The relationship between non-orthographic language abilities and reading performance: An exploration of the primary systems hypothesis in chronic aphasia

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A dissertation

submitted in partial fulfillment of the

requirements for the degree of

Doctor of Philosophy

University of Washington

2016

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Program Authorized to Offer Degree:

Speech & Hearing Sciences

University of Washington

Abstract

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Individuals with aphasia, an acquired language processing disorder, commonly present with both spoken (i.e., language production and comprehension) and written (i.e., reading and spelling) language impairments. Traditionally, spoken and written language have been assumed to rely on distinct linguistic representations and processing mechanisms. Alternatively, the primary systems hypothesis, which is grounded in parallel-distributed processing theory, proposes written language abilities developed from and are reliant on the same primary brain systems that support spoken language. Therefore, the primary systems hypothesis postulates all language activities, including naming, reading, and spelling, are supported by an interconnected language system. Empirical support for this hypothesis is promising, yet limited, and therefore

these claims remain controversial. Motivated by the primary systems hypothesis, the purpose of this study was to examine the relationship between non-orthographic (i.e., no letters) spoken language abilities and written language abilities, specifically reading performance, in aphasia.

Forty-three individuals with chronic, left-hemisphere stroke-induced aphasia participated in the study. Performance on non-orthographic semantic, phonologic, and syntactic tasks, as well as performance on oral reading and silent reading comprehension tasks was assessed and analyzed. Specifically, Pearson correlations were calculated to determine the size and strength of the associations between non-orthographic language abilities and reading abilities. Additionally, non-orthographic language composite scores were entered as predictors of reading performance in multiple linear regression models. Lastly, a reading profile (i.e., surface, phonological, deep, global alexia or within normal limits) was determined for each participant based on oral reading accuracy and types of reading errors produced. Then, the relationship between degree of semantic and phonologic impairment and type of acquired reading impairment (i.e., alexia) was examined.

Results showed that non-orthographic language abilities were statistically significantly related to oral reading and silent reading comprehension abilities, as well as alexia subtype, in this diverse sample of individuals with aphasia. In regard to oral reading ability, semantic abilities were found to be most predictive of regular and irregular word reading, while phonologic abilities were most predictive of pseudohomophone and nonword reading. The silent reading comprehension analyses revealed written word and written paragraph comprehension were primarily supported by semantics. Whereas, written sentence comprehension was significantly related to semantic, phonologic, and syntactic performance, with the strongest association with syntax. Finally, severity of alexia was found to reflect severity of semantic and phonologic impairment.

The results of this work offer promising support for the primary systems view of language processing by showing non-orthographic language abilities are closely linked to oral reading and silent reading comprehension performance in chronic aphasia. Additionally, the data suggest alexia subtype in aphasia can be described based on non-orthographic semantic and phonologic performance. This finding further endorses the primary systems notion that alexia stems from an underlying general language, as opposed to reading-specific, impairment. Moreover, this work clinically suggests that assessing and treating non-orthographic semantic and phonologic abilities may be useful in alexia rehabilitation. These findings are preliminary, and therefore this work needs to be replicated and extended to further understand the connection between acquired spoken and written language impairments in aphasia.

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Department of Speech & Hearing Sciences • University of Washington Doctoral Dissertation • 2016

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Acknowledgements

A University of Washington training grant (*Research Training in Speech & Hearing Sciences*) from the National Institute on Deafness and Other Communication Disorders (NIDCD) of the National Institutes of Health (NIH) (T32000033) funded this work and is greatly appreciated.

I am extremely grateful for the tremendous support I received during the completion of my doctorate. I would first like to acknowledge my mentor and chair of my dissertation committee, Dr. Diane Kendall. I am eternally appreciative of Diane's phenomenal guidance over the past five years. She went above and beyond the expected role of a mentor. The hundreds of hours Diane spent with me in her office and in the lab not only supported my academic growth, but my personal growth as well. I am forever thankful for the self-confidence she unknowingly helped instill in me by strongly, yet patiently, encouraging me to rejoin the doctoral program after my leave of absence. I hope I am able to channel Diane's mentoring style when advising students in the future. In addition to Dr. Diane Kendall, I am deeply thankful for the other members of my committee, Drs. Tim Conway, Maya Henry, Kristie Spencer, and Kathy Yorkston, who have challenged me with hard questions, inspired me with their sound research, and encouraged me to pursue my research and teaching interests. I credit much of my success in the doctorate program to the valuable time and effort all of my committee members devoted to evaluating and refining my work.

Many others have supported me throughout my doctorate experience. Namely, I would like to acknowledge members of Dr. Kendall's outstanding Aphasia Research Laboratory. I could not have completed this process without the help of Irene Minkina, Lauren Bislick Wilson, JoAnn Silkes, Rebecca Hunting Pompon, Megan Oelke, Wesley Allen, Reva Robinson, Janaki

Torrence, Christina del Toro, and Kerry Lam who were always willing to answer my questions, read my drafts, and listen to my concerns. I am so fortunate to have worked with such intelligent, collaborative, and caring individuals.

This work would not exist without the time and energy so graciously volunteered by the 47 individuals with aphasia who participated in this study. Their determination and perseverance inspire me professionally and personally, and I am very thankful for their interest and participation in my research. I am also indebted to the careful, thorough work of my research assistants, Lauren Belongia, Shanni Geller, Nicole Okada, and Alexa Wilkenson, who diligently helped me analyze amazing amounts of data in a timely manner.

Lastly, but certainly not least, I would like to recognize the unconditional support and encouragement I received from my family. I will fondly remember the countless reassuring phone calls with my parents, Julie and George, and the many trips they made out to Seattle to visit me. Words cannot express how grateful I am for the committed love and support of my husband, Dave, who believes in me and keeps me grounded when I get overwhelmed. I am humbled by the sacrifices he has made so that I can pursue my passion, and I'm comforted knowing that he will be by my side as I continue my academic journey.

Chapter 1: Introduction

Background and Motivation

Aphasia is a pervasive acquired communication disorder that impairs the processing of language (Papathanasiou, Coppens, & Davidson, 2016). Aphasia is most commonly the result of left-hemisphere brain injury, typically stroke, with approximately 25%-40% of stroke survivors acquiring aphasia and approximately 1 million Americans currently living with aphasia (National Aphasia Association, 2016). Persons with aphasia (PWA) show individual variation in their language abilities; however, despite these differences all PWA demonstrate word retrieval difficulty (i.e., anomia) (Benson, 1988; Hickin, Best, Herbert, Howard, & Osborne, 2002). Therefore, much of aphasia research has been directed towards understanding and rehabilitating spoken language impairment (Raymer, Maher, Foundas, Gonzalez-Rothi, & Heilman, 2000).

It is generally accepted, theoretically and empirically, that spoken language difficulties stem from underlying impairment to semantics and/or phonology. For example, Dell's prominent interactive spreading activation model highlights the critical collaboration needed between semantic and phonologic language networks in order to give rise to intact spoken production and comprehension (Dell, 1986; Dell, Schwartz, Martin, & Saffran, 1997). When the semantic components, phonologic components, or interaction between these language networks are damaged, then so too is word retrieval. In addition to this theoretical work, empirical findings have documented that PWA demonstrate impaired semantics and phonology, to varying degrees, with the extent of semantic and phonologic impairment accounting for the severity of word retrieval impairment (Lambon Ralph, Moriarty, & Sage, 2002; Martin, Schwartz, & Kohen, 2006). Thus, it is no surprise that many aphasia treatments target semantics (Boyle & Coelho, 1995; Coelho, McHugh & Boyle, 2000) or phonology (Kendall et al., 2008; Kendall, Oelke, Brookshire & Nadeau, 2015) in order to strengthen connections between semantic and phonologic language networks and consequently improve word retrieval.

In addition to acquired word retrieval impairment, the majority of PWA also present with alexia, an acquired disorder of reading (Brookshire, Wilson, Nadeau, Gonzalez Rothi, & Kendall, 2014a; Cherney, 2004; Riley, Brookshire & Kendall, 2016; Patterson & Marcel, 1977; Webb & Love, 1983). Interestingly, reading impairment is studied less often than spoken language impairment in aphasia (Knollman-Porter, Wallace, Hux, Brown, & Long, 2015). Furthermore, acquired reading impairment has traditionally been modeled in isolation from acquired spoken language impairment.

Acquired reading impairment was originally modeled in the late 1800's from a neuroanatomical perspective by Dejerine (1891) who coined the terms "alexia with agraphia" and "alexia without agraphia". In the 1970's, there was a shift away from neuroanatomical explanations of alexia to psycholinguistic accounts (Cherney, 2004; Marshall & Newcombe, 1973). In particular, the dual route model of reading became the most well-known cognitive neuropsychological explanation of normal and impaired reading, and remains influential today (Coltheart, Curtis, Atkins, & Haller, 1993; Coltheart & Rastle, 1994; Coltheart, Rastle, Perry, Langdon, & Zeigler, 2001).

Unlike spoken language impairment, alexia can exist without damage to central semantic and phonologic networks, according to the dual route model of reading (Henry, Beeson, Alexander, & Rapcsak, 2012). This is because the dual route model views alexia as a reading-specific disorder that results from impairment to one or both of two proposed reading routes. Specifically, the lexical reading route consists of an orthographic input lexicon and a phonologic output lexicon that each store whole-word knowledge and allow phonology to be derived directly from orthography (i.e., written word recognition). The second reading route, the non-lexical route, consists of a grapheme-to-phoneme converter that allows written words to be sounded out based on letter-sound correspondences. Reading impairment is claimed to only result from damage to components in these two reading routes. Given this exclusive view of the reading process, the dual route account of reading does not consider how spoken language impairment and reading impairment may be interrelated (Crisp & Lambon Ralph, 2006; Lambon Ralph & Patterson, 2007). For example, according to dual route theory, poor nonword repetition should not be related to poor grapheme-to-phoneme correspondence (GPC) knowledge (Jefferies, Sage, & Lambon Ralph, 2007). The common co-occurrence of alexia and other language impairments is explained by a brain injury causing simultaneous impairment of functionally unrelated modality-independent modules (i.e., damaged spoken language modules and reading modules) (Henry et al., 2012; Lambon Ralph & Patterson, 2007; Patterson & Lambon Ralph, 1999; Rapcsak et al., 2009).

It appears that over the years, spoken language and written language have been studied and modeled simultaneously, yet in parallel, separate theoretical universes. For instance, spoken language models do not typically consider the relevance or impact of orthographic abilities on spoken language abilities, and likewise, most reading models do not consider the relevance or impact spoken language abilities may have on reading abilities. Some models exist that illustrate both spoken and written language (Beeson, Rising, & Volk, 2003; Rapcsak & Beeson, 2000); however, these models depict spoken and written language as relying on independent components specific to each language modality. The disconnect between spoken and written language models may contribute to spoken and written language disorders being examined in isolation, despite their frequent co-occurrence. This separation is commonly seen in research studies that investigate an individual's aphasia *or* alexia, as well as in clinical treatments that focus on spoken *or* written language abilities.

Relatively recently, a model has emerged that proposes primary visual, semantic, and phonologic systems support both orthographic language processing (i.e., reading and writing) and non-orthographic language processing (i.e., language production and comprehension).The primary systems hypothesis (PSH; Lambon Ralph et al., 2002; Patterson & Lambon Ralph, 1999; Woollams, 2014) is controversial and a theoretical disagreement concerning the extent to which orthographic (i.e., written) and non-orthographic (i.e., spoken) language share underlying cognitive-linguistic mechanisms is ongoing (Coltheart et al., 2001; Harm & Seidenberg, 2004; Henry et al., 2012; Woollams, 2014).

The PSH postulates that there are intimate relationships between acquired spoken and written language disorders within an individual. Moreover, the PSH view of acquired language disorders posits that damage to a primary system will result in impaired processing across language modalities. For example, if there is an underlying impairment in phonologic representation or processing, a phonologically-related deficit will be seen in written language (e.g., difficulty reading nonwords), as well as in spoken language (e.g., difficulty repeating nonwords). Therefore, the PSH may be seen as a parsimonious theoretical explanation for simultaneous written and spoken language impairments in PWA.

The purpose of this study was to test assumptions of the primary systems hypothesis, and in particular to discover to what extent non-orthographic language abilities and reading abilities are related in PWA. In doing so, this study attempted to gather information about reading impairment in aphasia that can be used to inform future assessment and treatment approaches. Before the specific aims and predictions of this study are conveyed, pertinent background information concerning the primary systems hypothesis will be described, including its origin from and relationship with the connectionist, parallel distributed processing (PDP) theory. Then, an explanation of how the PSH/PDP view of reading accounts for acquired reading disorders (i.e., alexias) will be discussed. Finally, relevant PSH experimental research findings will be reviewed to provide sufficient context for the current study.

Primary Systems Hypothesis (PSH)

The PSH views written language from an evolutionary and developmental perspective (Woollams, 2014). This hypothesis opposes the idea of discrete neural regions dedicated solely to reading, and instead proposes reading abilities developed from and rely upon pre-existing primary brain systems (i.e., vision, phonology, and semantics) that humans had been using for spoken communication long before they began to engage in written communication (Woollams & Patterson, 2012). Reading development in children continues to parallel this evolution with written language acquisition occurring after and building off of spoken language abilities (Jefferies et al., 2007). Unlike spoken language, written language has to be explicitly taught, and spoken language abilities directly influence the success of written language acquisition (Wagner & Torgesen, 1987). Hulme and Snowling (2014) report this intimate relationship between spoken and written language is generally accepted in the developmental dyslexia literature, but less so in the acquired alexia literature, which traditionally views reading as relying on reading-specific modules (e.g., grapheme-phoneme rule system, orthographic input lexicon).

PSH challenges the traditional view of alexia (i.e., selective disorder of reading) by proposing reading is part of the larger language system with a reading impairment being indicative of impairment to one or more primary brain systems used for all communication (Lambon Ralph & Patterson, 2007). According to PSH, reading involves a simultaneous interaction between primary visual and language systems with mechanisms involved in reading also being involved in other language functions, such as speech production and comprehension (Crisp & Lambon Ralph, 2006; Woollams 2014).

The PSH assumptions described above are not completely novel, as these ideas reflect principles from the parallel distributed processing (PDP) theory (Harm & Seidenberg, 2004; Plaut, McClelland, Seidenberg, & Patterson, 1996; Seidenberg & McClelland, 1989). In fact, the PSH was motivated by, and is allied with, the PDP theoretical view of language processing. The primary systems hypothesis and PDP theory, therefore, share many similarities and have been jointly referred to as the "triangle model/primary systems hypothesis" (Crisp & Lambon Ralph, 2006). PDP models can be understood as an embodiment or instantiation of the primary systems framework (Henry et al., 2012; Jefferies et al., 2007; Woollams, 2014), and core elements of this theory will be discussed below.

Parallel Distributed Processing (PDP) Theory

The essence of PDP theory is the belief that word knowledge exists as a learned pattern of neural activity that involves simultaneous input from orthographic, phonologic, and semantic units that are distributed throughout the brain (Patterson & Lambon Ralph, 1999; Plaut, 1999 Plaut et al., 2006; Seidenberg, 2012) (see Figure 1). In other words, word processing involves synchronized activation of multiple linguistic information units, as opposed to sequential access to word-specific information units. Therefore, there are no proposed lexicons or grapheme-phoneme rule systems, as is commonly hypothesized in traditional views of language processing.

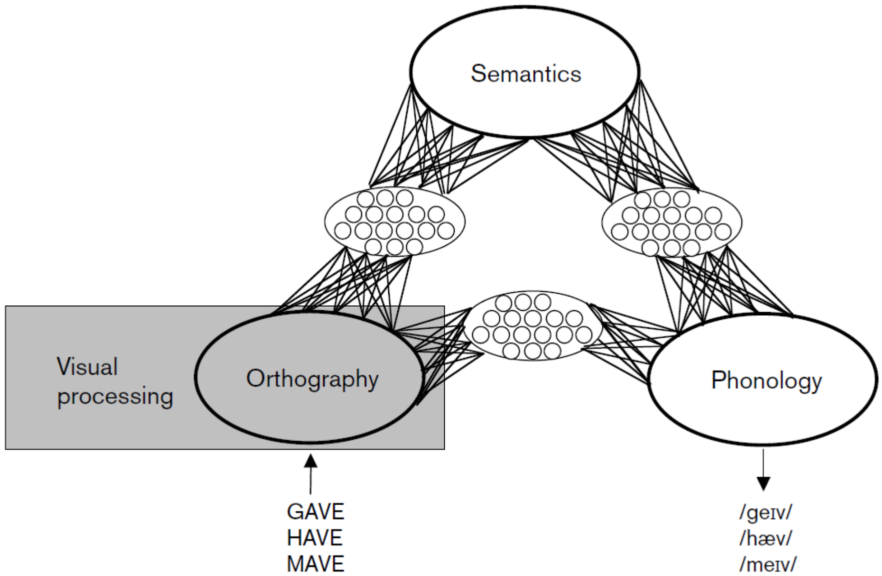


Figure 1. Primary Systems/PDP Model of Reading from Patterson and Lambon Ralph (1999)

The actions of a PDP computational model are theorized to be an approximation of neural computation. Figure 1 exemplifies a PDP network of distributed neuron-like processing units. The orthographic, phonologic, and semantic units are pooled together into respective groups. The unlabeled groups of units represent hidden units. These hidden units are essential because they capture relationships between the other units (e.g., between orthography and phonology) and allow the system to encode complex relationships. Despite there being only a finite number of units in the model (and presumably in the brain), these processing units interact to create thousands of activation patterns, similar to how only 26 alphabetic letters can be combined to create many words.

Each unit's activity is synonymous to a neuron's firing rate, and the connections between the units are synonymous to synapses. To produce activation, each processing unit integrates information from other units. This means that words are activated based on the knowledge (or connection weights) of other words. For example, learning to read "save" and "gate" also helps determine the connections for reading “gave” since these words involve similar, overlapping activation patterns. In the case of a nonword such as “shoop”, the computational language system relies on input from connections used to process related real words (e.g., “ship”, “shoot”, “loop”). These connections between language units are modifiable, and after each exposure to a word, the connection weights are adjusted through a learning algorithm, with greater connection changes being made to incorrect weight settings.

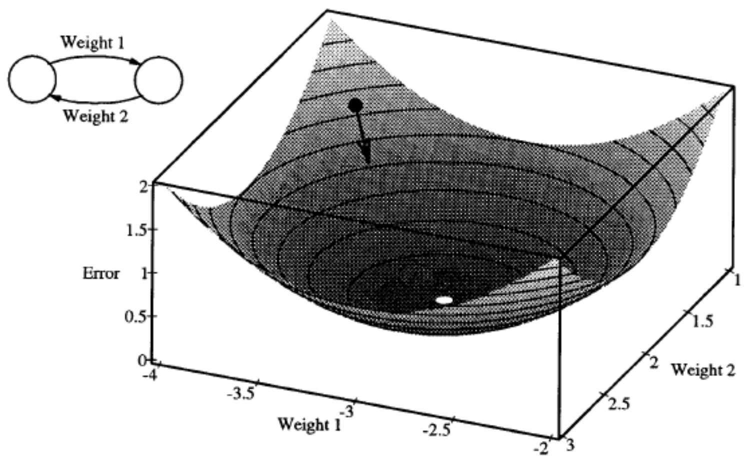


Figure 2. Illustration of PDP learning and weight adjustments from Plaut (1996)

Figure 2 above illustrates how the computational language units interact and learn to adjust connection weights within a PDP model. This figure shows a space with dimensions for each unit’s connection weights and a point in the middle of this space where the correct connection weights reside (the white dot). When the pattern of activity of two weights stops changing, the units then reach their final attractor pattern. The connection weights (Weight 1 = -3.5; Weight 2 = 1.5) for the black dot in Figure 2 would produce an error because their final attractor is far from the correct weights. With experience and repeated exposure, a learning algorithm slowly adjusts the weights (represented by the black arrow) to arrive at connection weights that result in the least error and ideally the correct output (Weight 1 = -3; Weight 2 = 2). This type of learning results in familiar patterns eventually forming stable attractors. The area around the attractor contains similar patterns and is called the basin of attraction. This attractor basin explains why similar words have similar patterns of activity in a PDP model (Plaut, 1996).

For a real world example, in a child's brain the connection weights between letter "b" and sound /b/ would slowly be strengthened and the connection between letter "b" and sound /m/ would be weakened over time through experience. Therefore, according to PDP theory, the reading process essentially involves learning the appropriate set of neural connection weights between orthographic, phonologic, and semantic units. Forming these connections, however, initially takes time since every orthographic, phonologic, and semantic unit could potentially be involved in the activation pattern of a new word due to the interconnectedness of the system (Seidenberg, 2005).

To help encode connections between the language units, fortunately PDP models (and presumably the brain) pick up on statistical aspects of language. This is especially useful in the English language where the relationship between orthography and phonology is quasi-regular (i.e., not all words have a 1:1 grapheme-phoneme relationship). Specifically, the language system is able to take into account the frequency and consistency of words. This is known as the frequency x consistency effect and is illustrated below in Figure 3. This figure shows that if a word is high in frequency, the system can quickly calculate the weights (due to repeated exposure), even if the word is not all that consistent with others. On the other hand, if a word is consistent with other spelling-sound relationships (e.g., shares sub-word patterns with other words; "sheep-jeep") then the system can rely on those familiar patterns and compute the weights quickly even if it has had little exposure to the word (low frequency). The easiest connections, of course, are made for those words that are both high in frequency and consistency.

