non-significant moderate positive correlation between language severity and gaze duration (r = .50), indicating longer gaze duration is associated with less language severity. Additionally, there was a non-significant moderate negative association between reading comprehension and the average of saccade amplitude (r = -.55), indicating that poorer reading comprehension is associated with a larger saccade amplitude. For persons with anomic aphasia, non-significant moderate negative associations were found between reading comprehension and first fixation duration (r = -.56), regression path duration (r = -.60), and sum of words skipped (r = -.60). These associations indicate that poorer reading comprehension is associated with longer fixation duration, longer regression path

duration, and an increase in the number of words skipped. Lastly, for persons with Wernicke's/conduction aphasia, the relationship among variables were weak, indicating very little association between eye movement measures and language severity and reading comprehension ability.

Table 5. Spearman's Correlation Between Eye Movement Measures, Language Severity (WAB-R AQ) and Reading Comprehension (RCBA-2)

	Simple Fixation Duration	Regression Path duration	Total Duration	Gaze Duration	Sum of Words Skipped	Average Saccade Amp	First Fixation Duration
Whole Group of Persons with Aphasia (n = 24)							
WAB-R AQ	.13	-.01	.34*	.18	-.09	-.29	.06
RCBA-2	-.11	-.36*	.25	-.12	-.42*	-.33	-.04
Broca's Aphasia (n = 8)							
WAB-R AQ	.36	.31	.45	.50	.26	-.14	.74*
RCBA-2	.19	-.10	.21	.33	-.14	-.55	.14
Anomic Aphasia (n = 8)							
WAB-R AQ	.12	-.41	-.05	.10	-.41	.17	-.07
RCBA-2	-.56	-.60	.01	-.47	-.60	-.34	-.10
Wernicke's/ Conduction Aphasia (n = 8)							
WAB-R AQ	.38	.19	.21	.19	.17	-.33	.26
RCBA-2	.39	-.21	.36	.07	-.29	-.21	.14

*Note: * indicates significant at the .05 level*

CHAPTER VII

DISCUSSION

The purpose of this research study was to examine whether eye movement measures, specifically, fixation duration, regression path duration, total duration, gaze duration, word skipping, and saccade amplitude differ among persons with aphasia and their age matched controls. It also examined whether eye movement measures from reading connected text were associated with language impairment and reading comprehension skills.

Research Question 1

The first hypothesis predicted that persons with aphasia would have a longer fixation duration, higher gaze duration, longer viewing time, more refixations, shorter saccade amplitude, and a lower skipping rate. Results indicated there was a significant difference between the whole control group and persons with aphasia for regressive path duration, suggesting control participants refixated on words less than persons with aphasia. The results also indicated persons with aphasia skipped more words than the control group. There were no other eye movement measures that were significantly different between persons with aphasia, in any subtype, and the control groups. Additionally, the first hypothesis predicted eye movement measures for persons with anomic aphasia would not significantly differ from the control group, while eye movement measures for persons with Broca's and Wernicke's/conduction aphasia would show a significant difference. Results indicated there was no significant difference between eye movement measures for any of the aphasia subtypes and their controls.

Because the current literature suggests a strong association between eye movement measures and cognitive-linguistic processing (Rayner & Liversedge, 2011; Rayner et al., 2012; Henderson & Luke, 2012; Rayner & Pollastek, 2013; Luke & Henderson, 2013), it was expected that there would be differences in eye movement measures during reading among aphasia subtypes and controls groups; however, our results indicated only two significant main effects between controls and persons with aphasia, with no differences among the subtypes. There are a few explanations for these results. The small size of the groups (n = 8) may have prevented the linear mixed effects model from yielding significant results. A larger sample size would lead to greater statistical power, and greater confidence in the mean's ability to represent the sample group. In the current study, the group sizes were relatively small; therefore, it is possible with more participants, more significant differences would be seen between subtypes of aphasia and their eye movements.