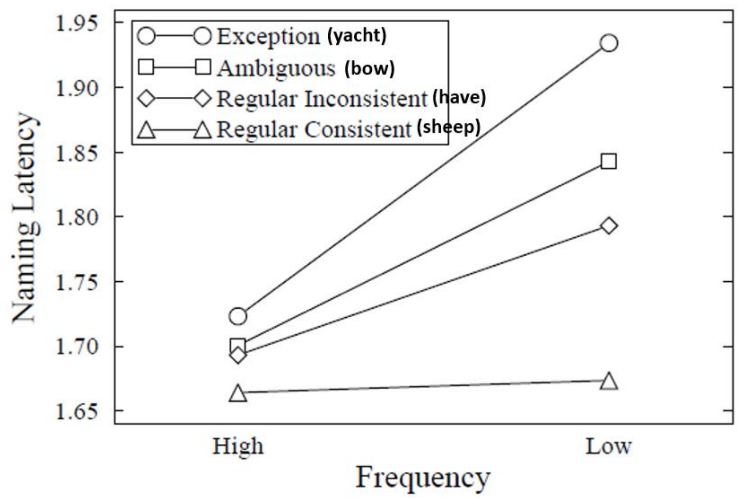


Figure 3. Frequency x consistency effect (Plaut, 1999)

As mentioned previously, word processing involves simultaneous input from connections between semantic, phonologic, and orthographic units to produce the correct activation pattern needed to arrive at the final attractor. PDP theory proposes, however, the language system will initially rely most heavily on connections between orthography and phonology to process words since the relationship between letters and sounds is more direct, and easier to learn, than the relationship between letters and meaning. Over time as the semantic system is developed and refined, connections between orthography and semantics start to play a larger role in reading, especially for low-frequency irregular words that are particularly slow and difficult for the phonologic pathway (orthographic- phonologic connections) to process (Lambon Ralph & Patterson, 2007).

The theoretical assumptions discussed above describe normal reading processes. However, the PSH/PDP view of reading accounts for impaired reading processes (i.e., alexia) as well. These perspectives will be explained below. First, however, alexia subtypes will be defined.

Alexia: Definitions and PSH/PDP Perspectives

In addition to aphasia, alexia is known to co-occur with other acquired neurogenic communication disorders such as semantic dementia (Patterson & Hodges, 1992; Woollams, Hoffman, Roberts, Lambon Ralph, & Patterson, 2014; Woollams, Lambon Ralph, Plaut, & Patterson, 2007), primary progressive aphasia (Farah, Stowe, & Levinson, 1996; Henry et al., 2012; Woollams & Patterson, 2012), and traumatic brain injury (Coltheart & Byng, 1989; Marshall & Newcombe, 1973; Moss, Gonzalez Rothi, & Fennell, 1991). The PSH/PDP explanation of alexia applies to all of these disorders; however, this study was focused solely on alexia in chronic aphasia.

Aphasia is more often associated with central alexias (i.e., surface, phonological, and deep alexias) that involve difficulty deriving sound and/or meaning from print, as opposed to peripheral alexias (i.e., pure, neglect, and attentional alexias) that involve difficulty with the visual processing of letters (Cherney, 2004; Riley et al., 2016). The behavioral reading profiles of the central alexia subtypes will be briefly described. Then, these alexia subtypes will be interpreted from a PSH/PDP perspective.

Central alexias are historically diagnosed based on observations of dissociations in oral reading of regular, irregular, and nonwords (Coltheart & Rastle, 1994; Seidenberg, 2012). In particular, surface alexia is characterized by a regularity effect which entails difficulty reading irregularly spelled words (e.g., “comb”), especially those low in frequency, with relatively preserved reading of regularly spelled words (e.g., “sheep”) and nonwords (e.g., “peef”) (Lambon Ralph & Patterson, 2007). Individuals with surface alexia often produce regularization errors when reading irregular words (e.g., pronouncing “pint” to rhyme with “mint”). In addition, a word is often comprehended based on the individual’s pronunciation (Coltheart, 1981; Humphreys & Evett, 1985). For example, the word “none” might be pronounced and comprehended as “known”, or a homophone (e.g., “bury”) may be pronounced correctly, but its meaning interpreted incorrectly (e.g., “berry”).

Conversely, the hallmark feature of phonological alexia is impaired nonword reading with relatively intact reading of real words (i.e., lexicality effect). Nonwords are often lexicalized or read aloud as real words (e.g., “fesh” read as “fish”), and unknown real words may be pronounced as a similar looking word (e.g., “signal” read as “single”). Other common error types include omissions and nonword errors (Crisp & Lambon Ralph, 2006). In addition, these individuals often have difficulty reading function words (e.g., “of”) (Coltheart, 1981; Humphreys & Evett, 1985) and low frequency words (Cherney, 2004).

Deep alexia resembles phonological alexia; however, in addition to the reading difficulties mentioned above, semantic paralexias are present (e.g., “shoe” read as “boot”). This error type is considered the hallmark of deep alexia, is often used to differentiate phonological alexia from deep alexia (Friedman, 1996). Traditionally, individuals with deep alexia are also known to demonstrate other reading symptoms, such as morphological errors (e.g., “washing” read as “wash”), better reading of concrete words than abstract words (e.g., “dog” vs. “hope”), and a part of speech effect (nouns > adjectives > verbs > function words) (Coltheart, 1981; Lambon Ralph & Patterson, 2007). However, many of these reading errors have also been reported in phonological alexia. Due to the observation of overlapping symptoms between phonological and deep alexia, and the observation that deep alexia often evolves into phonological alexia, it is now generally accepted that a phonological-deep alexia continuum exists with deep alexia representing the severe endpoint on the reading continuum (Crisp & Lambon Ralph, 2006; Crisp, Howard, & Lambon Ralph, 2011; Friedman, 1996; Glosser & Friedman, 1990).

The PSH framework provides a unique perspective on the suspected causes of these different alexia subtypes. Instead of promoting impairment to reading specific modules (e.g., impaired GPC rule system or impaired orthographic input lexicon) as is proposed by traditional models of reading (Coltheart et al., 2001), the PSH posits that alexias arise from impairment to one or more primary brain systems (i.e., vision, semantics, and/or phonology). In particular, surface alexia is proposed to be the result of general semantic impairment. More specifically, Plaut et al. (1996) explain surface alexia as a division of labor problem between the semantic and phonological pathways in the PDP model.

As previously described, PDP theory proposes that normal reading requires collective input from both semantic (orthography to semantics) and phonological (orthography to phonology) pathways in the connectionist language network. Over time, a division of labor between these pathways occurs making the reading process more efficient. For example, the semantic pathway tends to provide greater input when reading words low in frequency and/or letter-to-sound consistency; whereas the phonological pathway tends to provide greater input when processing words high in frequency and/or consistency. With that said, individuals with surface alexia are thought to have a damaged semantic pathway that leaves the intact phonological pathway working mostly alone. Although once capable of reading all word types, the phonological pathway learned to rely on input from semantics, especially for irregular words, and is unable to correctly function without support from semantics.

Phonological alexia is proposed to reflect a general, primary phonological impairment. Specifically, the phonological impairment hypothesis (Harm & Seidenberg, 2001) suggests phonological alexia stems from impaired representation and use of phonology. PDP theorists propose phonological impairment results in more impaired nonword reading than word reading because nonwords have "less stable" phonological representations. These unstable and unfamiliar patterns receive much less, if any, semantic activation, making processing more phonologically demanding. Therefore, a phonological impairment makes the letter-sound translation of a nonword (e.g., "phocks") extremely difficult, or even impossible depending on the degree of phonologic impairment.

Finally, deep alexia is explained as resulting from severe primary phonologic impairment that makes the phonological pathway extremely error prone. Therefore, reading in deep alexia is proposed to be more reliant on semantic knowledge. However, in addition to phonologic impairment, some degree of semantic impairment is also hypothesized to exist. This claim is supported by computational work showing damage to a semantic pathway in a PDP computational model (Plaut & Shallice, 1993) resulted in semantic and visual reading errors, similar to those produced by individuals with deep alexia.

The proposed underlying causes of alexia described above were graphically summarized by Crisp and Lambon Ralph (2006) (Figure 4). Their figure illustrates the PSH view of alexia with severity and type of alexia reflecting the status of primary language systems. Normal reading is represented by intact semantic and phonological processing abilities. Surface alexia is proposed to entail a high degree of semantic impairment and no (or very little) phonological impairment, while phonological alexia entails a high degree of phonological impairment with no (or very little) semantic impairment. Deep alexia is hypothesized to include some semantic impairment, in addition to severe phonologic impairment. Finally, global alexia includes severe semantic and phonological impairment abolishing, or nearly abolishing, reading ability. Recent research endeavors, which will be discussed below, investigating these proposed relationships between reading impairments and semantic and phonologic impairments, have started to emerge and provide empirical support for the PSH/PDP theoretical assumptions.

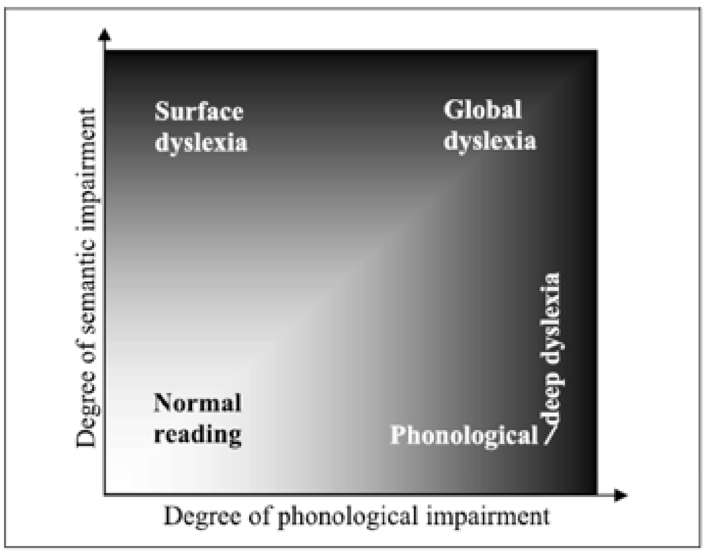


Figure 4. Depiction of central alexias in a phonological-semantic space (Crisp & Lambon Ralph, 2006)

<u>Review of Relevant PSH Research</u>

Empirical support for the PSH stems from multiple studies showing significant associations between reading impairments and non-orthographic language impairments in various populations, including individuals with chronic aphasia (Crisp & Lambon Ralph et al., 2006; Patterson & Marcel, 1992; Rapcsak et al., 2009); primary progressive aphasia (Henry et al., 2012; Woollams & Patterson, 2012), and semantic dementia (Woollams et al., 2007). Furthermore, the respective primary systems impairments proposed by the PSH have been found across alexia types. These findings pertaining to pure alexia, surface alexia, and phonological-deep alexia will be briefly reviewed to showcase the current literature that supports the notion that reading disorders are a reflection of primary language processing impairment, instead of isolated impairment to a reading-selective process.

Pure alexia, a peripheral alexia, is traditionally associated with slow processing and impaired visual perception of letter symbols resulting in hallmark letter-by-letter oral reading (Starrfelt & Shallice, 2014). However, many researchers have shown that if tested on non-orthographic visual stimuli, individuals with pure alexia demonstrate effortful processing beyond letters. Performance is slow and less accurate for identification of numbers (Miozzo & Caramazza, 1998), music notation (Horikoshi et al., 1997), letter-like symbols (Mycroft, Behrmann, & Kay, 2009) visually complex stimuli, such as checker board patterns, (Roberts et al., 2012) and even faces (Behrmann & Plaut, 2012). These findings support the PSH view that pure alexia stems from impairment to the primary vision system and is not a reading-specific deficit, but instead reflects impaired ability to rapidly discriminate complex visual items.

Similar to pure alexia, symptoms of surface alexia have also been found to extend beyond oral reading tasks. In particular, individuals with surface alexia not only have trouble reading aloud low-frequency irregular words, they also have trouble with written lexical decision tasks (e.g., preferring "goast" to "ghost") and producing the past tense form of verbs (e.g., saying "grinded" instead of "ground"), especially for items that are low-frequency and less consistent (Patterson, Lambon Ralph, Hodges, & McClelland, 2001; Rogers, Lambon Ralph, Hodges, & Patterson, 2004). Moreover, this frequency by consistency effect has also been observed with object recognition. Individuals with surface alexia had trouble identifying line drawings of animals if the drawings included atypical/less frequent features, such as animals with humps, stripes, or antlers (Rogers, Hodges, Patterson, & Lambon Ralph, 2003). Additionally, individuals with surface alexia have been observed to omit unusual/inconsistent features (e.g., no stripes) or over apply consistent features (e.g., duck with four legs) when attempting to draw animals (Bozeat et al., 2003). These described difficulties reflect impaired semantic knowledge. Interestingly, many individuals with semantic dementia have co-occurring, or eventually acquire, surface alexia (Lambon Ralph & Patterson, 2007; Woollams et al., 2007; Woollams et al., 2014). These findings support the PSH view that surface alexia is not a reading-specific impairment, but instead reflects impairment to central semantics that makes processing of any low-frequency, irregular/inconsistent stimuli challenging.

Finally, phonological-deep alexia symptoms have also been observed in non-reading tasks. Individuals with phonological-deep alexia typically demonstrate traditional alexia symptoms, such as the lexicality effect and imageability effect, in spoken language tasks (i.e., repetition and naming) suggesting these effects hold across language modalities and are not specific to reading (Crisp & Lambon Ralph, 2006; Patterson & Marcel, 1992; Rapcsak et al., 2009). Furthermore, individuals with phonological-deep alexia are known to have impaired phonological processing (i.e., difficulty with rhyming, repetition, and parsing/blending of phonemes, etc.), and moreover, their non-orthographic phonological abilities have been shown to significantly predict oral reading abilities (Crisp & Lambon Ralph, 2006; Jefferies et al., 2007; Rapcsak et al., 2009). These findings support the PSH view that phonological-deep alexia stems from impairment to the primary phonology system.

Most of these phonological-deep alexia studies only compared phonological and reading abilities, and few researchers have looked at the influence of semantics on reading in phonological-deep alexia. Rapcsak et al. (2009, pg. 581) stated "it remains to be determined, however, whether the proposed continuum is best characterized by the severity of the phonological deficit, the degree of semantic impairment, or a combination of both factors". Two studies that have assessed semantic and phonologic performance in alexia found both of these primary language systems underpinned written language performance (Crisp & Lambon Ralph, 2006; Henry et al., 2012). Specifically, in individuals with primary progressive aphasia, non-orthographic semantic and phonologic measures accounted for a significant amount of the variance in oral reading and spelling of single words. Henry et al. (2012) found that performance on semantic measures (i.e., picture category association, synonym judgment, spoken word to picture matching, picture naming) related more strongly with irregular word reading and spelling and performance on phonologic measures (i.e., rhyme judgment, minimal pair discrimination, phoneme manipulation) related more strongly with nonword reading and spelling.

The findings summarized above clearly advocate for the PSH view of peripheral alexias (i.e., pure alexia) resulting from impairment to the primary vision system and central alexias (i.e., surface, phonological, deep) reflecting impairment to primary language systems (semantics and phonology). This research appears promising, yet relatively limited, and therefore additional work is warranted to further test the PSH. For example, PSH research could be extended and advanced by diversifying the participants, reading measures, and language measures utilized.

In regard to participants, the PSH needs to be studied in a larger, more diverse group of individuals to determine if the predictions still hold true. Previous studies included small sample sizes, which can restrict range of performance. Additionally, a sample representative of the general aphasia population has yet to be examined. Instead, participants were recruited based on particular type of alexia (Crisp & Lambon Ralph, 2006; Crisp et al., 2011; Jefferies et al., 2007; Patterson & Marcel, 1992), particular type of aphasia (Henry et al., 2012), or particular lesion site (Rapcsak et al., 2009).

In previous PSH work, reading ability was typically measured as single word oral reading accuracy. This is logical given alexia subtypes are determined by oral reading performance, and furthermore, PDP theory is focused primarily on single word processing. However, many PWA demonstrate impaired reading comprehension and request to work on this skill in hopes of improving functional reading abilities (Webster et al., 2013). Currently, the influence of non-orthographic language abilities on silent reading comprehension performance in PWA remains unknown, and this information may be valuable to inform reading assessments and treatments.

In regards to the language measures previously used, only semantic and phonologic abilities have been assessed in past PSH-motivated studies. This is likely for two reasons. First, PSH/PDP models specifically identify semantics and phonology as primary language systems. Second, as mentioned above, reading was only measured at the single-word level and therefore only semantic and phonologic influence was of interest. Future work is needed examining non-orthographic language and its relation to reading beyond the single-word level.

When reading beyond the single-word level, other language abilities, such as syntax, are likely to influence reading success, and therefore need to be included in non-orthographic language assessments. Despite syntax not being shown in the PSH/PDP model, it is probable that this theoretical framework would endorse an association between non-orthographic syntactic abilities and text-level reading abilities since written language skills are hypothesized to hinge on spoken language skills. In fact, Seidenberg (1997), one of the pioneers of PDP-connectionist theory, explained that the complexities involved in mastering a language's grammar are the perfect computational problems for a connectionist model that is fueled by probabilistic learning. In other words, syntactic knowledge is proposed to be acquired in the same fashion as other language activities. That is via repeated experiences with the language that result in the establishment of learned statistical patterns. This learning phenomenon has been demonstrated in a connectionist computational model that was successfully trained to make grammaticality judgments, and furthermore, was able to compute semantic representations (i.e., comprehension) from a sequence of words (i.e., sentence) and vice versa (Allen & Seidenberg, 1999). Thus, it appears syntax can be modeled in a parallel distributed fashion, yet it remains to be determined what role non-orthographic syntactic knowledge plays in orthographic processing in aphasia.

Due to the previously applied participant and outcome measurement criteria mentioned above, we remain uncertain about the relationship between non-orthographic language abilities and reading performance (reading aloud and silent reading comprehension) in the heterogeneous chronic aphasia population. Therefore, the ultimate purpose of the current study was to thoroughly investigate reading performance in PWA from a primary systems perspective so that acquired reading impairment in aphasia may be better understood and new directions for treatment might be revealed. Specifically, the current work explored the extent to which non-orthographic semantic, phonologic, and syntactic language abilities are associated with oral reading and silent reading comprehension in PWA. Subsequently, the specific aims, research questions, and predictions are reported.

Specific Aims, Research Questions, and Predictions

Aim 1 (replicate and extend prior PSH work): The goal of Aim 1 was to replicate and extend previous PSH-motivated work conducted with individuals with aphasia (Crisp & Lambon

Ralph, 2006; Henry et al., 2012; Jefferies et al., 2007; Rapcsak et al., 2009). Specifically, the relationship between non-orthographic semantic and phonologic abilities and single word oral reading abilities was examined in order to assess if shared linguistic representations are utilized for both spoken and written language tasks. The addition of new stimuli (i.e., pseudohomophones) and a larger, broader sample (i.e., diverse group of PWA) extended the previous studies. To address Aim 1, the following research question was proposed:

> ***RQ1:*** To what extent does performance on non-orthographic semantic and phonologic measures predict single word oral reading performance on regular words, irregular words, pseudohomophones, and nonwords in PWA?

Predictions: In accordance with the primary systems/PDP framework and findings from previous work (Crisp & Lambon Ralph, 2006; Jefferies et al., 2007; Henry et al., 2012; Rapcsak et al., 2009), it is hypothesized that non-orthographic semantic and phonologic measures will significantly predict overall oral reading performance in PWA. Specifically, phonologic measures will be most highly correlated with and significantly predictive of nonword reading, and semantic measures will be most highly correlated with and significantly predictive of irregular word reading. Both phonologic and semantic measures are expected to positively correlate with and significantly predict oral reading of regular words. Oral reading accuracy of pseudohomophones (e.g., "hevin") was not directly compared with non-orthographic language abilities in previous PSH-motivated studies; however, it is anticipated that phonologic and semantic measures will both positively relate to this task given the phonology of these orthographically unfamiliar words corresponds with familiar semantic knowledge. If these predictions are confirmed, the PSH view of central semantic and phonologic systems supporting spoken and written language processing will be supported. However, if these predictions are not confirmed, the traditional notion of distinct spoken and written processing mechanisms will be upheld.

Aim 2 (discover how PSH relates to silent reading comprehension): The goal of Aim 2 was to further extend previous PSH work that investigated oral reading at the single word level by investigating silent reading comprehension at multiple linguistic levels (i.e., single word, phrase/sentence and paragraph levels). In particular, the relationship between silent reading comprehension abilities and non-reading language abilities (i.e., non-orthographic semantics, phonology, and syntax) was investigated. To address Aim 2, the following research question was proposed:

> ***RQ2:*** To what extent does performance on non-orthographic semantic, phonologic, and syntactic measures predict silent reading comprehension performance at the single word, phrase/sentence, and paragraph levels in PWA?

Predictions: There is currently little evidence in the aphasia literature upon which to base these predictions. Developmental reading literature exists, however, that makes the case that oral language impairment is at the core of reading comprehension impairment (Hulme & Snowling, 2014). For example, Perfetti, Landi, and Oakhill (2007) report phonological awareness and semantic knowledge are essential for written word identification and comprehension in young readers. Additionally, syntactic skills are known to play a role in reading success since children with poor reading comprehension abilities typically demonstrate syntactic impairment (Nation, 2007). The developmental literature highlights that higher-level reading comprehension abilities (e.g., inference making and comprehension monitoring) cannot be achieved without adequate basic level linguistic processing. Nation (2007, p. 249) explains, “There can be no reading comprehension without the ability to decipher or recognize words”.

Subscribing to the notion that reading rehabilitation is fundamentally similar to reading acquisition, it is expected that non-orthographic semantic, phonologic, and syntactic measures will all positively correlate with and significantly predict overall reading comprehension performance in PWA. It is anticipated that phonology and semantics will relate more strongly with reading comprehension performance at the single word level, and syntax will relate more strongly with reading comprehension at the sentence level. Weaker, yet still positive, correlations are expected at the paragraph level given written paragraph comprehension is a more complex, multi-factorial task (Compton, Miller, Elleman, & Stacy, 2014). It is hypothesized that semantics will account for more of the variance than phonology given that reading comprehension can occur without full access to each phoneme in a word (Crisp et al., 2011). However, it is still expected that phonology will play a unique role in reading comprehension given the importance of orthographic-phonologic correspondence knowledge in reading. If these predictions are confirmed, the PSH notion of connected spoken and written language systems will be supported. However, if the predictions are not supported, this work will imply reading comprehension and non-orthographic language abilities may be unrelated and rely on distinct mechanisms.