Although most eye movement measures did not yield a significant result, regression path duration did reflect a significant difference between the control group and persons with aphasia, indicating controls had a shorter fixation duration following the first fixation than persons with aphasia. Due to slow lexical access, persons with aphasia may need to re-fixate on a word more frequently and for a longer duration to process its meaning (Huck et al., 2017). Additionally, Huck and colleagues' (2017) results indicated linguistic features of the text, specifically word frequency, can affect fixation duration for both neurotypical individuals and persons with aphasia. In their study, high frequency words were associated with a shorter fixation duration where as low frequency words were associated with a longer fixation duration. In contrast to the present study, a study conducted by Knilans and Dede (2015) found that controls had a longer regression path duration than persons with aphasia. However, those researchers controlled for structural frequency and complexity of the stimuli. The significant difference between persons with aphasia and controls for regression path duration suggests persons with aphasia may use a different reading strategy when reading sentences with complex structures. Knilans and Dede (2015) used sentence level stimuli, while the current study used paragraph level stimuli. This difference may have also led to different findings, suggesting despite the complex structure or structural frequency of the sentence, persons with aphasia may process information differently at the paragraph level than at the sentence level when comprehending the text.

The second significant finding was word skipping at a higher rate for persons with aphasia compared to controls. This finding was contrary to my hypothesis. Based on the previous literature that suggested reading more complex and difficult text leads to fewer words skipped (Vitu et al., 1995), I expected persons with aphasia to skip fewer words due to reading difficulty. Rather, persons with aphasia skipped more words which might suggest a different reading strategy than predicted. On the contrary Perhaps, persons with aphasia skip words they do not know rather than fixate on them. This is interesting when considered in the context of the other significant finding of higher regression path duration for persons with aphasia compared to controls. Persons with aphasia appear to skip more words but refixate more following the first fixation. In a follow up study, it would be interesting to analyze the words that are not skipped and re-fixated for linguistic characteristics.

Research Question 2

The second hypothesis predicted there would be a strong negative association between gaze duration, fixation duration, regressions, word skipping, and refixations and connected text reading ability (RCBA-2) and language processing severity (WAB-R). Overall, there was one significant, strong, positive association between the first fixation duration and language severity for persons with Broca's aphasia. Although I hypothesized that longer first fixation duration would be associated with more language impairment, the results indicated persons with Broca's aphasia, who had a longer fixation duration, had less language impairment. A possible explanation may be persons with Broca's aphasia with a longer fixation time process the text without needing to re-fixate on the word again, suggesting persons with Broca's aphasia utilize a different reading strategy. Thus, this subtype may have greater awareness of their deficits and compensated by fixating for longer on the text. A longer gaze duration was also associated with less language impairment. The same explanation for fixation duration may also reveal why longer gaze duration indicates less language impairment, as persons with Broca's aphasia are attempting to process that specific area of the text and need to fixate on it for a longer period of time.

A larger saccade amplitude was associated with poorer reading comprehension ability for persons with Broca's aphasia. Research in neurotypical individuals has shown that linguistic processing is largely suppressed during a saccadic eye movement (Wolverton & Zola, 1983). Current research also suggests harder texts leads to smaller or shorter saccades (Rayner, 1998; Rayner & Pollastek, 2013). Additionally, processing information at the current fixation point plays an important role in determining the next saccadic eye movement (Gilchrist, 2011). This may explain why a larger saccade amplitude is associated with poorer reading comprehension, suggesting persons with Broca's aphasia may have difficulty processing information at the current point of fixation and thus proceed to jump further in the text because of difficulty with lexical access. It is also possible that those with more severe impairment, show larger saccadic movements because they are not processing any of the text and therefore their eyes continue to jump from one point to the next.