Aim 3 (explore the relationship between alexia subtypes and primary systems impairment): The goal of Aim 3 was to determine if central alexia subtypes (e.g., surface alexia, phonological alexia, deep alexia) can be described by degree of non-orthographic phonologic and semantic impairments, as predicted by the primary systems hypothesis. To address Aim 3, the following research question was proposed:

> ***RQ 3:*** What is the relationship between degree of non-orthographic semantic and phonologic impairment and alexia type in PWA?

Predictions: In accordance with the PSH predictions, it is anticipated that degree of semantic and phonologic impairment will be directly linked to alexia type. Specifically, it is hypothesized that impaired semantics and relatively intact phonology will correspond to surface alexia, and conversely impaired phonology and relatively intact semantics will be related to phonological alexia. Deep alexia is expected to be associated with severely impaired phonology and mildly impaired semantics, and global alexia is predicted to be associated with severely impaired semantics and phonology.

Similar to findings from Crisp and Lambon Ralph (2006) and Jefferies et al. (2007), significant correlations between alexia symptoms and semantic and phonologic measures are anticipated. Specifically, semantic abilities are expected to correlate positively with lexicality and frequency effects and negatively with the regularity effect. Additionally, semantic performance is anticipated to show negative correlations with semantic, omission, and unrelated reading errors and positive correlations with visual-phonologic and lexicalized reading errors. Phonologic abilities are predicted to be negatively correlated with the lexicality effect. It is also anticipated that as phonologic performance improves, the frequency of reading errors will decline, evidenced by significant, negative correlations.

It is important to note that most, but not all, PWA are expected to show signs of alexia. It is hypothesized that PWA who do not demonstrate alexia (i.e., perform within normal reading limits) will have a mild aphasia evidenced by some of the highest phonologic and semantic scores. Surface alexia is relatively uncommon in aphasia (Luzzatti, Toraldo, Zonca, Cattani, & Saletta, 2006) and is more often associated with semantic dementia (Woollams et al., 2007); therefore, few, if any, cases of surface alexia are predicted. Since many others (Brookshire et al., 2014a, Crisp & Lambon Ralph, 2006; Lambon Ralph et al., 2002; Rapcsak et al., 2009;

Woollams, 2014) have found phonological-deep alexia to be common in PWA, it is anticipated that the majority of PWA in this study will present somewhere on the phonological-deep alexia continuum. Finally, it is hypothesized individuals with the most severe aphasia, evidenced by substantial phonologic and semantic impairments, will present with global alexia. If these predictions are confirmed, then alexia in chronic aphasia may be described based on degree of underlying central language impairment (semantics and/or phonology) instead of being described solely by traditional reading symptoms. If these predictions are not confirmed then alexia in aphasia cannot be adequately explained from a primary systems perspective, and the notion of alexia being a reading-specific disorder will be upheld.

Chapter 2: Method

Participants

To achieve adequate statistical power, the target sample size for this study was 45 participants. This number was derived from a 15:1 rule of thumb for regression analyses, which states that 15 participants are recommended for each predictor (L. Sanders, personal communication, April 16, 2012). Given three regression predictors were planned (see "Statistical Analysis"), 47 persons with aphasia (PWA) were recruited and participated in the study in an attempt to have viable data from 45 participants. Participants were recruited through the University of Washington (UW) and Northwest Aphasia Registry and Repository Databases (IRB #37400 and 47727). Each participant signed a consent form approved by the UW Institutional Review Board (IRB #49756). Inclusion/exclusion criteria used to determine participant eligibility are described below.

Inclusion Criteria

To be included in the study, participants were required to present with aphasia and be at least six months post onset of a left-hemisphere stroke. More than one stroke was permissible, as long as injury was confined to the left hemisphere. Presence of aphasia was determined by performance on the Comprehensive Aphasia Test (CAT; Swinburn, Porter, & Howard, 2004). Specifically, participants needed to score at or below 56 on CAT Comprehension of Spoken Language, at or below 69 on CAT Naming, or below 33 on CAT Picture Description. These CAT cut-off scores represent performance two standard deviations below the normal control mean performance. In addition to the presence of chronic stroke-induced aphasia, participants must have obtained at least a high school education and speak English as their primary language.

Finally, given that right-hand dominance is associated with primarily left-hemisphere localized language abilities, it was preferred participants be right-hand dominant.

Exclusion Criteria

Individuals were excluded if they reported a history of developmental dyslexia or neurological diagnosis other than left-hemisphere stroke (e.g., Parkinson's disease, traumatic brain injury, right-hemisphere stroke, dementia, etc.). Individuals were also excluded if they demonstrated non-verbal cognitive impairment (i.e., performing below 23/36 on Raven's Coloured Progressive Matrices (Raven & Raven, 1998), visual impairment (i.e., failing CAT line bisection or visual acuity worse than 20/40 on the Tumbling E eye chart (Chang, 1995), or hearing impairment (i.e., failure to pass audiometric pure-tone, air conduction screening at 25 dB at 500, 1,000, and 2,000 Hz for at least one ear).

In addition to 500, 1,000, and 2,000 Hz, hearing was tested at 25 dB at 4,000 Hz since this frequency represents the high end of speech sound frequencies. However, inability to detect this sound level did not exclude participants from this study, for two reasons. First, given the hearing screening was not conducted in a sound-proof booth it is possible that environmental noise (e.g., clock ticking, fan, etc.) could preclude some individuals from detecting this sound. Second, due to the common occurrence of age-related high frequency hearing loss (Roth, Hanebuth, & Probst, 2011) it would have proved most difficult to find a large number of individuals with aphasia who all had intact high-frequency hearing at 25 dB.

Finally, individuals with severe motor speech impairment (i.e., apraxia of speech or dysarthria) were excluded. This exclusion criteria was motivated by Rapcsak et al. (2009) who eventually excluded individuals with "severe speech production impairments" because these individuals "produced few recognizable responses" preventing the researchers from accurately interpreting oral reading responses. To determine if severe motor speech impairment was present, two videos of spoken production tasks (i.e., picture description and word repetition) for each participant were viewed by five speech-language pathologists (SLPs) in the UW aphasia research lab. Spoken production was evaluated for atypical behaviors associated with apraxia of speech (i.e., abnormalities in motor speech planning and programming, such as slow rate, prolonged segment durations, intrusive schwa, distorted substitutions, abnormal stress) and dysarthria (i.e., abnormalities with resonance, phonation, articulation and/or prosody, such hyper/hypo-nasality, impaired vocal quality, muscle weakness, imprecise articulation, reduced breath support) (Duffy, 2005).

Participant Characteristics

Forty-three of the 47 enrolled participants met the study inclusion/exclusion criteria and were included in the final analyses. Two participants were excluded due to lesion location. Specifically, P32 had a history of right-hemisphere stroke and P40 experienced bilateral strokes. Two additional participants (P28 and P31) were excluded due to severe motor speech impairment. The five SLPs agreed their motor speech abilities were too severely impaired to allow for fair/accurate assessment of oral reading abilities.

Aphasia profiles were variable among the 43 eligible PWA (See CAT scores in Table 2). Two participants (P16 and P33) actually scored slightly above all three CAT cut-off scores. However, the developers of the CAT acknowledge that individuals with mild aphasia are likely to score within normal limits on some subtests (Howard, Swinburn, & Porter, 2010). Therefore, these two individuals were still included in the study due to demonstration of marked language production and comprehension difficulties during conversational speech and throughout the experimental tasks. Moreover, presence of aphasia in these two individuals was confirmed by consensus clinical judgment of speech-language pathologists who took into account language performance observed during interactions with the participants in the aphasia laboratory.

The majority (86%) of participants acquired aphasia due to a single left-hemisphere stroke. Six individuals had more than one left-hemisphere stroke. Specifically P17's, P22's, and P43's stroke events consisted of two strokes occurring only a few days apart. P41 initially experienced a small left-hemisphere stroke with minimal change to language function that was followed by an additional left-hemisphere stroke six months later that resulted in exaggerated language deficits. Similarly, P15 had two left-hemisphere strokes that were several years apart; however, he reports he did not demonstrate language difficulties until his second, more recent stroke. Finally, P44 experienced a large left-hemisphere stroke and other smaller stroke-like events (e.g., transient ischemic attacks) that occurred over several months.

All participants, except P14 and P42, were monolingual speakers of English. Both P14 and P42 acquired English as young children and their significant others confirmed that English was spoken fluently and as their primary language prior to their strokes. Most participants were right-handed; however, 4 participants (P5, P9, P29, and P44) reported dominant use of their left hand prior to stroke. Since these individuals all met the neurological (i.e., left-hemisphere stroke) and behavioral (i.e., impaired language performance on the CAT) study requirements, they were deemed eligible for the study.

All participants demonstrated adequate vision and hearing to participate in the study. Seventeen participants were unable to detect a low-volume (25 dB), high frequency sound (4,000 Hz) in at least one ear. It should be noted that all participants were able to detect 4,000 Hz when the dB level was increased. During experimental testing, individualized accommodations were made in an effort to ensure that each participant was able to comfortably hear all auditory stimuli (See “Testing Administration” for details).

In sum, the sample consisted of 25 males and 18 females (n=43) with chronic, left-hemisphere stroke-induced aphasia. The participants’ average age was 62. 12 years (*SD* = 11.39; range = 31-92), average time since post-stroke onset was 69.16 months (*SD* = 45.42; range = 8-216), and average education was 15.72 years (*SD* = 2.62; range = 12-22). Individual demographic information is presented in Table 1.

Table 1. Participant demographic information

ID	***Age***	***MPO***	***Education***	***Sex***	***Handedness***
P1	55	57	14	F	R
P2	77	47	13	F	R
P3	31	71	14	M	R
P4	62	82	16	M	R
P5	71	112	14	M	L
P6	71	216	14	F	R
P7	64	135	16	F	R
P8	70	60	18	M	R
P9	58	131	18	M	L
P10	67	65	16	M	R
P11	55	79	16	M	R
P12	45	16	16	F	R
P13	61	76	14	F	R
P14	51	74	12	F	R
P15	68	102	22	M	R
P16	71	59	20	F	R
P17	47	28	17	F	R
P18	72	156	16	M	R
P19	64	59	17	F	R
P20	73	38	18	F	R
P21	59	118	21	F	R
P22	71	91	12	F	R
P23	92	18	18	F	R
P24	65	48	17	F	R
P25	77	132	18	M	R
P26	66	109	16	M	R
P27	58	28	12	M	R
P29	47	91	13	M	L
P30	42	139	18	M	R
P33	68	46	12	M	R
P34	63	50	13	M	R
P35	56	22	15	M	R
P36	66	11	16	M	R
P37	62	8	16	M	R
P38	73	11	14	F	R
P39	69	46	12	M	R
P41	57	51	12	M	R
P42	71	32	20	M	R
P43	38	47	12	F	R
P44	58	96	18	F	L
P45	55	26	16	M	R
P46	66	22	18	M	R
P47	59	69	16	M	R
				25 M, 18 F	39 R, 4 L
AVG	62.12	69.16	15.72		
SD	11.39	45.42	2.62		
Range	31-92	8-216	12-22		

MPO = months post-stroke onset; R = right-handed; L = left-handed

Procedure

Testing Administration

Participants were seen in the UW Aphasia Research Lab or at their home to complete the experiment. The length of testing ranged between 4 and 9 hours. Each participant was seen for 2 or 3 sessions, with each session lasting between 2 and 3 hours. Breaks were offered frequently and taken as needed to help prevent fatigue. Each participant was tested in a quiet room, and seated at a table to complete pen and paper and computer-based tasks (described below). For tests that involved an auditory stimulus, accommodations were made to ensure the stimulus was audible. For example, practice trials for all auditory tasks were provided and each participant was able to instruct the examiner to adjust the volume until the stimulus was easily detectable, and in addition, repetition of auditory stimuli was allowed. Furthermore, visual cues from the examiner's mouth were available for most of the auditory tasks.

For the oral reading tasks, participants wore a head mounted microphone, and responses were roughly transcribed and scored online, as well as audio-video recorded for offline scoring and error and reliability analyses. For all other tasks, responses were non-verbal in nature and were recorded online. The study consisted of two testing phases: 1) descriptive testing (See Table 2) and 2) experimental testing (See Tables 3 and 4, respectively).

Descriptive Testing

During the first testing session participants completed a number of tasks to determine their eligibility for the study, as well as to describe their speech, language, and cognitive abilities. After discussing and signing the consent and HIPPA authorization forms, participants completed the Tumbling E eye chart (Chang, 1995) and CAT line bisection (Swinburn et al., 2004) to assess vision, and a pure tone audiometry test to assess hearing. Then, the following speech, language and cognitive tests were administered:

Descriptive Speech and Language Testing. Listed below are spoken production and auditory comprehension subtests from the Comprehensive Aphasia Test (CAT; Swinburn et al., 2004). Table 2 illustrates individual and group performance on these descriptive language measures.

1) Comprehension of Spoken Language: Comprehension of spoken language production was assessed via comprehension of spoken words (subtest 7) and spoken sentences (subtest 9), which involved matching a spoken word or sentence to a picture, as well as comprehension of spoken paragraphs (subtest 11), which involved answering yes/no questions about a short story that was read aloud by the examiner.
2) Naming: Naming ability was assessed by performance on word fluency tasks (subtest 3) that measured the number of animals and number of words beginning with the letter "s" that could be named in one minute, respectively. Naming was also assessed by ability to accurately name line drawings of objects (e.g., star) (subtest 17) and actions (e.g., eating) (subtest 18).
3) Repetition: Performance on repetition of words (e.g., table), complex words (e.g., unthinkable), and nonwords (e.g., gart) was assessed on subtests 12, 13, and 14, respectively.
4) Picture Description: Spontaneous speech and language production was assessed by performance on subtest 19 which involved telling a narrative to describe a line drawing of a family living room scene.

Descriptive Cognitive Testing. Attention, working memory, and problem-solving abilities were assessed by performance on the tests described below. Table 2 illustrates individual and group performance on these descriptive cognitive measures.

1) Letter cancellation: This subtest from the Behavioral Inattention Test (Wilson, Cockburn, & Halligan, 1987) required the participant to manually cross out all of the "E" and "R" letters which were randomly scattered throughout five rows of letters that each contained 34 letters per line.
2) Symbol trails: This subtest from the Cognitive Linguistic Quick Test (Helm-Estabroks, 2001) required the participant to draw a continuous line to connect circles and triangles. The participant had to alternate between touching a circle and touching a triangle while simultaneously going from the smallest to largest shapes.
3) Forward and backward visual spatial span: Participants completed the forward and backward Corsi Block Span Task (De Renzi & Nichelli, 1975). This task involved the experimenter pointing to wooden blocks and the participant mimicking the pointing pattern either exactly as it was demonstrated (forward condition) or in the reverse order (backward condition). Pointing spans began with only one block to ensure the task was understood and then continued to increase (2, 3, 4, and so on) until the participant failed two trials within a pointing span. There were five trials for each pointing span.
4) Visual problem solving: Participants completed the Raven's Coloured Progressive Matrices (Raven & Raven, 1998) which involved analyzing 36 visual geometric designs each of which had a piece of the design missing. From a field of six choices, the participant pointed to the pattern that would fit into the geometric design.

Table 2. Individual and group performance on descriptive testing

ID	Raven's Matrices (cut off 23)	Letter cancellation (max 40)	CLQT symbol trails (max 10)	Corsi Block Forward	Corsi Block Reverse	CAT Spoken Comprehension (cut off 56)	CAT Naming (cut off 69)	CAT Repetition (cut off 39)	CAT Picture Description (cut off 33)
P1	32	40	8	4	3	44	57	40	11
P2	35	40	9	5	5	59	69	44	31.5
P3	34	40	10	4	4	40	58	46	18.5
P4	34	37	10	3	5	56	72	42	29
P5	35	39	10	4	4	51	35	28	11.5
P6	35	40	10	4	3	44	58	34	21.5
P7	28	40	7	4	4	40	56	35	22
P8	32	40	6	5	4	56	49	39	19.5
P9	23	39	10	4	3	41	42	34	10
P10	28	36	8	4	4	43	1	20	4
P11	34	38	10	5	5	51	67	44	30
P12	36	39	10	5	3	56	63	48	21
P13	23	37	5	4	2	42	46	32	17.5
P14	35	38	10	4	3	56	58	48	18.5
P15	30	38	5	3	4	49	22	32	15
P16	35	40	10	5	5	57	76	46	39
P17	29	39	10	5	4	57	61	30	23
P18	34	40	10	4	3	54	61	39	20
P19	34	40	10	4	5	58	77	42	28
P20	33	39	10	3	4	60	67	40	30
P21	36	38	10	4	4	43	38	48	12
P22	23	38	6	1	2	32	10	28	7.5
P23	DNC	38	10	2	3	29	15	6	14.5
P24	28	39	10	3	2	58	57	46	29.5
P25	29	40	10	4	4	43	2	8	7.5
P26	36	39	10	5	5	36	16	0	-3
P27	29	40	10	3	1	55	55	22	21
P29	34	35	10	3	2	40	21	44	3.5
P30	31	40	10	3	4	46	60	23	36.5
P33	30	40	10	4	4	61	79	48	47
P34	35	40	10	3	3	55	39	40	23
P35	36	37	10	6	5	64	72	42	24
P36	36	40	10	4	4	56	60	46	16
P37	35	38	10	4	4	55	56	42	31
P38	25	38	8	4	4	30	15	23	0.5
P39	28	38	9	4	4	51	45	34	10
P41	25	38	10	3	3	42	16	16	3
P42	27	38	10	4	3	47	26	36	6.5
P43	29	39	9	3	3	54	50	48	17
P44	23	38	10	2	2	32	17	12	6
P45	36	40	10	5	6	49	20	46	24.5
P46	31	38	6	5	5	54	77	46	27.5
P47	33	39	8	5	4	48	68	48	17.5
AVG	31.29	38.77	9.16	3.88	3.67	48.70	46.72	35.23	18.67
SD	4.19	1.23	1.51	0.98	1.06	9.00	22.68	12.72	10.94
Range	23-36	35-40	5-10	1-6	1-6	29-64	1-79	0-48	-3 - 36.5

Raven's Matrices = Raven's Coloured Progressive Matrices (Raven et al., 1998); Letter Cancellation = Subtest of Behavioral Inattention Test (Wilson et al., 1987); CLQT = Cognitive Linguistic Quick Test (Helm-Estabrooks, 2001); Corsi Block =Corsi Block Span Task (De Renzi &Nichelli, 1975); CAT = Comprehensive Aphasia Test (Swinburn et al., 2004); DNC =did not complete

Experimental Testing

After descriptive testing was complete, participants entered the experimental testing phase of the study. During this phase semantic, phonologic, syntactic, oral reading, and silent reading comprehension abilities were assessed (described below). Many of the tasks were similar to those used in other studies that have investigated the relationship between reading and primary language systems (Crisp & Lambon Ralph, 2006; Henry et al., 2012; Jefferies et al., 2007; Rapcsak et al., 2009). However, the inclusion of syntactic and silent reading comprehension measures was novel. It is imperative to note that no language task can be purely semantic, phonologic, or syntactic. With that said, tasks that rely more heavily on one language domain were selected. The semantic, phonologic, and syntactic tasks did not include any letters (i.e., no orthography) and are therefore referred to as “non-orthographic”. In addition, the non-orthographic language tasks all involved non-verbal responses (e.g., pointing to a picture, thumbs up or down, etc.) to reduce the impact of any motor speech impairment.

Multiple measures for each language domain were administered since no single task can encompass the entire domain (e.g., 3-4 tasks were administered for each domain and then performance was averaged; see “Calculating Composite Scores”). Moreover, use of multiple tasks per language domain created variation in overall domain difficulty which allowed for sensitivity to a range of impairment severity and should have helped to prevent a participant with milder impairments from reaching a ceiling effect on all tasks and helped to prevent an individual with more severe impairments from reaching a floor effect on all tasks (Lambon Ralph et al., 2002; Martin et al., 2006). For each participant the experimental tasks were administered in random order. Specifically, order of language domain presentation (e.g., semantics, phonology, syntax, oral reading, and silent reading comprehension) and order of tasks within each language domain were presented in random order. The non-orthographic language tasks and reading tasks are listed in Tables 3 and 4, respectively, and included the following:

***Non-orthographic Semantic Tasks*.** Conceptual and lexical semantic processing abilities were tested by evaluating performance on the following tasks that assess auditory or pictorial single word comprehension:

1) Picture Association (Camel and Cactus Test from the Cambridge Semantic Memory Test Battery; Adlam, Patterson, Bozeat, & Hodges, 2010): The participant saw a target picture (e.g., cactus) at the top of the page and four pictures (e.g., mountain, beach, desert, and iceberg) at the bottom of the page. He or she then pointed to the picture (e.g., desert) that was most associated with the target picture.
2) Spoken Word-Picture Matching (Psycholinguistic Assessments of Language Processing in Aphasia (PALPA), subtest 47) (Kay, Coltheart, & Lesser, 1992). The participant heard a word (e.g., carrot) and then pointed to the corresponding picture from a field of five pictures that included a close semantic distractor (e.g., cabbage), a distant semantic distractor (e.g., lemon), a visually related distractor (e.g., saw), an unrelated distractor (e.g., chisel), and the target picture (e.g., carrot).
3) Auditory Synonym Judgment (PALPA, subtest 49): The participant heard two words (e.g., marriage-wedding) and indicated if the words were related in meaning by shaking head "yes" or "no" and/or showing a thumbs up or down.
4) Auditory Comprehension of Verbs & Adjectives (PALPA, subtest 57): The participant heard a word and a definition (e.g., "kicking"- "hitting something with your hand") and then decided if the definition was correct or not by shaking head "yes" or "no" and/or showing a thumbs up or down.

Non-orthographic Phonologic Tasks. Phonologic processing was tested by evaluating performance on the following auditory tasks that assess the identification, maintenance, and manipulation of phonemes:

1) Phoneme Discrimination- Minimal Pairs (Standardized Assessment of Phonology in Aphasia (SAPA), subtest 2) (Kendall et al., 2010): The participant heard two syllables (e.g., "PAH-BAH") and decided if the sounds were the same (shaking head "yes") or different (shaking head "no").
2) Real Word Rhyme Judgment (SAPA, subtest 2): The participant heard two real words (e.g., "head-bed") and decided if the words rhymed (shaking head "yes") or not (shaking head "no").
3) Nonword Rhyme Judgment (SAPA, subtest 2): The participant heard two nonwords (e.g., "fet-het") and decided if the nonwords rhymed (shaking head "yes") or not (shaking head "no").
4) Phoneme Manipulation (Lindamood Auditory Conceptualization Test (LAC) (Lindamood & Lindamood, 1979): Participants first listened to trials of sounds in isolation (e.g., /s/, /s/, /sh/) and then the task became more complex and involved listening to sounds in syllables (e.g., zaf vs. zag). For both of these tasks, the participants used colored wooden blocks to represent how many phonemes were heard, whether the phonemes were the same or different, and in what order they occurred. For example, if the sound pattern was "/s/, /s/, /sh/", the participant would select three blocks, with the first two blocks matching in color, to represent the number, likeness, and order of the sounds. Therefore, the participant might display a blue block, a blue block, and then a red block to represent this sound pattern. For the sounds in syllables, the syllable patterns

built off of one another and the participant identified which sound had been added, substituted, omitted, or transposed using the blocks. For example, the first syllable might be “af” represented by two different colored blocks, then the next syllable might be “zaf”, and a third block would be added to the first position to represent the addition of /z/. The next syllable might be “zag” and the third block would be replaced to represent the substitution of /f/ for /g/. The syllable chain would continue to change by one phoneme, but did not exceed four phonemes in length. The task ceased if five errors were made.

Non-orthographic Syntactic Tasks. Syntactic processing was tested by evaluating performance on the following tasks that assess comprehension of spoken phrases and sentences of varying syntactic structure.

1) Spoken Sentence-Picture Matching (PALPA, subtest 55): The participant listened to a spoken sentence (e.g. “The dog’s got more cats to chase”) and then selected from a field of three pictures which picture matched the sentence. Incorrect pictures illustrated the reverse sentence (e.g., The dog’s got less cats to chase”) and a distractor subject (“The man’s got more cats to chase”).
2) Auditory Comprehension of Locative Relations (PALPA, subtest 58): The participant listened to a spoken phrase (e.g., “box in front of bucket”) and then chose which of four pictures best matched the phrase. The incorrect pictures illustrated distractor locations, such as “box behind bucket”, “box in bucket”, or “bucket in front of box”.
3) Comprehension of Spoken Sentences (CAT, subtest 9): The participant listened to a spoken sentence (e.g., “She is laughing.”) and then selected from a field of four pictures which picture matched the sentence. Incorrect pictures illustrated a distractor subject

(e.g., "He is laughing"), a distractor verb (e.g., "She is crying") and combined distractor subject and verb (e.g., "He is crying").

Table 3. Non-orthographic language assessment battery

Language Domain	*Type of Assessment*	*Tasks (Number of items)*
Semantics	Nonverbal assessment of conceptual and lexical knowledge (comprehension tasks)	CCT: Picture Association (64)
		PALPA 47: Spoken word-to-picture match (40)
		PALPA 49: Auditory synonym judgment (60)
		PALPA 57: Auditory comprehension of verbs & adjectives (41)
Phonology	Nonverbal assessment of phonological processing	SAPA: Minimal pairs (13)
		SAPA: Real word rhyme judgment (15)
		SAPA: Nonword rhyme judgment (22)
		LAC: Sounds in isolation (16) and Sounds in syllables (12)
Syntax	Nonverbal assessment of syntactic processing (comprehension tasks)	CAT 9: Comprehension of spoken sentences (16)
		PALPA 55: Spoken sentence-to-picture match (60)
		PALPA 58: Auditory comprehension of locative relations (24)

CCT = Cactus and Camel Test (Adlam et al., 2010); PALPA = Psycholinguistic Assessment of Language Processing in Aphasia (Kay et al., 1992); SAPA = Standardized Assessment of Phonology in Aphasia (Kendall et al., 2010); CAT =Comprehensive Aphasia Test (Swinburn et al., 2004); LAC = Lindamood Auditory Conceptualization Test (Lindamood &Lindamood, 1988)

Oral Reading Tasks. Oral reading abilities were tested by evaluating ability to read aloud various word types (i.e., regular, irregular, pseudohomophones, and nonwords). The following oral reading stimuli were presented one at a time in large, bold font on a computer screen.

1) Regular words (Arizona Battery for Reading and Spelling (ABRS), Beeson, Rising, Kim, & Rapcsak, 2010): Regularly spelled words contained all high-probability grapheme to phoneme correspondences (e.g., "sheep") and were monosyllabic or disyllabic, three to seven letters in length, and consisted of nouns, verbs, and adjectives.
2) Irregular words (ABRS): Irregular words contained at least one low-probability grapheme-phoneme correspondence (e.g., "chef") and were matched with the regular

words for word frequency, imageability, grammatical class, and number of letters. The regular and irregular words were not tested in separate lists, but instead, were presented simultaneously as designed by Beeson and colleagues (2010). Order of presentation of the real word lists and the nonword and pseudohomophone lists (described below) was random for each participant.

3) Nonwords (ABRS): Nonwords consisted of orthographically and phonologically plausible English words that lacked meaning (e.g., "glope") and were derived from real words by changing at least one phoneme/grapheme. The nonwords were monosyllabic or disyllabic and ranged from four to six letters in length.

4) Pseudohomophones (Long form of Standardized Assessment of Phonology in Aphasia (SAPA), subtest 1) (Kendall, del Toro, Nadeau, Johnson, Rosenbek, & Velozo, 2010): Pseudohomophones consisted of unfamiliar orthography yet familiar phonology that corresponded to a real word (e.g., "hevin"). Pseudohomophones were monosyllabic or disyllabic and ranged from four to six letters in length.

Silent Reading Comprehension Tasks. Reading comprehension abilities were tested by evaluating performance on the following tasks that assess written comprehension of single words, sentences, and paragraphs.

1) Single words:

   a. Written Word-Picture Matching (CAT, subtest 8): The participant silently read a printed target word (e.g., mug) and then pointed to the corresponding picture. Picture options included the target (mug), semantic distractor (cup), phonological distractor (rug), and an unrelated distractor (carpet).

b. <u>Written Synonym Judgment</u> (PALPA, subtest 50): The participant silently read two printed words (ocean –sea) and then decided if the words were related in meaning (shaking head "yes") or not (shaking head "no").

c. <u>Written Word Semantic Association</u> (PALPA, subtest 51): The participant silently read a written target word (comb) and then pointed to one of four written words (door, brush, gate, tweezers) that was closest in meaning.

2) Phrases/sentences:

a. <u>Written Sentence Comprehension</u> (CAT, subtest 10): The participant silently read a sentence (e.g., "The dancer is painted by the policeman".) and then chose one of four pictures that best illustrated the sentence. Incorrect pictures illustrated syntactically related distractors such "The policeman is painted by the dancer", "The dancer is chased by the policeman", and "The policeman is chased by the dancer".

b. <u>Written comprehension of locatives</u> (PALPA 59): The participant silently read a phrase (e.g., squares in circles) and then chose one of three pictures that best illustrated the sentence. Incorrect pictures illustrated pictures with the same objects as the target sentence, but located in distractor positions (e.g., squares between circles).

c. <u>Functional Reading</u> (Reading Comprehension Battery of Aphasia (RCBA), subtest 4) (LaPointe & Horner, 1984): The participant silently read a sentence and then followed its instruction. For example, the sentence might say "Point to the one you would use to get out" and the participant would choose between 3 line drawings of doors labeled: "exit", "women", or "do not enter".

3) Paragraphs:

   a. Short Paragraph Comprehension (RCBA, subtest 7): The participant silently read a short paragraph (25 words; 2-3 sentences) and chose one of three pictures that best matched the paragraph. Example item: “The man liked fruit in the morning, steak for lunch, and eggs for supper. Point to the picture showing what the man ate for breakfast”. There were 10 short paragraphs.

   b. Factual and Inferential Comprehension (RCBA, subtests 8 and 9): The participant silently read a paragraph (50 words; 3-6 sentences) and then completed sentences (2 factual, 2 inferential) by pointing to one of three printed words. Example item: “This trip was made in the….. A. fall, B. summer, C. morning”. There were 5 paragraphs, each with four sentences to complete.

Table 4. Reading assessment battery

Language Domain	*Type of Assessment*	*Tasks (Number of items)*
Oral Reading	Oral reading of single words	ABRS regularly spelled words (40)
		ABRS irregularly spelled words (40)
		ABRS nonwords (20)
		SAPA pseudohomophones (12)
Silent Reading Comprehension	Single words	CAT 8: Written word-to-picture match (15)
		PALPA 50: Written synonym judgment (60)
		PALPA 51: Written word semantic association (30)
	Sentences	CAT 10: Written sentence-to-picture match (16)
		PALPA 59: Written comprehension of locatives (24)
		RCBA 4: Functional Sentence Reading (10)
	Paragraphs	RCBA 7: Paragraph-to-picture match (10)
		RCBA 8: Paragraph-factual (10)
		RCBA 9: Paragraph-inferential (10)

ABRS= Arizona Battery for Reading and Spelling (Beeson et al., 2010); SAPA =Standardized Assessment of Phonology in Aphasia (Kendall et al., 2010); CAT =Comprehensive Aphasia Test (Swinburn et al., 2004);PALPA = Psycholinguistic Assessment of Language Processing in Aphasia (Kay et al., 1992); Reading Comprehension Battery for Aphasia (LaPointe & Horner, 1984)

Scoring

A raw accuracy score (correct = 1; incorrect = 0) for every item in the semantic, phonologic, syntactic, and silent reading comprehension tasks was determined by the examiner online during testing. The oral reading accuracy scores were determined off-line via analysis of the participants' audio-video recordings. For the oral reading tasks, responses with distorted or prolonged sounds were scored as correct. Sound omissions, substitutions, transpositions, additions, and non-responses were scored as incorrect. For all tasks, the participant's final response was scored, and therefore, self-corrections were permitted.

The total raw score for each task was converted into a z-score. A z-score indicates how well the individual performed in relation to all other participants (Martin et al., 2006). Specifically, a z-score reports how many standard deviations (SD) away from the group mean the individual performed (Z = (individual score – group mean)/SD). Converting to z-scores allowed for a standard comparison across the various measures that differed in language domain (e.g. semantics, phonology, syntax, oral reading, and silent reading comprehension), number of items, and/or level of difficulty. The z-score values were then used to create composite scores for each participant in each language domain (described below).

Data Analysis

Calculating Composite Scores

Similar to other studies (Crisp & Lambon Ralph, 2006; Henry et al., 2012; Rapcsak et al., 2009), composite language scores were calculated to predict reading. Specifically, composite scores for semantics, phonology, syntax, oral reading, and silent reading comprehension were determined for each participant for use in the correlational and regression analyses.

A composite score consisted of the average of the z-scores from each language domain (Martin et al., 2006). For example, each participant's phonologic composite score was derived by averaging his/her four z-scores from the four phonologic tasks. Likewise, each participant's semantic composite score was derived by averaging his/her four z-scores from the four semantic tasks, and so on for each language domain. The selection of tests to be included within each composite was based on theoretical assumptions that each test within the semantic composite is measuring semantic abilities; each test within the phonologic composite is measuring phonological abilities, and so on for each composite.

In order to statistically rationalize these a priori decisions, the tests in each language domain (i.e., semantics, phonology, syntax, oral reading, and silent reading comprehension) were correlated with one another. All the tasks in each domain were significantly correlated with one another, except for the phonologic tests. Only 3 of the 4 phonological tasks were significantly correlated. Performance on minimal pairs was not significantly correlated with performance on the LAC phoneme manipulation test (See Appendix I for language domain correlation tables).

To further validate the composite scores, a principal components analysis (PCA) was performed on the tests that comprise each language domain to determine if each composite represented only one factor. Indeed, the PCA analyses revealed only one factor with an eigenvalue greater than one in each language domain, statistically justifying the formation of the composite scores. The output for each PCA reported, "Only one component was extracted". In particular, the semantic tests loaded on one factor with an eigenvalue of 2.8 that explained 70% of the variance, and the phonologic tests loaded on one factor with an eigenvalue of 2.26 that explained 56.59% of the variance. An eigenvalue of 2.54 explained 84.68% of the variance in the syntactic tests, and an eigenvalue of 3.41 explained 85.35% of the variance in the oral reading tests. Finally, the silent reading comprehension tests loaded on one factor with an eigenvalue of 6.45 that explained 71.70% of the variance.

It should be noted that when the predictors of the regression models (i.e., semantic, phonologic, and syntactic tasks) were all entered into one PCA analysis, three independent components were not identified. Instead two factors were identified and the rotated component plots showed the phonologic tests had component values further away from the overlapping semantic and syntactic tests (See Appendix II). The overlap of the semantic and syntactic tests is not that surprising, and is nicely explained by Schneider et al. (2016, pg.20) who said "the distinction between syntactic and semantic processing is difficult because syntactic differences have consequences on semantic processing".

Calculating Alexia Subtypes

A reading profile (i.e., surface alexia, phonological alexia, deep alexia, global alexia or within normal reading limits) was calculated for each participant so the relationship between alexia type and non-orthographic semantic and phonologic abilities could be explored. Alexia type was determined for each participant based on his/her oral reading accuracy and types of oral reading errors produced. Below, the following will be defined and explained: 1) calculation of oral reading accuracy score ranges 2) oral reading error analysis, and 3) how oral reading accuracy score ranges and oral reading errors were used to determine each participant's reading profile.

Oral reading accuracy score ranges (95% CI): Methods similar to those used by Brookshire et al. (2014b) were also used in this study to calculate oral reading accuracy score ranges. To determine an individual's oral reading accuracy score ranges, first the standard error of measurement (SEM), or the amount of random error in assessment, was calculated for each of the different oral reading lists (i.e., all real words, regular words, irregular words, nonwords, and pseudohomophones). The SEM represents the spread of scores an individual would obtain if he or she were tested repeatedly. SEM for each word type was calculated using the following formula:

$$SEM = SD \sqrt{(1-r)}$$

In this equation, *SD* stands for standard deviation and this number was derived from the participants' percent accuracy for each word type (*SD* real words = 0.33, SD regular words = .33, *SD* irregular words = .33, *SD* nonwords = .35, and *SD* pseudohomophones = 0.33). The *r* stands for reliability and refers to the internal consistency of the words within each reading list. Cronbach's alpha (α) was calculated for the items that make up the regular word (α =.98), irregular word (α =.98), all real words (α =.99), nonwords (α =.95), and pseudohomophone (α =.90) reading lists. Each word list demonstrated high item reliability given a Cronbach's alpha greater than 0.7 is generally accepted to indicate a good level of internal consistency among test items (Laerd Statistics, 2016).

Once the SEM for each word type was calculated, this number was used in the formula above to determine the 95% reading confidence interval (CI) for each participant for each word type (See Appendix III for SEM and 95% CI equations and calculations). Specifically, the derived SEM value for each word list (real words =.03, regular = .05, irregular =.05, nonwords = .08, pseudohomophones = .10) was multiplied by 1.96 to create the 95% confidence interval values (real words = .06, regular = .09, irregular = .10, nonwords = .15, pseudohomophones = .21) that were then added and subtracted from each participant's average reading score for each word list.

In summary, each participant's reading accuracy score ranges are represented by 95% CIs for his/her real word (RW), nonword (NW), regular word, irregular word, and pseudohomophone reading performance. These calculations were made using the following formula:

95% CI = participant's average score +/- (1.96 x SEM)

For example, P39 read real words with 80% accuracy so her real word 95% CI = .80 +/ - (1.96 x .03) = .80 +/-.06 for a RW accuracy score range of 86%-74%. Calculating oral reading accuracy score ranges via 95% CIs provides a more comprehensive estimate of reading ability compared to only measuring the average percent correct score.

Oral Reading Error Analysis: Oral reading errors were analyzed and classified to help determine alexia subtype. The hallmark errors of surface alexia (i.e., regularization errors), phonological alexia (i.e., visual/phonological errors and lexicalization errors), and deep alexia (i.e., semantic errors) were coded by trained research assistants using audio-video recordings of each participant's oral reading. In addition, unrelated errors and omissions were identified and coded as these error types are also commonly found in alexia (Lambon Ralph et al., 2002; Jefferies et al., 2007; Patterson & Lambon Ralph, 1999; Welbourne & Lambon Ralph, 2007). The error types are defined below.

- <u>Regularization reading errors</u> were defined as reading an irregularly spelled word with a "regular" grapheme-phoneme pronunciation, such as reading "pint" to rhyme with "mint".
- <u>Visual/phonological reading errors</u> were defined as responses that had at least 50% of the phonemes/graphemes in the stimulus (Crisp & Lambon Ralph, 2006). These errors consisted of real words that looked and sounded similar to the target (i.e., "milk" for "mile") or

nonwords that were the result of a phoneme addition, deletion, substitution, transposition, or combination of sound errors (i.e., “seef” for “chief”).

- Lexicalization reading errors were defined as reading a nonword as a real word, such as saying “fig” for “flig” or “globe” for “glope”.
- Semantic reading errors were defined as producing a semantically related response, such as reading “boat” for “yacht” or “soldier” for “sergeant”.
- Unrelated real word errors were defined as real words that were not semantically or visually/phonologically related to the target word, such as reading “bed” for “count”.
- Unrelated nonword errors were defined as nonword responses that did not share sounds or letters with the target word, such as saying “eebee” for “gang”.
- Omissions were defined as no response or responses that indicated the participant was not able to read the stimulus (e.g., “I don’t know”, “skip”, “I can’t”, “no”, etc.).

Alexia Subtyping Criteria: The following reading accuracy and error type criteria were used to determine each participant’s reading profile:

- Surface alexia*:* Given the hallmark feature of surface alexia is impaired irregular word reading compared to reading of words with predictable letter-to-sound correspondences (i.e., regularity effect) (Lambon Ralph & Patterson, 2007), surface alexia was characterized by better reading of regular words and nonwords compared to irregularly spelled words. This discrepancy was defined by non-overlapping regular word and irregular word reading ranges (95% CIs), as well as non-overlapping nonword and irregular word reading ranges with the regular and nonword reading ranges being superior to the irregular word reading range. In addition, regularization errors (e.g., reading "blood" to rhyme with "food") were required to be a predominant error type when reading irregular words.

- Phonological Alexia: Given the lexicality effect (i.e., real word reading > nonword reading) is the hallmark feature of phonological alexia, phonological alexia was characterized by better reading of real words (RW) than nonwords (NW). The lexicality effect was defined by non-overlapping RW and NW reading accuracy ranges (i.e., RW = 95%-85% vs. NW = 70%-60%). Moreover, real word reading ability in phonological alexia is known to be quite variable, yet typically still relatively well preserved (Farah et al., 1996; Patterson & Lambon Ralph, 1999). Therefore, the high end of the RW 95% CI was at least 60% to ensure RW reading was fairly accurate. In addition, the predominant error types included visual/phonologic errors (e.g., reading "single" for "signal") and lexicalization errors (e.g., reading "fish" for "fosh").
- Deep alexia (i.e., Severe Phonological Alexia)*:* Given that overall greater reading impairment and the production of semantic reading errors (e.g., reading "goat" for "sheep") are the hallmark features of individuals on the deep end of the phonological-deep continuum (Crisp & Lambon Ralph, 2006; Lambon Ralph & Patterson, 2007), deep alexia was characterized by overall reading being 50% accurate or less with the presence of semantic errors. Additionally, the high end of the real word 95% CI was less than 60% accurate and the high end of the nonword 95% CI was less than 30% accurate to ensure a lexicality effect was present.
- Global alexia*:* Given that global alexia represents the inability or near inability to read any words, real or made up, global alexia was defined as reading 10% or less of the oral reading stimuli (i.e., no more than 11 out of the total 112 words read aloud correctly).

- Within normal limits (WNL): If a participant performed within two standard deviations of the normal controls on the regular words (*M* = 99.56%; *SD* =2.17%), irregular words (*M* =98.06%; *SD* = 4.57%), nonwords (*M* = 95.74%; SD = 7.30%), and pseudohomophones (*M* = 79.30; *SD* = 18.24%) then he or she did not receive an alexia typing and was considered to read within normal limits (WNL). Normal control data for the regular, irregular, and nonwords comes from the ABRS (Beeson et al., 2010) and normal control performance on pseudohomophones comes from the SAPA (Kendall et al., 2010).

Reliability

Intra- and inter-rater reliability for oral reading accuracy (e.g., determining if a word was read aloud correctly or not) was performed for 25% of each participant's oral reading data. Specifically, a randomly selected 25% of each word type (i.e., 10 regular, 10 irregular, 5 nonwords, and 3 pseudohomophones) was re-analyzed for each participant. The overall proportion of agreement between the initial accuracy ratings and the intra-rater accuracy ratings was .97 or 97%, and the proportion of agreement between the two raters (initial rating vs. the inter-rater ratings) was .96 or 96%. These percentages of agreement do not take into account chance agreement, however. Cohen's Kappa (*k*) was also calculated because this formula does account for chance agreement among two raters and therefore represents the amount of genuine agreement (Laerd Statistics, 2016). Cohen's Kappa values range from -1 to 1 with 0 indicating that agreement was no better than chance. Cohen's Kappa values of .93 ($p < .001$) and .91 ($p < .001$) were found for the intra-rater and inter-rater accuracy agreements, respectively. A Cohen's Kappa between 0.81-1.00 indicates that the strength of the agreement was "very good" (Altman, 1999; Laerd Statistics, 2016).