Findings for persons with anomic aphasia suggests poorer reading comprehension is associated with longer first fixation duration, longer regression path duration, and more words skipped. This is consistent with previous research that shows a longer fixation duration and longer regression path duration is associated with more difficulty processing the text (Rayner & Pollastek, 2013). On the contrary, a longer fixation duration in persons with Broca's aphasia suggested less language impairment and possibly the use of a different strategy for language processing in this specific subtype of aphasia.

Associations for persons with Wernicke's/conduction aphasia were weak. When graphed on a scatter plot there was little to no association due to all points being in one area or all of them being spread out across the graph. Scatter plots for language severity and saccade amplitude, fixation duration, sum of words skipped, regression duration, gaze duration, and words skipped showed all points on the graph were in one area, indicating language impairment did not have an impact on eye movement measures. A possible explanation may be the wide range of severity of deficits among participants with Wernicke's/conduction aphasia prevented any patterns from emerging within the eye movement measures. Persons with Wernicke's aphasia tend to have more severe language impairments, while persons with conduction aphasia are milder. Total duration resulted in a wider spread across the top of the scatter plot. Although some participants' total duration increased with an increase in WAB-R AQ score, outliers within a small sample size affected the relationship between the two variables. For reading comprehension, first fixation duration, gaze duration, sum of words skipped, average saccade amplitude, and average of the first fixation duration also showed all the points to be clumped together on the graph, indicating reading comprehension and eye movement measures were not strongly associated for this subgroup. Total duration and regression path duration both resulted in a larger spread at the top of the graph, with the lack of a stronger association coming from the outliers in the group.

In regards to the eye measure utilized in this study, it is important to question whether these measures are sensitive enough to predict severity of overall language impairment and reading comprehension ability; and thus, whether or not these measures truly reflect linguistic processing. In a scoping review, Sherma and colleagues (2021) analyzed studies looking at eye tracking measures for studying language comprehension in aphasia; however, research was limited on predicting overall language severity or reading comprehension ability. Although temporal measures such as fixation duration, regressions path duration, and gaze duration are most commonly used for studying language comprehension in neuro-atypical populations, there is limited research to know whether these same measures are capable of predicting overall language processing severity for other assessment measures (Staub & Rayner, 2007). In other words, it is unclear whether eye movement measures from a separate language task can predict language processing abilities on another task. Therefore, further research is needed to determine if the eye movement measures utilized in this study can make these predictions or if other eye movements such as other spatial measures (e.g., fixation position) would be more sensitive for this prediction. Lastly, utilizing the paragraphs from the eye tracking protocol rather than comparing measurements to scores from the RCBA-2 may be a more accurate representation of the participants' reading comprehension. The RCBA-2 contains multiple parts including word, sentence, and text level reading to gain an overall reading comprehension score, whereas the stimuli used for calculating eye movement measures only utilize text level reading.

Statistical power may have also influenced a possible type II error. Norton and Straub (2001) indicate there are 4 factors that may influence statistical power: α level, differences between group means, variability among subjects, sample size. In the current study, mean differences, variability, and sample size may have influenced the results. Despite participants with aphasia fitting a specific subtype, variability in WAB-R and RCBA-2 scores among aphasia subtypes may have prevented significant differences from emerging in the data between these groups. A smaller standard deviation from the mean for WAB-R and RCBA-2 scores for each group would have allowed for a greater chance for the results to show a significant difference between participant groups; however, RCBA-2 and WAB-R scores deviated from the mean by five points or more for each subtype. Because of the increased variability, overlapping scores between groups made it difficult to detect differences, should there be some present. For example, persons with Wernicke's/conduction aphasia had a mean score of M=60.0, SD=20.7 on the WAB-R, and persons with Broca's aphasia also had a similar mean with a large standard deviation (M=64.1, SD=10.5). Thus, the similarities between groups make the different subtypes look similar when looking only at the data.

Research Limitations and Future Suggestions

Despite strong evidence for the relationship between eye movement measures and cognitive-linguistic processing in neurotypical readers, our results were limited in reflecting the relationship for eye movement measures between neurotypical individuals, persons with aphasia, aphasia subtype, reading comprehension, and language impairment. Linguistic characteristics of the text stimuli, specifically word frequency, could impact eye movement measures. Furthermore, the text stimuli was at approximately an 8^{th} grade reading level, which may be too easy for individuals with aphasia and fail to reflect their reading impairments through eye movements. Lastly, even though eye movements are likely mediated by cognitive-linguistic processing in neurotypical readers, eye movement measures could be mediated more by the oculomotor system in individuals with aphasia due to the impairments in cognitive-linguistic abilities.

Additionally, less variance among WAB-R AQ and RCBA-2 for aphasia subtypes will create less overlap among groups and be more likely to show a significant difference between aphasia subtypes. For future studies, controlling for the lexical complexity of the text may also give greater insight into the complexity of text persons with aphasia are able to comprehend. Lastly, it may be beneficial to associate the eye movement measure with the paragraphs used for the eye tracking protocol rather than comparing measures to standardized tests scores (i.e., WAB-R, RCBA-2). These associations may be more accurate than comparing eye movement measures to a standardized test that contains multiple parts.

Clinical Implications

Results from this study continue to give insight into the uses of eye tracking with neuro-atypical individuals, and specifically for individuals who have aphasia. Although the majority of the eye movement measures were insignificant, using eye tracking to study aphasia is still relatively new, especially when it comes to using these measures to predict language severity and reading comprehension abilities. Results from this study can be used to continue to learn how persons with aphasia process language and help to determine if eye tracking is a reliable future source for measuring pre and post treatment progress. The results from the present study can be used to further determine which eye movement measures may be most suited for studying language processing in neuro-atypical individuals and further determine whether persons with aphasia may use different strategies for reading comprehension than neurotypical individuals. It is my hope that the findings from this study will continue to prompt further research into the uses of eye tracking in studying language deficits in persons with aphasia and will help to inform future clinical practice for speech-language pathologist who are working with this population.

Conclusion

The purpose of this study was to examine whether eye movement measures obtained from connected text reading differ among persons with aphasia compared to an age- matched control group and explore whether eye movement measures are associated with language severity and reading comprehension deficits in persons with aphasia. It was found that persons with aphasia had a longer regression path duration than the controls. This result suggests regression path duration may be particularly sensitive in predicting language impairment. There were no other main effects or significant interactions. Additionally, there was a significant, strong, positive correlation between first fixation duration and language impairment in persons with Broca's aphasia. Associations for persons with anomic aphasia indicated moderate weak correlations found between reading comprehension and first fixation duration, regression path duration, and sum of words skipped, and there were no significant associations for persons with Wernicke's/conduction aphasia. These differences in correlations among subtypes suggests varying strategy use among persons with varying subtypes of aphasia. Limitations of this study include the small sample size for the correlation analysis, variability among participant groups and eye movement and assessment scores, and a lack of control for the linguistic complexity of the stimuli. For future studies, increasing the sample size, keeping participant groups more cohesive, and controlling for the linguistic complexity of the text through calculating word frequency and the complexity of the sentences of the stimuli, will help make the use of eye tracking a more reliable measure for language impairment and reading comprehension ability in persons with aphasia.

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APPENDICES

Appendix A: Linear Mixed Effects Models for Eye Movement Measures

Table A1. Linear Mixed Model- First Fixation Duration

Effect	*df*	*f*	*p*
PWA subtype	2, 32.47	0.69	0.51
Time	1, 32.48	2.05	0.16
Participant	1, 32.48	0.71	0.41
PWA Subtype ∗ Time	2, 32.47	0.33	0.72
PWA Subtype ∗ Participant	2, 32.47	0.94	0.40
Time ∗ Participant	1, 32.48	0.26	0.61
PWA Subtype∗Time∗Participant	2, 32.47	0.66	0.52