Intra- and inter-rater reliability for oral reading error types (e.g., determining if a reading error should be classified as semantic, visual/phonological, lexicalization, regularization, omission, unrelated RW or unrelated NW) was also performed for 25% of each participant's data. The same words analyzed in the accuracy reliability analyses were also analyzed in the error coding reliability analyses. The overall proportion of agreement between the initial error ratings and the intra-rater ratings was .95 or 95%, and the proportion of agreement between the two raters (initial rating vs. the inter-rater ratings) was .92 or 92%. As mentioned, these percentages of agreement do not take into account chance agreement. Cohen's Kappa values of .90 ($p < .001$) and .86 ($p < .001$) were found for the intra-rater and inter-rater error coding agreements, respectively, indicating "very good" above chance agreement (Altman, 1999; Laerd Statistics, 2016).

Statistical Analysis

The statistical analyses employed are described per research question (RQ) below. The Statistical Package for Social Sciences, Version 17.0 (SPSS Inc., 2008) was used to complete these analyses. All comparisons reported below were motivated by a priori hypotheses, and therefore corrections for multiple comparisons were not performed. The probability of Type I error is smaller for a priori than post hoc multiple comparisons (Ash et al., 2011; Hurlbert & Lombardi, 2012). For all analyses, a p-value of 0.05 (two-tailed) was used to indicate statistical significance.

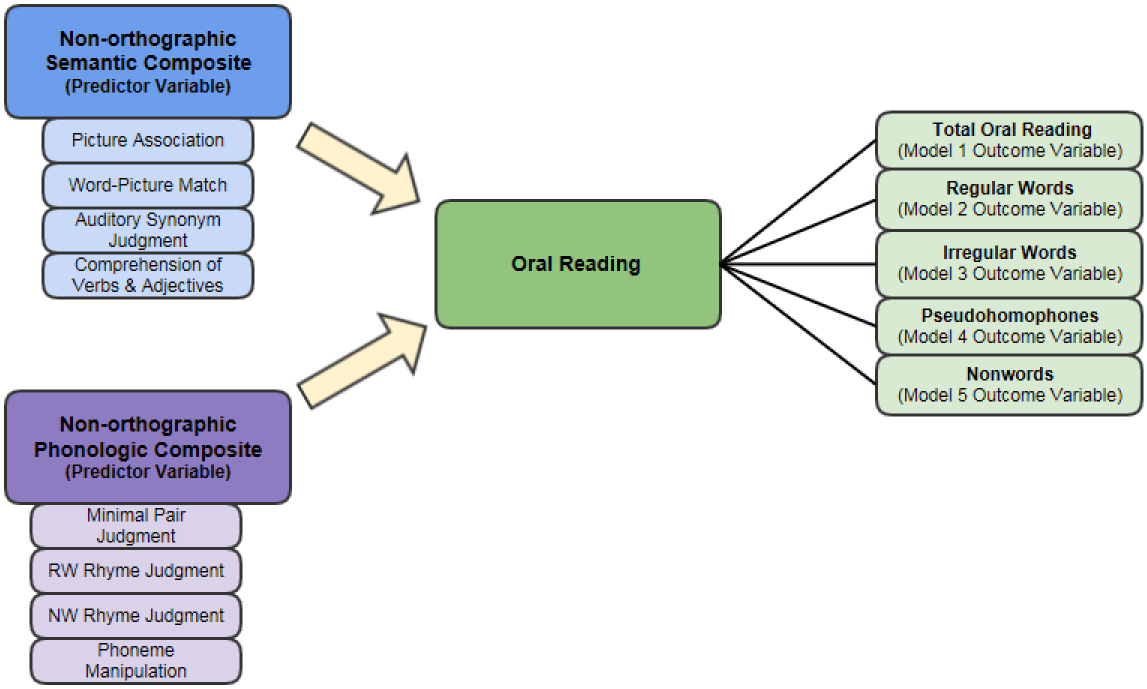
RQ1: To what extent does performance on non-orthographic semantic and phonologic measures predict single word oral reading performance on regular words, irregular words, pseudohomophones, and nonwords in PWA?

To address RQ1, correlation and regression analyses were performed.

1) Correlation Analysis: To determine the relationship between single word oral reading abilities and non-orthographic semantic and phonologic abilities, oral reading z-scores for regular words, irregular words, pseudohomophones, nonwords, and overall oral reading composite z-scores were correlated against all of the phonological and semantic z-scores, as well as the semantic and phonologic composite z-scores.

2) Regression Analysis: After the correlation analyses, multiple linear regression models were performed. Specifically, five multiple linear regressions were completed using the phonology and semantic composite z-scores as predictors of 1) overall oral reading , 2) regular word reading, 3) irregular word reading, 4) pseudohomophone reading, and 5) nonword reading to determine to what extent phonology and semantics could account for the variance in oral reading of different word types. Figure 5 below illustrates the predictors and the outcome variables in these regression models.

Figure 5. Illustration of the predictor and outcome variables in the 5 regression models for RQ 1



Note: All variables above were entered in the regression models as z-scores

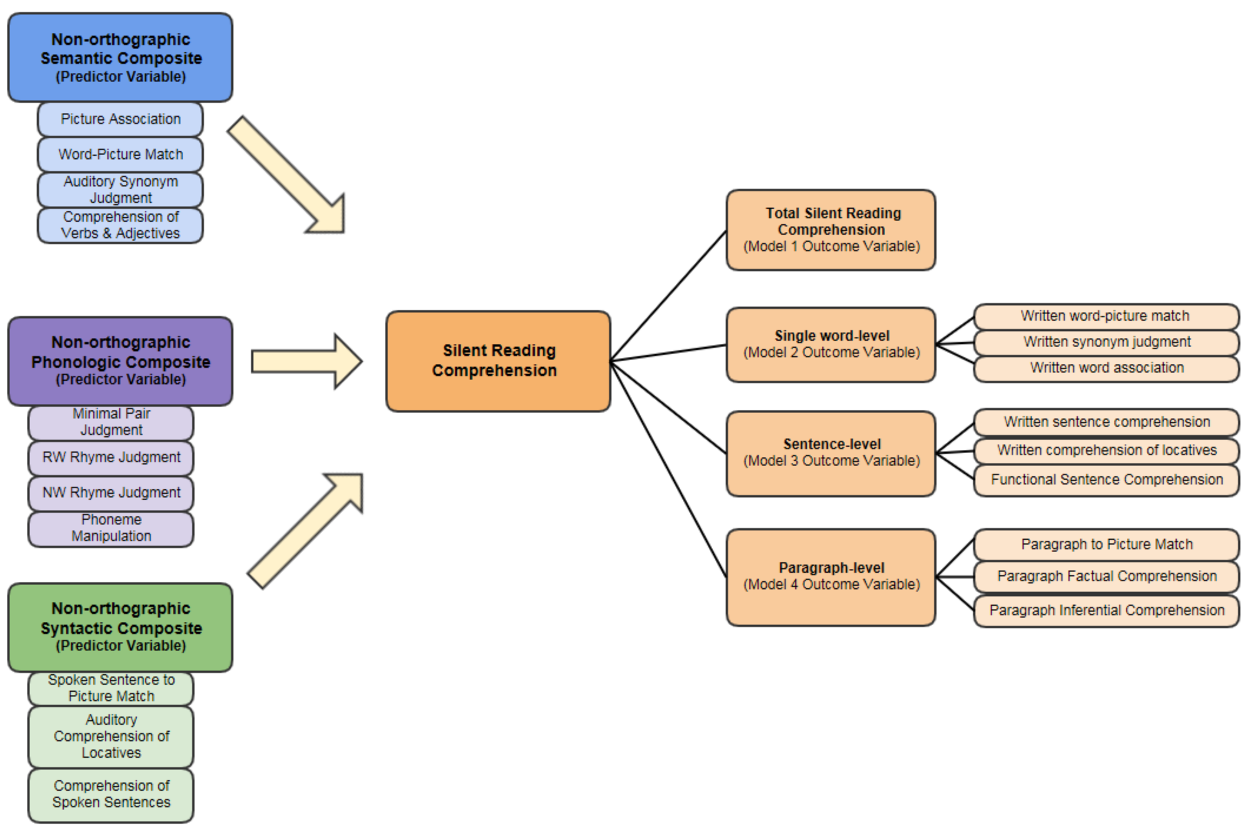
RQ2: To what extent does performance on non-orthographic semantic, phonologic, and syntactic measures predict silent reading comprehension performance at the single word, phrase/sentence, and paragraph levels in PWA?

To address RQ2, correlation and regression analyses were performed.

1) Correlation Analysis: To determine the relationship between silent reading comprehension abilities and non-orthographic language abilities, silent reading comprehension accuracy (measured in z-scores) for single words, phrases/sentences, paragraphs, and the overall reading comprehension composite z-score were correlated against performance (measured in z-scores) on all of the semantic, phonologic, and syntactic tasks, as well as the semantic, phonologic, and syntactic composite z-scores.

2) Regression Analysis: Four multiple linear regressions were completed using the semantic, phonologic, and syntactic composite z-scores as predictors of 1) overall silent reading comprehension, 2) single-word reading comprehension, 3) sentence-level reading comprehension, and 4) paragraph-level reading comprehension to determine to what extent semantics, phonology, and syntax could account for the variance in silent reading comprehension, and at what linguistic level. Figure 6 below illustrates the predictors and outcome variables in these regression models.

Figure 6. Illustration of the predictor and outcome variables in the 4 regression models for RQ 2



Note: All variables above were entered in the regression models as z-scores

RQ3: What is the relationship between degree of non-orthographic semantic and phonologic impairment and alexia type in PWA?

To address RQ3, correlation and visual analyses were completed.

1) Correlation Analysis: Correlations between performance on all non-orthographic semantic and phonologic measures and hallmark alexia symptoms (i.e., regularity, lexicality, and frequency effects, as well as proportion of regularization, visual/phonologic, lexicalization, semantic, omission, and unrelated reading errors) were calculated to determine the strength and direction of the association between these alexia symptoms and underlying semantic or phonologic impairment. For each participant, a regularity effect was calculated by determining the difference between percent correct regular and irregular word reading accuracy, and a lexicality effect was determined by calculating the difference between percent correct real word and nonword reading accuracy. Frequency effect reflected the difference between percent correct reading high vs. low frequency words.
2) Visual Analysis: Scatterplots illustrating the relationship between each participant's alexia profile and his/her non-orthographic semantic and phonologic abilities were created and analyzed. Specifically, participants' phonologic performance was plotted against their semantic performance with each participant's position on the graphs labeled according to his/her reading profile (i.e., surface alexia, phonological alexia, deep alexia, global alexia, or within normal reading limits)

Before moving to the results section, a review of the RQs, methods, and predictions is provided in Table 5.

Table 5. Summary of research questions, methods, and predictions

	Research Questions	Tasks and Outcome Measures	Data Analysis	Predictions
RQ 1	1. To what extent does performance on semantic and phonologic measures predict **single word oral reading** performance in PWA?	1) **Non-orthographic semantic tasks**: picture association, word-picture match, synonym judg., and comprehension of verbs & adj. 2) **Non-orthographic phonologic tasks**: minimal pairs, real and nonword rhyme judgment, and phoneme manipulation 3) **Oral reading tasks**: regularly and irregularly spelled words, pseudohomophones, and nonwords **Composite scores**: Raw scores on each task were converted into z-scores and averaged to create semantic, phonologic, and oral reading composite scores.	1) **Correlation Analysis:** Semantic and phonologic z-scores were correlated with oral reading z-scores. 2) **Regression Analysis:** Semantic and phonologic composite z-scores were entered as predictors of overall oral reading, regular word reading, irregular word reading, pseudohomophone reading, and nonword reading.	Phonology and semantics will account for a significant amount of the variance in the overall oral reading regression model. Phonology will show a stronger relationship with nonwords and pseudohomophones, semantics with irregular words, and both semantics and phonology will show a similar, positive relationship with regular words.
RQ 2	2. To what extent does performance on semantic, phonologic, and syntactic measures predict **silent reading comprehension** performance in PWA?	1) **Non-orthographic semantic tasks**: same as RQ1 2) **Non-orthographic phonologic tasks**: same as RQ1 3) **Non-orthographic syntactic tasks**: sentence-to-picture match and comprehension of locative relations 4)**Silent reading comprehension tasks**: single words, phrases/sentences, and paragraphs **Composite Scores**: Raw scores on each task were converted into z-scores and averaged to create syntactic and silent reading comprehension composite scores.	1) **Correlation Analysis**: Semantic, phonologic, and syntactic z-scores were correlated with silent reading comprehension z-scores. 2) **Regression Analysis**: Semantic, phonologic, and syntactic composite z-scores were entered as predictors of overall reading comprehension, single word, sentence, and paragraph comprehension.	Phonology, semantics, and syntax will account for a significant amount of the variance in the overall reading comprehension regression model. Phonology and semantics will show a stronger relationship with single word comprehension and syntax will relate more strongly with sentence level comprehension. All measures will show weaker, yet positive, relationships with paragraph level comprehension.
RQ 3	3. What is the relationship between degree of non-orthographic semantic and phonologic impairment and **alexia type** in PWA?	1) **Non-orthographic semantic tasks**: same as RQ1 2) **Non-orthographic phonologic tasks**: same as RQ1 3) **Alexia symptoms**: Regularity, lexicality, and frequency effects, as well as proportion of regularization, lexicalization, visual/phonologic, semantic, omission, and unrelated reading errors were calculated. 4) **Reading profile:** Alexia subtype (surface, phonologic, deep, or global alexia) or readign WNL was determined based on oral reading accuracy and types of oral reading errors produced.	1) **Correlation Analysis**: Semantic and phonologic z-scores were correlated with alexia symptoms. 2) **Visual Analysis**: Scatterplots illustrating the relationship between each reading profile and non-orthographic semantic and phonologic abilities were created and analyzed.	1) **WNL** = intact phonology and semantics 2) **Surface alexia** = impaired semantics and relatively intact phonology 3) **Phonological alexia** = impaired phonology and relatively intact semantics 4) **Deep alexia** = impaired phonology and semantics 5) **Global alexia** = severely impaired phonology and semantics

Chapter 3: Results

The results are described per research question (RQ) below.

Research Question 1

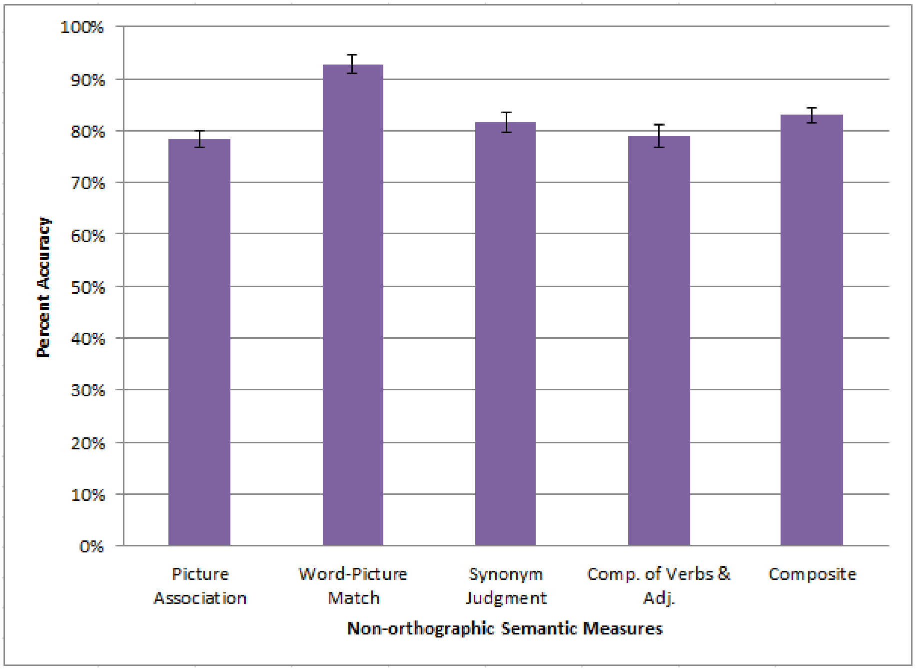
RQ1: To what extent does performance on non-orthographic semantic and phonologic measures predict single word oral reading performance on regular words, irregular words, pseudohomophones, and nonwords in PWA?

Descriptive statistics (e.g., means, standard deviations, and ranges) for the non-orthographic semantic and phonologic tasks and oral reading tasks will be presented first, followed by the correlation and regression results.

<u>Descriptive Statistics</u>

Non-orthographic Semantic Tasks. In regard to the four non-orthographic semantic tasks, on average the group completed picture category association (CCT; Adam et al., 2010) with 78% accuracy (*SD* = 0.11; range = 48%-95%), spoken word-to-picture match (PALPA 47; Kay et al., 1992) with 93% accuracy (*SD* = 0.11; range = 58%-100%); auditory synonym judgment (PALPA 49) with 82% accuracy (*SD* = 0.12; range = 55%-100%), and comprehension of verbs & adjectives (PALPA 57) with 79% (*SD* = 0.14; range = 49%-100%). By averaging the mean percent correct for each task, a percent correct composite of 83% accuracy (SD = 0.10; range = 55%-98%) was obtained (see Figure 7).

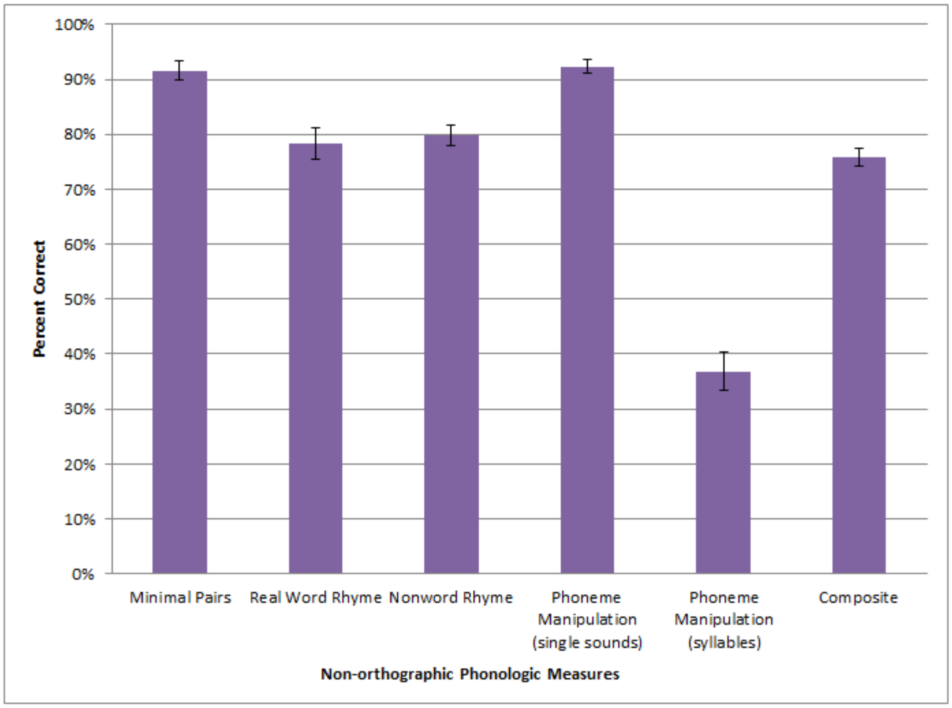
Figure 7. Average % correct on the non-orthographic semantic measures for 43 PWA



Note: Error bars represent standard error

Non-orthographic Phonologic Tasks. The average performance on minimal pair discrimination (SAPA; Kendall et al., 2010) was 92% accuracy (*SD* = 0.11; range = 62%-100%), RW rhyme judgment (SAPA) was 79% accuracy (*SD* = 0.19; range = 20%-100%); NW rhyme judgment (SAPA) was 80% accuracy (*SD* = 0.12; range = 45%-100%), and phoneme manipulation (LAC; Lindamood & Lindamood, 1988) of single sounds was 92% accuracy (*SD* = 0.08; range = 69%-100%) and phoneme manipulation of sounds in syllables was 37% accuracy (*SD* = 0.23; range = 8%-100%) . By averaging the mean percent correct for each task, a percent correct composite of 76% accuracy (SD = 0.10; range = 53%-97%) was obtained (See Figure 8).

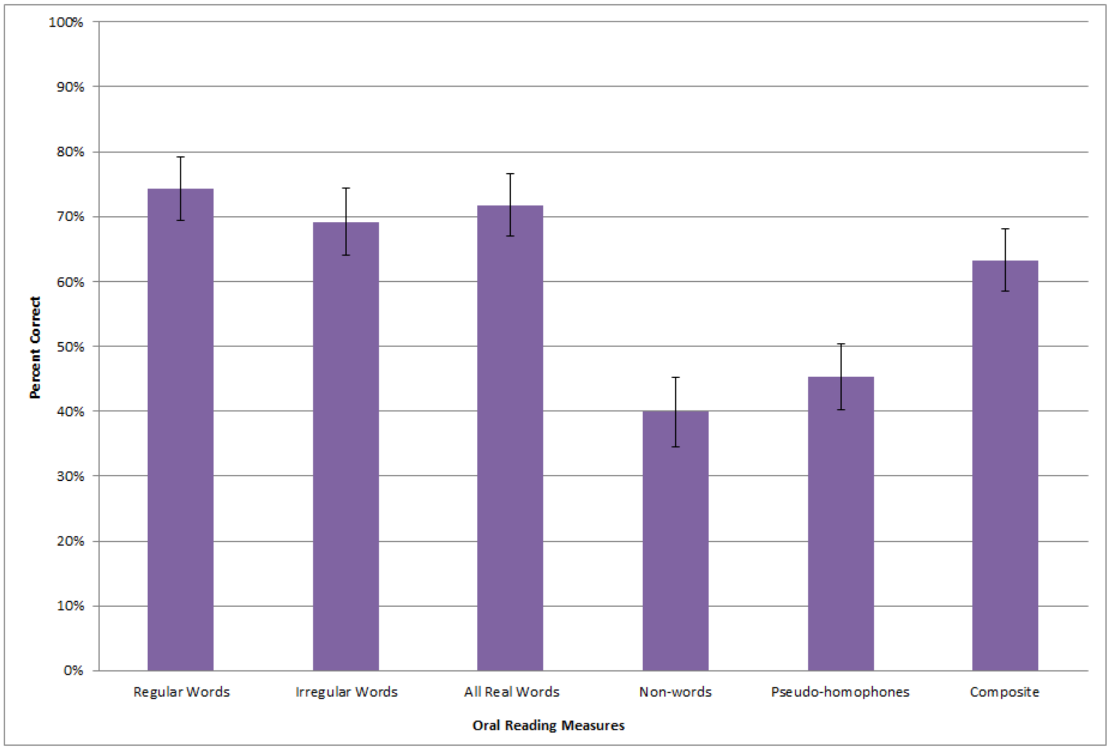
Figure 8. Average % correct on the non-orthographic phonologic measures for 43 PWA



Note: Error bars represent standard error

Oral Reading. Group average performance on oral reading of regularly spelled words (ABRS; Beeson et al., 2010) was 74% accuracy (*SD* = 0.33 ; range = 3%-100%), irregularly spelled words (ABRS) was 69% accuracy (*SD* = 0.34; range = 3%-100%), all real words (regular and irregular combined) was 72% accuracy (*SD* = 0.33; range = 3%-100%), nonwords (ABRS) was 40% accuracy (*SD* = 0.35; range = 0%-100%), and pseudohomophones (ABRS) was 45% accuracy (*SD* = 0.33; range = 0%-100%). By averaging the mean percent correct on these oral reading tasks, a percent correct composite of 63% accuracy (SD = 0.32; range = 2%-97%) was obtained (See Figure 9).

Figure 9. Average % correct on the oral reading measures for 43 PWA



Note: Error bars represent standard error

The percent correct scores reported above were not used in the correlation and regression analyses. Instead, as previously described, semantic, phonologic, and oral reading z-scores were utilized because averaging z-scores, instead of averaging percent correct scores, allows for the tests to each contribute equally to the composite (Refer to "Scoring" and "Calculating Composite Scores" sections, pg. 55). The percent correct scores are shown in the figures above, however, to illustrate how well the participants performed on the tasks instead of how well they performed relative to one another, like z-scores indicate. Moreover, average z-score performance for the group cannot be shown because by definition the average group z-score will always be zero. In summary, Table 6 shows individual and group performance on the semantic and phonologic composites, as well as the oral reading tasks.

Table 6. Individual and group performance on semantic, phonologic, and oral reading tasks

	Non-orthographic Language		**Oral Reading**					
ID	*Semantic Composite*	*Phonology Composite*	*Regular Words*	*Irregular Words*	*All Real Words*	*Non-words*	*Pseudo-homophones*	*Composite (All words)*
P1	86%	75%	90%	95%	93%	10%	50%	73%
P2	93%	75%	100%	100%	100%	45%	58%	86%
P3	77%	78%	88%	78%	83%	5%	17%	62%
P4	88%	91%	98%	93%	95%	65%	75%	88%
P5	83%	80%	63%	48%	55%	0%	17%	41%
P6	89%	81%	100%	83%	91%	75%	50%	84%
P7	67%	62%	88%	78%	83%	50%	33%	71%
P8	92%	89%	98%	98%	98%	80%	92%	94%
P9	73%	71%	38%	43%	40%	0%	8%	29%
P10	55%	66%	13%	3%	8%	0%	8%	6%
P11	88%	84%	98%	98%	98%	80%	83%	93%
P12	96%	90%	100%	100%	100%	75%	75%	93%
P13	61%	67%	75%	58%	66%	40%	58%	61%
P14	79%	92%	100%	95%	98%	100%	92%	97%
P15	88%	74%	95%	93%	94%	90%	50%	88%
P16	94%	83%	98%	98%	98%	85%	83%	94%
P17	93%	91%	93%	90%	91%	45%	67%	80%
P18	89%	80%	90%	85%	88%	20%	67%	73%
P19	98%	89%	100%	98%	99%	70%	92%	93%
P20	94%	82%	95%	95%	95%	55%	92%	88%
P21	83%	53%	83%	75%	79%	15%	25%	62%
P22	67%	61%	78%	60%	69%	5%	17%	52%
P23	77%	70%	53%	38%	45%	0%	8%	33%
P24	89%	72%	98%	100%	99%	90%	92%	96%
P25	74%	70%	8%	3%	5%	0%	0%	4%
P26	81%	79%	25%	5%	15%	15%	25%	16%
P27	81%	72%	53%	40%	46%	55%	17%	45%
P29	69%	69%	5%	3%	4%	0%	0%	3%
P30	88%	74%	95%	90%	93%	100%	75%	92%
P33	90%	83%	98%	98%	98%	60%	67%	88%
P34	84%	83%	68%	70%	69%	10%	25%	54%
P35	96%	76%	100%	95%	98%	75%	58%	89%
P36	92%	67%	98%	93%	95%	10%	17%	71%
P37	94%	82%	93%	95%	94%	70%	83%	88%
P38	80%	68%	43%	25%	34%	0%	0%	24%
P39	79%	66%	80%	80%	80%	5%	25%	61%
P41	75%	70%	3%	3%	3%	0%	0%	2%
P42	71%	58%	18%	25%	21%	5%	0%	16%
P43	76%	74%	93%	83%	88%	40%	58%	76%
P44	70%	54%	5%	5%	5%	0%	0%	4%
P45	89%	97%	100%	93%	96%	100%	100%	97%
P46	89%	77%	95%	83%	89%	25%	25%	71%
P47	86%	83%	95%	95%	95%	45%	67%	83%
AVG	83%	76%	74%	69%	72%	40%	45%	63%
SD	10%	10%	33%	34%	33%	35%	33%	31%
Range	55-98%	53-97%	3-100%	3-100%	3-100%	0-100%	0-100%	2-97%

RQ 1 Correlation Results

Performance on the semantic and phonologic tasks was correlated with performance on the oral reading tasks in order to investigate the relationship between these abilities. Table 7 reports the Pearson correlation coefficients (*r*).

Table 7. Correlations between performance on non-orthographic language tasks and oral reading tasks

		Oral Reading				
		Regular Words	Irregular Words	Nonwords	Pseudo-homophones	Oral Reading Composite
Semantics	Picture Association	.45**	.45**	.28	.39*	.42**
	Word-to-picture match	.45**	.52**	.41**	.42**	.49**
	Synonym Judgment	.58**	.60**	.42**	.51**	.57**
	Comp. of Verbs & Adj.	.77**	.81**	.76**	.80**	.85**
	Semantic Composite	.67**	.71**	.56**	.63**	.70**
Phonology	Minimal pair discrimination	.65**	.60**	.38*	.51**	.58**
	RW rhyme judgment	.29	.30*	.39*	.49**	.40**
	NW rhyme judgment	.36*	.37*	.41**	.51**	.45**
	Phoneme manipulation	.35*	.38*	.53**	.59**	.50**
	Phonologic Composite	.55**	.55**	.57**	.71**	.65**

* $p < .05$, ** $p < .01$, (two-tailed).

Cohen (1988) suggested that an absolute value of *r* between 0.1-0.3 indicates a small correlation, 0.3-0.5 indicates a medium/moderate correlation, and above 0.5 indicates a large/strong correlation (Laerd Statistics, 2016). As seen in Table 7, the semantic composite was significantly correlated with all oral reading tasks. The strongest semantic composite relationship was with irregular words ($r = .71$, $p < .01$), then regular words ($r = .67$, $p < .01$), pseudohomophones ($r = .63$, $p < .01$), and the lowest correlation was with nonwords ($r = .56$, $p < .01$). This same relationship pattern (irregular > regular > pseudohomophone > nonword) was seen for all of the individual semantic tasks that made up the semantic composite. However, the semantic tasks varied in their level of correlation. Specifically, comprehension of verbs and adjectives showed the highest overall correlation with oral reading (*r* = 0.85, *p* < 0.01), followed by auditory synonym judgment (*r* = 0.57, *p* < 0.01), then spoken word-to-picture match (*r* = 0.49, *p* < 0.01), and finally picture category association (*r* = 0.42, *p* < 0.01).

Table 7 also shows that the phonology composite score was significantly correlated with all of the oral reading tasks. The strongest phonologic composite relationship was with pseudohomophone reading (*r* = .71, *p* < .01), followed by nonword reading (*r* = .57, *p* <.01), then regular and irregular word reading both showed the same smaller relationship (*r* =. 55, *p* < .01). This pattern of having the greatest relationship with pseudohomophones, followed by nonwords, and then real words (regular and irregular) was seen for three of the four phonologic tasks that comprised the phonology composite. Of these tasks, phoneme manipulation showed the greatest relationship with pseudohomophone and nonword reading (*r* =. 59, *p* < .01; *r* =. 53, *p* < .01, respectively).

RQ1 Regression Results

Table 8 below illustrates the results of five multiple linear regression (MLR) models with the semantic and phonologic composite z-scores entered simultaneously as the independent variables (i.e., predictors) and 1) total oral reading accuracy (all word types), 2) regular word accuracy, 3) irregular word accuracy, 4) pseudohomophone accuracy, and 5) nonword accuracy entered as the respective dependent or outcome variables. The predictors together accounted for a significant amount of the variance for total oral reading accuracy (R^2 = .57, *p* <.001), regular word accuracy (R^2 = .49, *p* <.001), irregular word accuracy (R^2 = .53, *p* <.001), pseudohomophone accuracy (R^2 = .57, *p* <.001), and nonword accuracy (R^2 = .40, *p* <.001).

When phonology was held constant, semantics was found to have a unique effect on all word types. Specifically, if semantic ability improves one standard deviation (SD) above average , there is an estimated mean increase of 0.54 SD on total reading ($p < .001$), 0.64 *SD* on regular words ($p < .001$), 0.71 *SD* on irregular words ($p < .001$), 0.38 *SD* on pseudohomophones ($p < .05$), and 0 .40 *SD* on nonwords ($p < .05$).

Holding performance on semantics constant, there is an estimated mean increase of 0.44 *SD* on total oral reading ($p <.05$), a 0.69 *SD* increase on pseudohomophone reading ($p < .001$), and a 0.50 *SD* increase on nonword reading ($p < .05$) for every 1 SD gain on phonology composite score. Phonology was not uniquely predictive of regular word reading (p=0.12) or irregular word reading (p=0.16).

Table 8. MLR results with semantics and phonology as predictors of oral reading

				Standard Regression			
	R^2_{total}	R^2_{Adj}	F_{total}	*b*	*(SE)*	*t*	*p* -value
Total Oral Reading	*.57*	*.54*	*26.07(2,40)****				
Semantics				0.54	(0.14)	3.70	0.00 **
Phonology				0.44	(0.16)	2.71	0.01 *
Regular Word Reading	*.49*	*.46*	*18.98(2,40)****				
Semantics				0.64	(0.17)	3.78	0.00 **
Phonology				0.31	(0.19)	1.60	0.12
Irregular Word Reading	*.53*	*.51*	*22.64(2,40)****				
Semantics				0.71	(0.16)	4.38	0.00 ***
Phonology				0.26	(0.18)	1.43	0.16
Pseudohomophone Reading	*.57*	*.55*	*26.28(2,40)****				
Semantics				0.38	(0.16)	2.26	0.02 *
Phonology				0.69	(0.18)	3.95	0.00 ***
Nonword Reading	*.40*	*.37*	*13.24(2,40)****				
Semantics				0.40	(0.18)	2.18	0.04 *
Phonology				0.50	(0.21)	2.40	0.02 *

** p < .05, ** p < .01, *** p < .001.*

The two figures below (Figures 10 and 11) illustrate the relationship between non-orthographic language performance and oral reading performance predicted by the regression models. On the x-axes, distribution of semantic or phonologic composite scores is represented by the average performance of the individuals that fell into different percentiles (<25th, 25th-50th,

50^{th}-75^{th}, and > 75^{th} percentile) for each language domain. Figure 10 illustrates that as semantic abilities improve, a greater improvement in real word reading (28% to 96% for regular words and 33% to 97% for irregular words) versus nonword reading (10% to 61%) is seen. The inverse is observed in Figure 11. As phonologic abilities improve, the greatest gains are made in pseudohomophone (18% to 83%) and nonword reading (13% to 76%) compared to lesser gains in regular word reading (58% to 98%) and irregular word reading (50% to 96%). Both figures show that improvement in reading all of the word types was seen as semantics and phonology improved. This improvement is supported by both semantics and phonology showing significant correlations with the overall reading composite (Table 7) and both being unique predictors of overall reading (Table 8).

Figure 10. Relationship between Semantics and Oral Reading

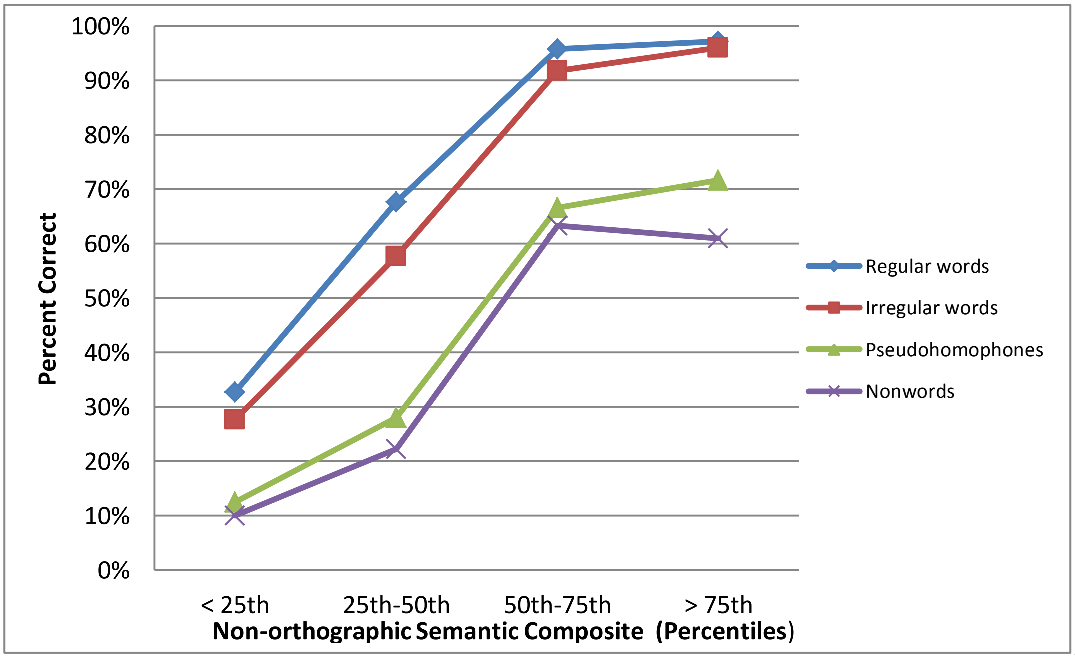


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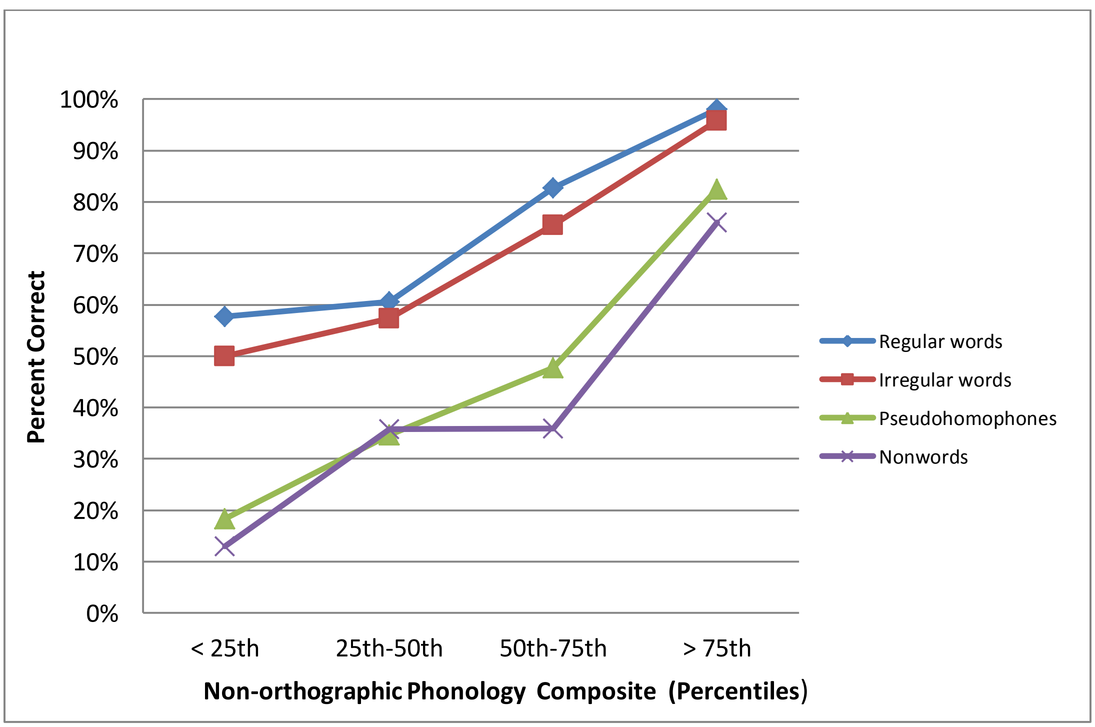
Figure 11. Relationship between Phonology and Oral Reading



Research Question 2

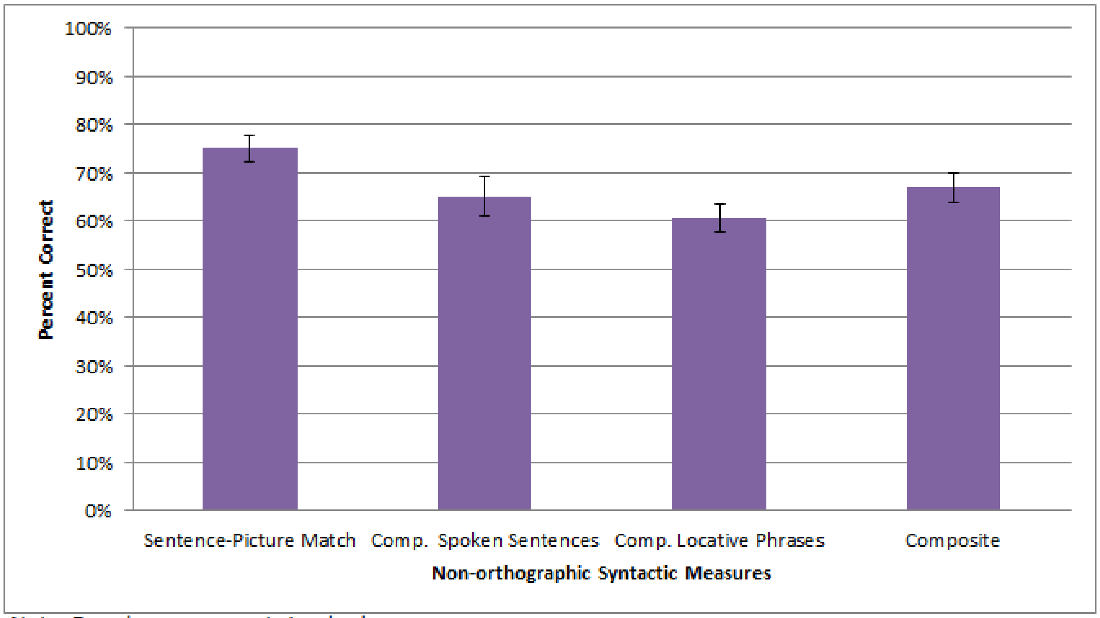
RQ2: To what extent does performance on non-orthographic semantic, phonologic, and syntactic measures predict silent reading comprehension performance at the single word, phrase/sentence, and paragraph levels in PWA?

First, descriptive statistics for the group (e.g., means, standard deviations, and ranges) will be reported for the non-orthographic syntactic tasks and silent reading comprehension tasks. Since group performance on the semantic and phonologic tasks was previously described, those results will be not repeated in this section. Correlation and regression results exploring the relationship between performance on the non-orthographic language tasks (i.e., semantics, phonology, and syntax) and silent reading comprehension tasks (i.e., single words, sentences, and paragraphs) will then be reported.

Descriptive Statistics

Non-orthographic syntactic tasks. The average performance on spoken sentence-to-picture match (PALPA 55; Kay et al., 1993) was 75% accurate (*SD* = 0.18; range = 43%-100%), comprehension of spoken sentences (CAT 9; Swinburn et al., 2004) was 65% accurate (*SD* = 0.18; range = 31%-94%), and comprehension of locative phrases (PALPA 58) was 61% accurate (*SD* = 0.27; range = 13%-100%). A percent correct syntax composite of 67% accuracy (SD = 0.19; range = 37%-97%) was obtained (See Figure 12).