Table A2. Linear Mixed Model- Total Duration

Effect	*df*	*f*	*p*
PWA subtype	2, 27.22	1.83	0.18
Time	1, 31.52	2.64	0.11
Participant	1, 31.52	0.01	0.92
PWA Subtype ∗ Time	2, 27.22	0.58	0.57
PWA Subtype ∗ Participant	2, 27.22	0.29	0.75
Time ∗ Participant	1, 31.52	0.04	0.84
PWA Subtype∗Time∗Participant	2, 27.22	1.21	0.31

Table A3. Linear Mixed Model- Gaze Duration

Effect	*df*	*f*	*p*
PWA subtype	2, 26.95	0.04	0.97
Time	1, 39.29	0.05	0.82
Participant	1, 39.29	0.58	0.45
PWA Subtype ∗ Time	2, 26.95	0.31	0.74
PWA Subtype ∗ Participant	2, 26.95	0.17	0.85
Time ∗ Participant	1, 39.29	8.40	0.99
PWA Subtype∗Time∗Participant	2, 26.95	0.70	0.51

Table A4. Linear Mixed Model- Regression Path Duration

Effect	*df*	*f*	*p*
PWA subtype	2, 19.84	1.00	0.40
Time	1, 26.10	0.33	0.57
Participant	1, 26.10	4.72	0.04*
PWA Subtype ∗ Time	2, 19.84	0.71	0.51
PWA Subtype ∗ Participant	2, 19.84	0.05	0.95
Time ∗ Participant	1, 26.10	6.84	1.00
PWA Subtype∗Time∗Participant	2, 19.84	0.72	0.50

*Note: * indicates significant at the .05 level*

Table A5. Linear Mixed Model- Saccade Amplitude

Effect	*df*	*f*	*p*
PWA subtype	2, 27.25	0.98	0.39
Time	1, 33.52	0.72	0.40
Participant	1, 33.52	1.84	0.18
PWA Subtype ∗ Time	2, 27.25	0.40	0.67
PWA Subtype ∗ Participant	2, 27.25	1.52	0.24
Time ∗ Participant	1, 33.52	0.97	0.33
PWA Subtype∗Time∗Participant	2, 27.25	0.55	0.59

Table A6. Linear Mixed Effects Model- Simple Fixation Duration

Effect	*df*	*f*	*p*
PWA subtype	2, 24.83	0.12	0.89
Time	1, 37.73	0.26	0.62
Participant	1, 37.73	3.92	0.98
PWA Subtype ∗ Time	2, 24.83	0.28	0.76
PWA Subtype ∗ Participant	2, 24.83	0.54	0.59
Time ∗ Participant	1, 37.73	0.01	0.95
PWA Subtype∗Time∗Participant	2, 24.83	0.19	0.83

Appendix B: Descriptive Statistics for all Participants

B1. Descriptive Statistics for All Participants

Participant	Simple fixation duration (ms)	Regression path duration (ms)	Total duration (ms)	Gaze duration (ms)	Sum of words skipped (ms)	Saccade amplitude (deg)	First fixation duration (ms)
Persons with Aphasia							
	M *(SD)*	*M* *(SD)*	*M* *(SD)*	*M* *(SD)*	*M* *(SD)*	*M* *(SD)*	*M* *(SD)*
Broca's							
1	236.8 (132.9)	483.3 (816.0)	195.1 (224.2)	284 (165.3)	951	4.4 (5.0)	114.7 (93.0)
2	231.8 (81.7)	522.2 (542.1)	189.9 286.0)	316 (216.7)	1015	5.0 (4.5)	169.9 (70.6)
3	2502. (99.0)	456.8 (426.9)	209.0 (241.4)	299 (149.2)	865	4.6 (5.1)	245.4 (95.3)
4	276.7 (88.0)	402.3 (414.4)	207.6 (229.0)	305 (124.6)	772	3.5 (4.1)	172.1 (44.2)

Table B1, cont.