Figure 12. Average % correct on the syntactic measures for 43 PWA



Note: Error bars represent standard error

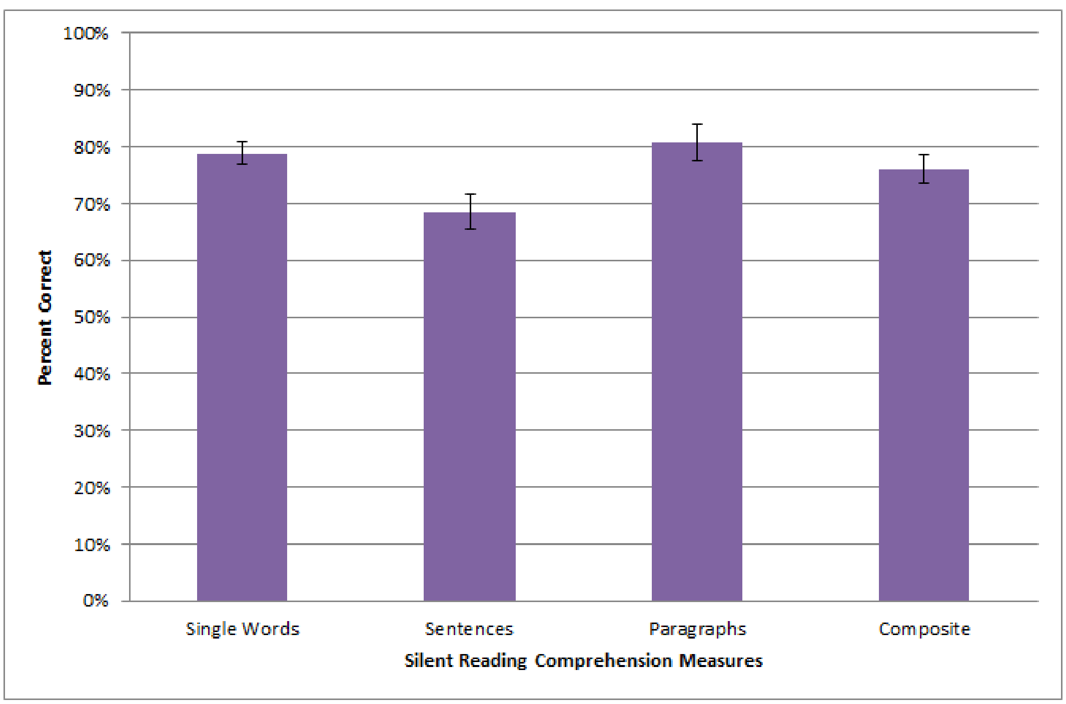
Silent Reading Comprehension: Single Words. Participants completed three reading comprehension tasks that assessed understanding of written words. On the written word-to-picture match task (CAT 8), average performance was 87% accurate (*SD* =.10; range =63%-100%), written synonym judgment (PALPA 50) was, on average, 84% accurate (*SD* =.13; range = 53%-100%), and average performance on written word semantic association (PALPA 51) was 67% accurate (*SD* =0.18; range =33%-90%). The single word reading comprehension group composite was 79% accuracy (*SD* =0.12; range =40%-95%) and is illustrated in Figure 13.

Silent Reading Comprehension: Sentences. Sentence-level reading comprehension was assessed by performance on three measures. Specifically, average performance on written sentence-to-picture match (CAT 10) was 66% accurate (SD = 0.19; range = 22%-100%), written comprehension of locative phrases (PALPA 59) was 60% accurate (SD = 0.30; range = 8%-100%), and functional sentence reading (RCBA 4) was 79% accurate (SD = 0.20; range = 40%-

100%). The sentence-level reading comprehension group composite was 68% accurate (SD = 0.20; range= 19%-100%), and is illustrated below in Figure 13.

Silent Reading Comprehension: Paragraphs. Comprehension of paragraphs was assessed by performance on the RCBA (LaPointe & Horner, 1984). On average, paragraph-to-picture match (RCBA 7) was 73% accurate (SD = 0.21; range = 30%-100%), factual paragraph understanding (RCBA 8) was 89% accurate (SD = 0.19; range = 10%-100%), and inference making (RCBA 9) was 80% accurate (SD = 0.27; range = 0%-100%). The paragraph-level group composite was 81% accurate (SD = 0.21; range = 13%-100%), and the overall silent reading comprehension composite (i.e., words, sentences, and paragraphs combined) was 76% accurate (SD = 0.17; range = 24%-96%). Average performance on silent reading comprehension measures is displayed in Figure 13.

Figure 13. Average % correct on the silent reading comprehension measures for 43 PWA



Note: Error bars represent standard error

As stated previously, the percent correct scores reported above were not used in the correlation and regression analyses; instead, semantic, phonologic, syntactic, and silent reading comprehension z-scores were used to allow for the tests to each contribute equally to the composite (Refer to “Scoring” and “Calculating Composite Scores” sections, pg. 55). Percent correct performance is reported to illustrate how well the participants performed on the tasks. Additionally, average z-scores for the group cannot be represented in a graph because this value will always be zero. In summary, Table 9 below shows individual and group performance on the semantic, phonologic, and syntactic composites, as well as the silent reading comprehension tasks.

Table 9. Individual and group performance on non-orthographic language and silent reading comprehension tasks

	Non-orthographic Language			**Silent Reading Comprehension**			
ID	*Semantic Composite*	*Phonologic Composite*	*Syntax Composite*	*Single Words*	*Sentences*	*Paragraphs*	*Composite*
P1	86%	75%	50%	85%	60%	93%	79%
P2	93%	75%	94%	86%	91%	90%	89%
P3	77%	78%	52%	71%	61%	83%	72%
P4	88%	91%	77%	85%	91%	100%	92%
P5	83%	80%	56%	89%	62%	83%	78%
P6	89%	81%	66%	82%	71%	87%	80%
P7	67%	62%	39%	69%	58%	67%	65%
P8	92%	89%	85%	82%	88%	80%	83%
P9	73%	71%	50%	66%	41%	50%	52%
P10	55%	66%	50%	59%	34%	47%	47%
P11	88%	84%	81%	84%	86%	93%	88%
P12	96%	90%	80%	84%	83%	97%	88%
P13	61%	67%	48%	72%	43%	57%	57%
P14	79%	92%	76%	66%	70%	93%	76%
P15	88%	74%	79%	88%	75%	87%	83%
P16	94%	83%	87%	95%	93%	100%	96%
P17	93%	91%	92%	92%	89%	97%	92%
P18	89%	80%	70%	88%	75%	83%	82%
P19	98%	89%	93%	93%	91%	100%	95%
P20	94%	82%	89%	87%	90%	97%	91%
P21	83%	53%	45%	77%	55%	77%	70%
P22	67%	61%	40%	71%	45%	90%	69%
P23	77%	70%	37%	87%	65%	80%	77%
P24	89%	72%	85%	82%	74%	93%	83%
P25	74%	70%	51%	81%	58%	73%	71%
P26	81%	79%	46%	81%	56%	90%	75%
P27	81%	72%	87%	80%	78%	93%	84%
P29	69%	69%	40%	54%	25%	30%	36%
P30	88%	74%	73%	88%	78%	97%	88%
P33	90%	83%	97%	89%	97%	97%	94%
P34	84%	83%	64%	79%	70%	90%	80%
P35	96%	76%	97%	94%	95%	97%	95%
P36	92%	67%	74%	82%	72%	80%	78%
P37	94%	82%	83%	91%	88%	100%	93%
P38	80%	68%	44%	79%	52%	73%	68%
P39	79%	66%	72%	78%	68%	70%	72%
P41	75%	70%	47%	40%	19%	13%	24%
P42	71%	58%	47%	58%	53%	53%	55%
P43	76%	74%	63%	74%	57%	57%	63%
P44	70%	54%	43%	52%	32%	53%	46%
P45	89%	97%	86%	81%	100%	100%	94%
P46	89%	77%	84%	86%	80%	97%	87%
P47	86%	83%	58%	84%	76%	83%	81%
AVG	83%	76%	67%	79%	69%	81%	76%
SD	10%	10%	19%	12%	20%	20%	17%
Range	55-98%	53-97%	37-97%	40-95%	19-100%	13-100%	24-96%

<u>RQ 2 Correlation Results</u>

Table 10 below shows the Pearson correlation coefficients (*r*) between non-orthographic language performance and silent reading comprehension at the single word, sentence, and paragraphs levels. The semantic composite was significantly correlated with all levels of reading comprehension. The strongest semantic composite relationship was with sentence-level comprehension ($r = .83$, $p < .01$), then single words ($r = .79$, $p < .01$), and paragraphs ($r = .72$, $p < .01$). Within the four tasks that made up the semantic composite there was no consistent pattern of having a stronger relationship with single words, sentences, or paragraphs. It is evident though that auditory synonym judgment and comprehension of verbs and adjectives show stronger relationships with overall reading comprehension ($r = .76$, $p < .01$, $r = .75$, $p < .01$, respectively) compared to picture association and word-to-picture match ($r = .64$, $p < .01$, $r = .57$, $p < .01$, respectively).

Table 10. Correlations between performance on non-orthographic language and silent reading comprehension tasks

		Silent Reading Comprehension			
		Single Words	Sentences	Paragraphs	Reading Comprehension Composite
Semantics	Picture Association	.66**	.58**	.60**	.64**
	Word-to-picture match	.55**	.61**	.49**	.57**
	Synonym Judgment	.78**	.75**	.66**	.76**
	Comp. of Verbs & Adj.	.64**	.83**	.67**	.75**
	Semantic Composite	.79**	.83**	.72**	.82**
Phonology	Minimal pair discrimination	.62**	.61**	.58**	.63**
	RW rhyme judgment	.36*	.42*	.37*	.40**
	NW rhyme judgment	.37*	.51**	.47**	.47**
	Phoneme manipulation	.30	.53**	.38*	.42**
	Phonologic Composite	.55**	.69**	.60**	.65**
Syntax	Sentence-to-picture match	.63**	.82**	.63**	.73**
	Comp. of Sentences	.52**	.70**	.49**	.60**
	Comp. of Locative Phrases	.66**	.81**	.65**	.74**
	Syntax Composite	.66**	.84**	.64**	.75**

* p < .05, ** p < .01 (two-tailed).

The syntactic composite was most strongly correlated with reading comprehension of sentences (*r* = .84, *p* < .01), and showed lower, yet still significant, correlational values with comprehension of words (*r* = .66, *p* < .01) and paragraphs (*r* = .64, *p* < .01). This same pattern of greater relation to sentences over words and paragraphs was seen in all three tasks that made up the syntactic composite. Comprehension of locative phrases was the syntactic task with the highest correlation with overall reading comprehension(*r* = .74, *p* < .01), followed closely by sentence-to-picture match (*r* = .73, *p* < .01).

The phonologic composite was significantly correlated with all levels of reading comprehension, although to a lesser extent than semantics and syntax. The strongest phonologic composite relationship was with sentence-level comprehension (*r* = .69, *p* < .01), then paragraphs (*r* = .60, *p* < .01), and single words (*r* = .55, *p* < .01). This pattern of having the greatest relationship with sentences, followed by paragraphs, and then single word comprehension was seen with three of the four phonologic tasks that comprised the phonology composite. Concerning the relationship with overall silent reading comprehension (i.e. all levels combined), minimal pair discrimination showed the strongest correlation *(r* =. 63, *p* < .01), followed somewhat distantly by nonword rhyme judgment *(r* =. 47, *p* < .01), phoneme manipulation *(r* = .42, *p* < .01), and real word rhyme judgment *(r* =. 40, *p* < .01).

<u>RQ 2 Regression Results</u>

Table 11 illustrates results of four multiple linear regression (MLR) models with the semantic, phonologic, and syntactic composite z-scores entered simultaneously as the independent variables (i.e., predictors) and 1) overall silent reading comprehension, 2) single word comprehension, 3) sentence-level comprehension, and 4) paragraph comprehension entered as the dependent or outcome variables. The predictors together accounted for a significant amount of the variance for overall reading comprehension (i.e., all reading levels combined) (R^2 = .72, p <.001), single word reading comprehension (R^2 = .63, p <.001), sentence-level reading comprehension (R^2 = .81, p <.001), and paragraph-level reading comprehension (R^2 = .57, p <.001).

Semantics had a unique effect on all reading comprehension levels. Specifically, there is an estimated mean increase of 0.71 standard deviations (*SD)* on written word comprehension (p < .001), 0.39 *SD* increase on written sentence comprehension (p < .01), and 0.54 *SD* increase on written paragraph comprehension (p < .001) for individuals who were one standard deviation higher than average on the semantic composite.

Phonology was shown to be uniquely predictive of sentence-level reading comprehension (p < .05). Specifically, if phonologic ability is 1 SD higher than average, there is an estimated mean increase of 0.23 SD on written sentence comprehension. Phonology was not uniquely predictive of overall reading comprehension (p =.10), single word comprehension (p = .41), or paragraph comprehension (p=.09).

Finally, syntax was also uniquely predictive of sentence-level comprehension (p <.01) with an estimated increase of 0.41 SD for individuals who are 1 SD higher than average on the syntactic composite. Syntax was not uniquely predictive of overall reading comprehension (p =.15), single word comprehension (p = .66), or paragraph comprehension (p=.57).

Table 11. MLR results with semantics, phonology, and syntax as predictors of silent reading comprehension

	R^2_{total}	R^2_{Adj}	F_{total}	Standard Regression *b*	*(SE)*	*t*	*p*-value
Total Reading Comprehension	*.72*	*.70*	*33.03(3,39)****				
Semantics				0.55	(0.14)	3.85	0.00 ***
Phonology				0.22	(0.13)	1.69	0.10
Syntax				0.19	(0.13)	1.46	0.15
Single Words	*.63*	*.60*	*21.98(3,39)****				
Semantics				0.71	(0.17)	4.14	0.00 ***
Phonology				0.13	(0.15)	0.89	0.41
Syntax				0.07	(0.16)	0.45	0.66
Sentence Level	*.81*	*.79*	*54.25(3,39)****				
Semantics				0.39	(0.12)	3.20	0.003 **
Phonology				0.23	(0.11)	2.11	0.04 *
Syntax				0.41	(0.11)	3.65	0.00 **
Paragraph Level	*.57*	*.54*	*17.16(3,39)**				
Semantics				0.54	(0.19)	2.89	0.006 **
Phonology				0.30	(0.17)	1.72	0.09
Syntax				0.10	(0.17)	0.56	0.57

** $p < .05$, ** $p < .01$, *** $p < .001$ (two-tailed).*

The three figures below (Figures 14, 15, and 16) illustrate the relationship between performance on the non-orthographic language tasks and performance on the silent reading comprehension predicted by the regression models. On the x-axes, the distribution of semantic, phonologic, or syntactic composite scores is represented by the average performance of the individuals who fell into different percentiles (<25th, 25th-50th, 50th-75th, and > 75th percentile) for each language domain. Figure 14 illustrates that as semantic abilities improve, improvement at all reading levels (word, sentence, and paragraph) is seen, and these gains are greater than the gains seen as a result of improved phonology (Figure 15) or syntax (Figure 16). As phonologic abilities improve, the greatest gain (38%) is made in sentence-level reading with accuracy improving from 51% accurate in the <25th percentile readers to 89% accurate in the >75th percentile readers (Figure 15). Figure 16 shows that as syntax improves, the greatest gain (45%) is also seen in sentence-level reading comprehension with sentence-level reading accuracy improving from 46% accurate in the <25th percentile readers to 91% accurate in the >75th percentile readers. All three figures below show improvement in reading comprehension at all reading levels. This is supported by all three of the non-orthographic language composite scores being significantly correlated with overall reading comprehension (Table 10).

Figure 14. Relationship between Semantics and Silent Reading Comprehension

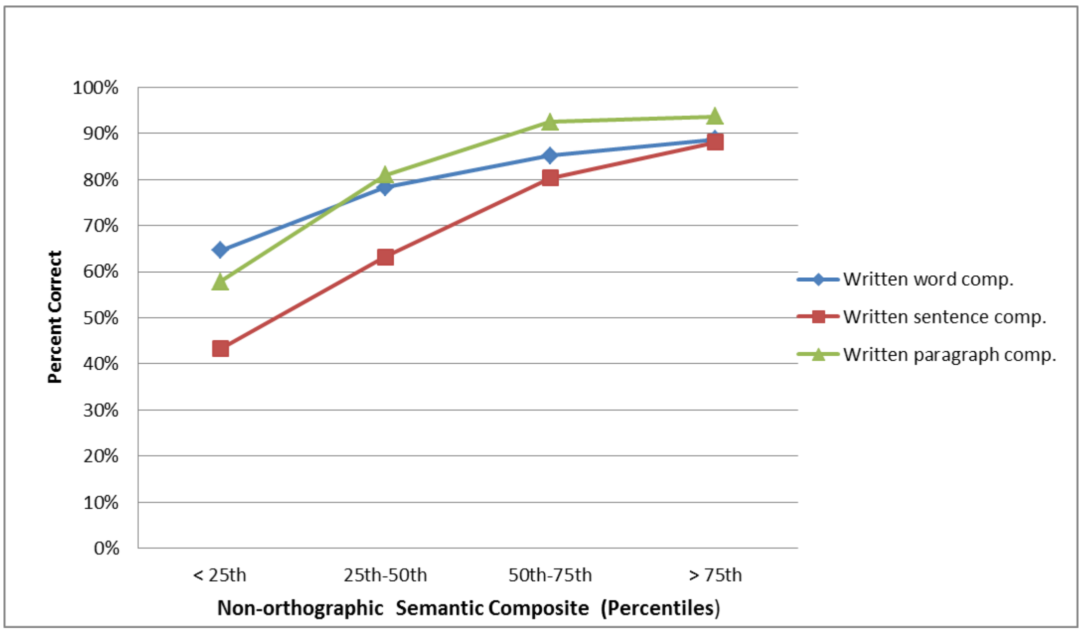


Figure 15. Relationship between Phonology and Silent Reading Comprehension

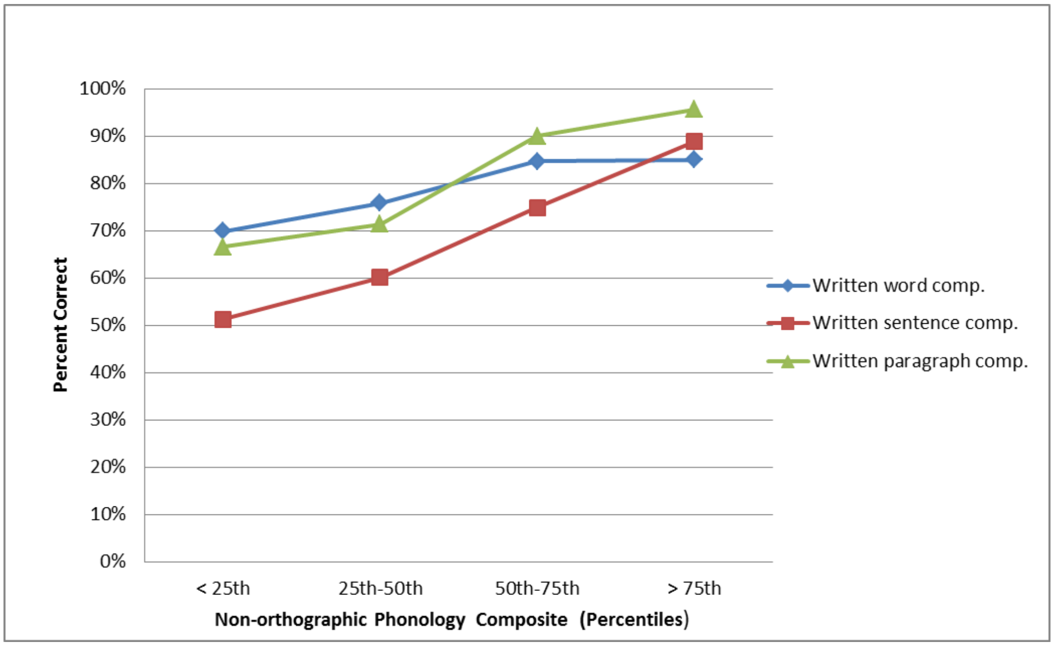
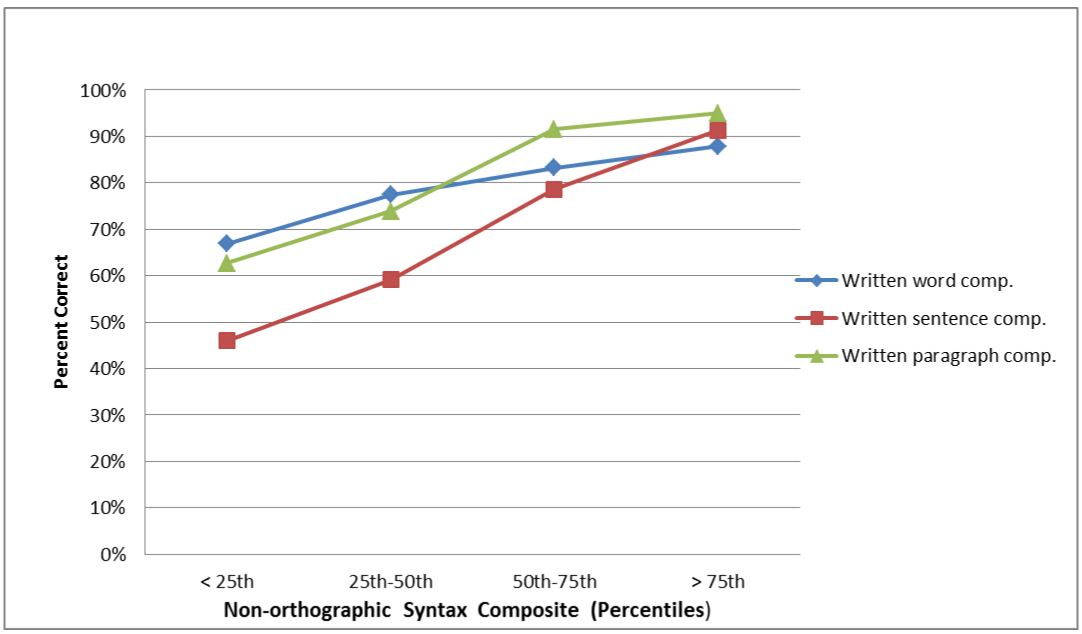


Figure 16. Relationship between Syntax and Silent Reading Comprehension



Research Question 3

RQ3: What is the relationship between degree of non-orthographic semantic and phonologic impairment and alexia type in PWA?