5	205.5 (88.6)	303.4 (242.0)	183.0 (200.0)	251 (148.2)	633	4.2 (3.8)	291.0 (57.2)
6	339.0 (120.9)	596.5 (557.5)	209.4 (375.2)	479 (312.6)	1035	5.1 (4.8)	287.0
7	264.4 (78.9)	443.2 (473.4)	188.8 (209.2)	311 (144.0)	934	5.3 (4.7)	243.1 (84.4)
8	189.0 (64.2)	311.2 (295.0)	169.8 (180.5)	231 (117.3)	739	5.7 (4.8)	186.8 (65.9)
				Anomic			
9	237.3 (110.6)	495.0 (417.9)	203.2 (284.2)	314 (192.5)	959	4.8 (4.6)	230.3 (104.3)
10	273.4 (111.8)	1076.2 (1669.4)	215.9 (411.3)	408 (299.1)	1275	4.3 (4.5)	144.5 (82.3)
11	180.8 (71.7)	352.8 (460.0)	189.3 (194.3)	244 (134.1)	739	4.0 (5.1)	161.9 (64.1)
12	208.0 (69.8)	305.2 (289.7)	200.9 (182.3)	246 (124.3)	545	4.4 (5.0)	169.0
13	272.4 (87.9)	378.5 (341.1)	184.4 (213.0)	315 (141.7)	818	5.5 (5.1)	208.9 (24.8)
14	200.1 (66.9)	363.2 (334.9)	191.3 222.7)	241 (122.3)	770	4.3 (5.0)	193.8 (69.7)

Table B1, cont.

15	210.6 (98.9)	750.0 (1033.3)	202.7 (224.2)	270 (158.4)	1164	4.8 (4.4)	236.1 (49.1)
16	217.4 (110.1)	414.6 (363.5)	199.6 (281.7)	316 (214.1)	827	4.9 (4.5)	304.0 (192.5)
				Wernicke's/Conduction			
17	199.2 (73.7)	298.7 (254.9)	182.6 (183)	228 (113.2)	598	4.4 (3.8)	186.0 (57.2)
18	174.2 (57.7	289.0 (369.1)	185.3 (175.6)	195 (76.4)	584	5.5 (4.7)	176.5 (57.9)
19	244.7 (99.8)	556.8 (495.9)	190.2 (318.3)	302 (190.4)	1050	5.2 (5.1)	164.8 (95.3)
20	203.1 (87.0)	733.1 (786.4)	177.5 (353.4)	275 (185.2)	1233	4.5 (3.4)	195.3 (73.7)
21	338.1 (147.7)	593.3 (571.4)	201.3 (325.1)	471 (293.2)	1075	4.3 (5.0)	317.9 (133.7)
22	213.0 (109.4)	574.8 (907.0)	190.4 (258.4)	282 (194.9)	1088	5.2 (5.1)	213.8 (69.2)
23	288.4 (128.5)	716.1 (690.5)	200.7 (407.7)	428 (318.3)	1171	3.9 (4.1)	262.5 (95.3)
24	213.4 (68.7)	314.0 (451.2)	191.1 (193.0)	229 (88.1)	637	5.6 (5.1)	217.0 (69.2)

Table B1, cont.

Age-Matched Controls

				Broca's			
1	203.4 (79.7)	323.2 (387.3)	183.0 (179.0)	230.9 (111.9)	692	5.0 (4.8)	133.5 (83.8)
2	166.7 (76.9)	347.3 (677.6)	167.9 (230.4)	189.9 (122.3)	824	3.7 (4.3)	180.5 (57.2)
3	270.3 (99.9)	379.6 (232.9)	214.9 (241.1)	346.6 (198.3)	692	4.7 (5.3)	189.7 (84.8)
4	245.8 (89.1)	340.4 (353.2)	203.2 (208.6)	279.1 (123.1)	643	5.1 (4.5)	186.8 (64.2)
5	205.7 (78.4)	320.4 (318.2)	192.6 (188.0)	244.6 (113.8)	649	5.9 (5.3)	201.7 (73.9)
6	201.1 (65.1)	328.1 (285.5)	172.4 (177.6)	257.3 (131.8)	772	4.7 (4.8)	192.8 (67.6)
7	254.6 (84.5)	318.8 (161.5)	197.9 (192.4)	301.3 (136.9)	617	5.1 (5.2)	249.1 (84.2)
8	214.3 (85.8)	306.4 (218.2)	185.9 (195.8)	259.9 (139.1)	640	4.6 (5.0)	216.5 (86.3)
				Anomic			

Table B1, cont.

9	214.9	392.6	189.8	244.8	824	4.4	179.0
	(77.6)	(470.4)	(191.5)	(106.3)		(4.9)	(113.3)
10	184.7	312.8	190.8	218.2	622	4.8	178.9
	(64.3)	(406.7)	(230.0)	(122.9)		(5.3)	(34.5)
11	297.7	478.6	209.1	363.7	898	5.7	250.8
	(115.5)	(352.1)	(270.4)	(196.8)		(4.8)	(21.4)
12	278.3	392.7	192.6	297.2	829	5.9	265.5
	(101.4)	(347.9)	(195.3)	(124.7)		(5.0)	(101.3)
13	222.5	288.4	198.9	239.1	495	4.7	213.7
	(66.6)	(311.8)	(162.0)	(87.4)		(5.0)	(79.1)
14	200.6	320.9	186.8	244.6	680	4.8	200.8
	(73.3)	(294.2)	(206.6)	(121.7)		(4.9)	(71.6)
15	284.2	437.4	201.1	348.4	879	4.4	261.8
	(121.2)	(565.2)	(237.4)	(183.8)		(5.0)	
16	190.4	290.4	188.3	221.5	572	5.5	192.6
	(71.3)	(369.3)	(178.1)	(105.2)		(5.0)	(86.3)
				Wernicke's/Conduction			
17	254.8	405.2	191.8	294.8	840	4.5	307.2
	(179.3)	(492.2)	(270.0)	(213.8)		(4.7)	(92.0)
18	264.4	509.6	212.1	349.1	931	5.1	170.8
	(98.1)	(532.9)	(272.1)	(185.5)		(5.7)	(89.5)

Table B1, cont.

19	242.3 (353.6)	385.8 (511.2)	195.9 (345.1)	290.8 (369.5)	785	4.2 (5.1)	309.3 (133.2)
20	206.1 (67.7)	285.4 (153.8)	183.3 (157.1)	244.6 (106.0)	582	5.2 (5.3)	196.2 (70.0)
21	231.2 (82.0)	302.4 (273.0)	195.3 (187.1)	253.2 (110.1)	576	5.2 (5.0)	232.7 (84.1)
22	212.8 (60.5)	306.9 (257.5)	190.9 (170.0)	247.4 (111.9)	615	5.2 (4.9)	210.2 (61.9)
23	247.3 (94.2)	462.8 (342.4)	186.3 (265.8)	304.3 (173.6)	972	3.8 (3.8)	244.9 (104.5)
24	275.0 (98.6)	398.6 (309.9)	167.6 (201.6)	307.9 (137.5)	943	6.6 (4.9)	266.1 (102.5)

BIOGRAPHICAL SKETCH

Sarah C. McWilliams was born in Birmingham, Alabama on October 7th, 1997. She graduated from the University of South Alabama in 2020 with a B.S. in Speech and Hearing Sciences and in 2022 with a Master's of Science in Speech- Language Pathology. She has served as a research assistant in the Adult Speech and Language Lab since 2017 and the Autism, Pediatric, Language, and Literacy Lab since 2020. She was awarded the Speech and Hearing Association of Alabama (SHAA) scholarship award for 2022 and the Speech Pathology and Audiology Outstanding Undergraduate student award for 2020.