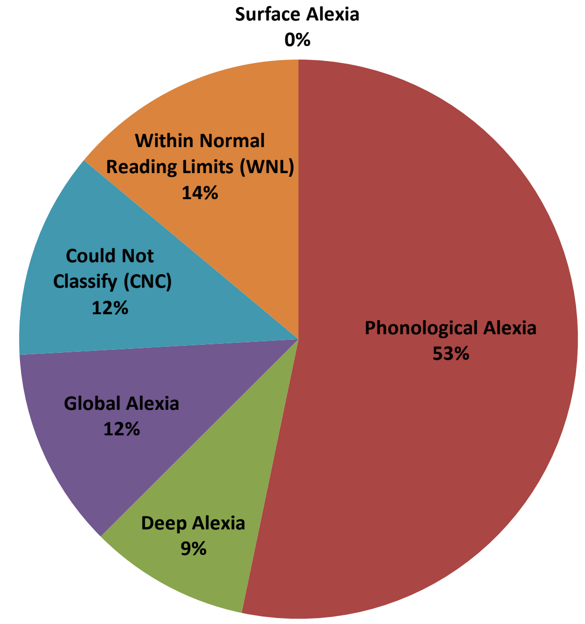
First, reading profiles based on each participant's oral reading accuracy and types of oral reading errors produced will be reported. Then, results of correlations between performance on the non-orthographic semantic and phonologic measures and hallmark alexia symptoms (i.e., regularity effect, lexicality effect, frequency effect, and proportion of regularization errors, visual/phonologic errors, lexicalization errors, semantic , omission, and unrelated reading errors) will be described. Finally, scatterplots illustrating the relationship between type of alexia and degree of underlying semantic and phonologic impairment will be presented, as well as results of post-hoc ANOVA and *t*-test analyses that were conducted to determine the statistical significance of these relationships.

Distribution and Description of Alexia Profiles

Following the methods previously described in "Calculating Alexia Subtypes" (pg. 57), each participant was classified as having surface alexia, phonological alexia, deep alexia, global alexia, or reading within normal limits (WNL). Thirty-seven of the 43 (86%) participants were identified to have alexia. No participants met the surface alexia criteria. P26 was the only participant to demonstrate the surface alexia characteristic of better regular word than irregular word reading evidenced by non-overlapping regular and irregular word reading ranges (i.e., 95% CIs). However, he demonstrated poor nonword reading, and moreover his errors were predominantly visual-phonologic in nature and not regularizations error. Therefore, he was not identified to have surface alexia. Twenty-three participants (53%) met the phonological alexia classification evidenced by a large lexicality effect (i.e., non-overlapping RW and NW reading ranges) and visual-phonologic errors as the predominant reading error type. Four participants (9%) were classified with deep alexia due to the reading profile of poor RW reading, severely poor NW reading, and the presence of semantic errors. Five participants (12%) were classified with global alexia due to extremely poor RW and NW reading evidenced by overall reading ability ranging between 2%-7% accurate. Six participants (14%) performed within 2 SD of the normal controls on all of the oral reading tasks and were classified as reading within normal limits (WNL).

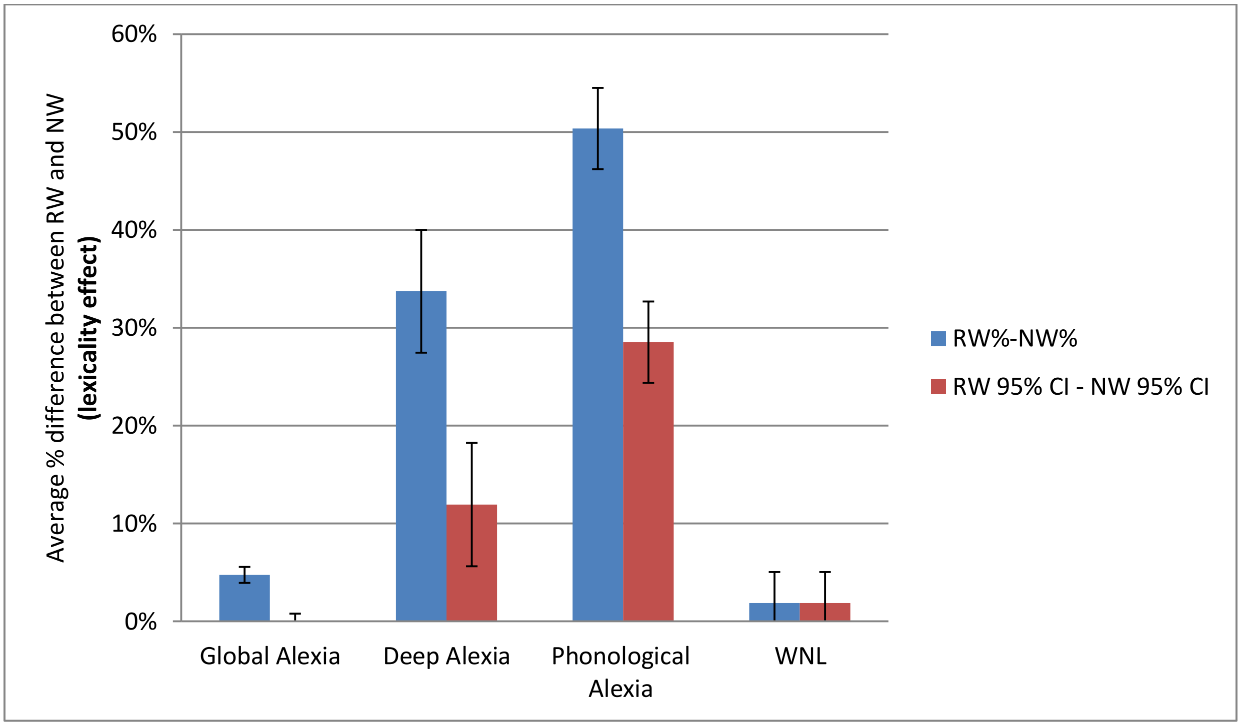
Five participants (12%) demonstrated an alexia that could not be classified (CNC) according to the study criteria. Three of these participants, P6, P8, and P11, could not be classified because they demonstrated relatively intact reading of both real words and nonwords (i.e., overlapping RW and NW 95% CIs); however despite their overall mild reading impairment they still performed more than 2 SD below the normal controls. P26 showed the reverse reading profile and demonstrated impaired reading of both real words and nonwords; however he did not make semantic errors so consequently he did not meet the deep alexia criteria. P27 demonstrated a unique reading profile that resulted in the CNC classification. His real word and nonword reading accuracies were similar (46% and 55%, respectively) and he therefore lacked a large lexicality effect which ruled out the phonological alexia classification, and his mediocre nonword reading and lack of semantic errors precluded him from a deep alexia profile. Figure 17 shows the percentage of each reading profile in this sample of 43 PWA.

Figure 17. Percentage of Each Reading Profiles in 43 PWA



The average size of the lexicality effect for each reading group is presented in Figure 18. This figure illustrates two different lexicality effect calculations. The blue bars show the difference between percent correct real word reading and percent correct nonword reading (RW%-NW %). The red bars show the difference between the low end of the RW 95% CI and the high end of the NW 95% CI. This second, more conservative calculation was used in this study to indicate if there was a significant difference between RW and NW reading ability for each PWA. Regardless of which calculation was used, on average small lexicality effects were seen for individuals in the WNL group (*M* = 2% and 2%, *SD* = 7.8%) and global alexia group (M = 5% and 0%, SD = 1.9%), and larger lexicality effects were seen for the individuals in the deep alexia (M = 34% and 12%, SD = 6.3%) and phonological alexia (M = 50% and 29%, SD = 4.2%) groups.

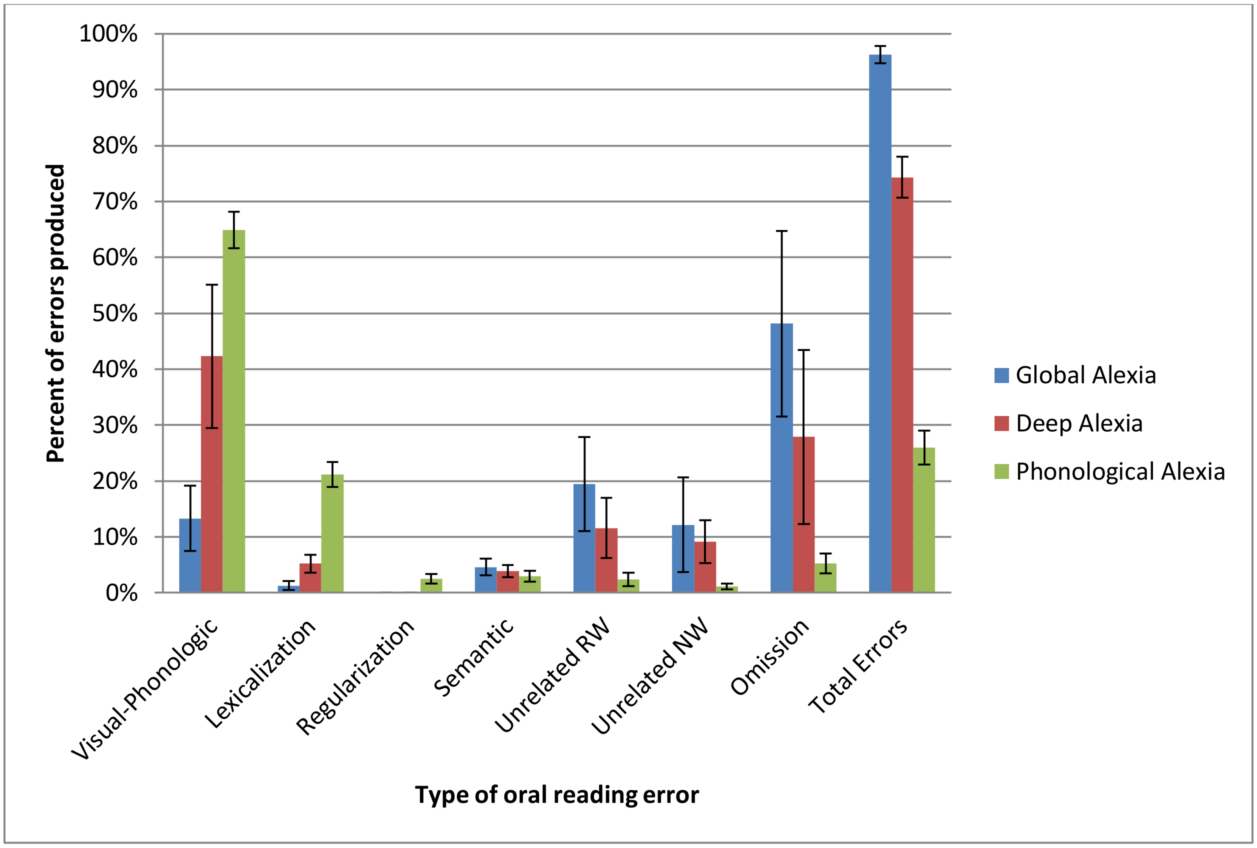
Figure 18. Size of lexicality effect per alexia subtype



Note: RW = real word reading accuracy; NW = nonword reading accuracy; error bars represent standard error

Oral reading errors were produced by all PWA, even those who read within normal limits. Figure 19 illustrates the type and frequency of reading errors made in the phonological, deep, and global alexia groups. Few errors (*M* = 6.5 total errors; *SD* = 3.9) were made by individuals with normal oral reading ability, therefore, the WNL group is not represented in this figure. Individuals with global alexia produced the most oral reading errors with an average of 95.36% (SD = 3.5%) of responses being incorrect, and omission errors accounting for nearly half (*M* = 48.15%, *SD* = 37.12%) of those incorrect responses. Unrelated real word errors were also prevalent in the global alexia group (*M* = 19.50%, *SD* = 18.80%). Visual-phonologic errors were the most common errors made by individuals with phonological alexia (*M* = 64.88%, *SD* = 15.59%) and deep alexia (*M* = 42.29%, *SD* = 25.71%). After visual-phonologic errors, omission errors (*M* = 27.90%, *SD* = 31.17%) were the second most frequent error made by individuals with deep alexia. For all three alexia subtypes, semantic errors and regularization errors were relatively uncommon.

Figure 19. Percent of oral reading errors per alexia subtype



Note: Error bars represent standard error of the mean

In sum, Table 12 reports the RW and NW reading accuracy ranges (95% CIs), proportion of oral reading error types, and the alexia classification for each participant.

Table 12. Individual oral reading accuracy, proportion of reading errors, and alexia classification

	Oral Reading Accuracy				**Frequency of Oral Reading Errors**																
	RW		*NW*		*Total Errors*		*Semantic*		*Visual-Phonological*		*Lexicalized*		*Regularized*		*Omissions*		*Unrelated RW*		*Unrelated NW*		
ID	*95% CI*		*95% CI*		*#*	*prop.*	*#*	*prop.*	*#*	*prop.*	*#*	*prop.*	*#*	*prop.*	*#*	*prop.*	*#*	*prop.*	*#*	*prop.*	**Reading Profile**
P1	99% -	86%	25% -	0%	30	0.27	0	0.00	17	0.57	11	0.37	1	0.03	1	0.03	0	0.00	0	0.00	Phonological
P2	100% -	94%	60% -	30%	16	0.14	0	0.00	10	0.63	6	0.38	0	0.00	0	0.00	0	0.00	0	0.00	Phonological
P3	89% -	76%	20% -	10%	43	0.38	2	0.05	21	0.49	7	0.16	0	0.00	10	0.23	0	0.00	3	0.07	Phonological
P4	100% -	89%	80% -	50%	14	0.13	0	0.00	12	0.86	1	0.07	1	0.07	0	0.00	0	0.00	0	0.00	Phonological
P5	62% -	49%	15% -	0%	66	0.59	0	0.00	34	0.52	8	0.12	1	0.02	13	0.20	8	0.12	2	0.03	Phonological
P6	98% -	85%	90% -	60%	18	0.16	1	0.06	12	0.67	2	0.11	1	0.06	2	0.11	0	0.00	0	0.00	CNC
P7	89% -	76%	65% -	35%	31	0.28	1	0.03	25	0.81	4	0.13	1	0.03	0	0.00	0	0.00	0	0.00	Phonological
P8	100% -	91%	95% -	65%	7	0.06	0	0.00	4	0.57	2	0.29	1	0.14	0	0.00	0	0.00	0	0.00	CNC
P9	47% -	34%	15% -	0%	79	0.71	2	0.03	12	0.15	3	0.04	0	0.00	56	0.71	2	0.03	4	0.05	Deep
P10	14% -	0%	15% -	0%	105	0.94	2	0.02	38	0.36	12	0.11	0	0.00	1	0.01	46	0.44	6	0.06	Global
P11	100% -	91%	95% -	65%	8	0.07	0	0.00	7	0.88	1	0.13	0	0.00	0	0.00	0	0.00	0	0.00	CNC
P12	100% -	94%	90% -	60%	8	0.07	0	0.00	3	0.38	3	0.38	1	0.13	1	0.13	0	0.00	0	0.00	Phonological
P13	73% -	60%	55% -	25%	44	0.39	1	0.02	36	0.82	3	0.07	3	0.07	1	0.02	0	0.00	0	0.00	Phonological
P14	100% -	91%	100% -	85%	3	0.03	0	0.00	3	1.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	WNL
P15	100% -	87%	100%-	75%	13	0.12	0	0.00	12	0.92	0	0.00	1	0.08	0	0.00	0	0.00	0	0.00	WNL
P16	100% -	91%	100%-	70%	7	0.06	0	0.00	6	0.86	0	0.00	1	0.14	0	0.00	0	0.00	0	0.00	WNL
P17	98% -	85%	60% -	30%	22	0.20	0	0.00	20	0.91	2	0.09	0	0.00	0	0.00	0	0.00	0	0.00	Phonological
P18	94% -	81%	35% -	5%	30	0.27	0	0.00	18	0.60	10	0.33	0	0.00	2	0.07	0	0.00	0	0.00	Phonological
P19	100% -	92%	85% -	55%	8	0.07	0	0.00	6	0.75	1	0.13	1	0.13	0	0.00	0	0.00	0	0.00	Phonological
P20	100% -	89%	70% -	40%	14	0.13	0	0.00	9	0.64	5	0.36	0	0.00	0	0.00	0	0.00	0	0.00	Phonological
P21	86% -	72%	30% -	0%	43	0.38	2	0.05	27	0.63	9	0.21	0	0.00	1	0.02	0	0.00	4	0.09	Phonological
P22	75% -	62%	20% -	0%	54	0.48	2	0.04	23	0.43	11	0.20	0	0.00	11	0.20	7	0.13	0	0.00	Phonological
P23	52% -	39%	15% -	0%	75	0.67	2	0.03	45	0.60	1	0.01	0	0.00	6	0.08	7	0.09	14	0.19	Deep
P24	100% -	92%	100% -	75%	4	0.04	0	0.00	3	0.75	1	0.25	0	0.00	0	0.00	0	0.00	0	0.00	WNL
P25	12% -	0%	15% -	0%	107	0.96	6	0.06	7	0.07	0	0.00	0	0.00	28	0.26	17	0.16	49	0.46	Global
P26	22% -	9%	30% -	0%	94	0.84	0	0.00	79	0.84	4	0.04	3	0.03	1	0.01	0	0.00	7	0.07	CNC

P27	53% -	40%	70% -	40%	62	0.55	1	0.02	49	0.79	2	0.03	3	0.05	1	0.02	1	0.02	5	0.08	CNC
P29	10% -	0%	15% -	0%	109	0.97	11	0.10	13	0.12	9	0.08	0	0.00	48	0.44	25	0.23	3	0.03	Global
P30	99% -	86%	100% -	85%	9	0.08	0	0.00	5	0.56	0	0.00	3	0.33	1	0.11	0	0.00	0	0.00	WNL
P33	100% -	91%	75% -	45%	14	0.13	0	0.00	10	0.71	4	0.29	0	0.00	0	0.00	0	0.00	0	0.00	Phonological
P34	75% -	62%	25% -	0%	52	0.46	9	0.17	21	0.40	7	0.13	0	0.00	3	0.06	12	0.23	0	0.00	Phonological
P35	100% -	91%	90% -	60%	12	0.11	0	0.00	10	0.83	1	0.08	1	0.08	0	0.00	0	0.00	0	0.00	Phonological
P36	100% -	89%	25% -	0%	32	0.29	0	0.00	21	0.66	10	0.31	0	0.00	0	0.00	0	0.00	1	0.03	Phonological
P37	100% -	87%	85% -	55%	13	0.12	2	0.15	8	0.62	3	0.23	0	0.00	0	0.00	0	0.00	0	0.00	Phonological
P38	40% -	27%	15% -	0%	85	0.76	6	0.07	22	0.26	7	0.08	0	0.00	26	0.31	23	0.27	1	0.01	Deep
P39	87% -	74%	20% -	0%	44	0.39	2	0.05	20	0.45	8	0.18	0	0.00	11	0.25	1	0.02	2	0.05	Phonological
P41	9% -	0%	15% -	0%	110	0.98	2	0.02	6	0.05	0	0.00	0	0.00	101	0.92	0	0.00	1	0.01	Global
P42	28% -	15%	20% -	0%	94	0.84	3	0.03	64	0.68	7	0.07	0	0.00	2	0.02	7	0.07	11	0.12	Deep
P43	94% -	81%	55% -	25%	27	0.24	2	0.07	19	0.70	5	0.19	0	0.00	0	0.00	1	0.04	0	0.00	Phonological
P44	12% -	0%	15% -	0%	108	0.96	4	0.04	7	0.06	0	0.00	0	0.00	84	0.78	7	0.06	6	0.06	Global
P45	100% -	90%	100% -	85%	3	0.03	1	0.33	2	0.67	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	WNL
P46	96% -	82%	40% -	10%	33	0.29	0	0.00	28	0.85	4	0.12	1	0.03	0	0.00	0	0.00	0	0.00	Phonological
P47	100% -	89%	60% -	30%	19	0.17	1	0.05	13	0.68	5	0.26	0	0.00	0	0.00	0	0.00	0	0.00	Phonological
AVG	68% -	55%	49% -	18%	41.14	0.37	1.51	0.03	18.77	0.60	4.16	0.14	0.56	0.03	9.56	0.12	3.81	0.04	2.77	0.03	
SD	0.33 -	0.33	0.35 -	0.35	35.19	0.31	2.42	0.06	16.51	0.25	3.65	0.12	0.91	0.06	22.26	0.22	8.92	0.09	7.86	0.08	

Note: RW = real word; NW = nonword; # = raw number of errors; Prop.= proportion of errors; Lexicalization errors only occur with nonword stimuli; Regularization errors only occur with irregular word stimuli; CNC = could not classify; WNL = within normal reading limits

RQ 3 Correlation Results

In order to understand the relationship between non-orthographic semantic and phonologic abilities and alexia in this sample of PWA, z-score performance on the semantic and phonologic tasks was correlated with several hallmark alexia symptoms (i.e., regularity, lexicality, and frequency reading effects and proportion of regularization, lexicalization, semantic, visual-phonologic, omission, and unrelated reading errors) (See Table 13). As previously mentioned, Cohen (1988) suggested that a Pearson correlation coefficient (*r*) with an absolute value between 0.1-0.3 indicates a small correlation, 0.3-0.5 indicates a medium/moderate correlation, and above 0.5 indicates a large/strong correlation (Laerd Statistics, 2016).

With regard to the alexia reading effects, the semantic composite showed small-medium significant associations with the regularity and frequency effects. As performance on semantics improved the regularity and frequency effects both decreased (r = -.30, p <.05; r = -.31, p <.05, respectively). No significant association was seen with the lexicality effect. With regard to alexia error types, the semantic composite showed moderate-large significant associations with regularization, lexicalization, visual-phonologic, omissions, and unrelated real word errors. As semantic abilities increased, the frequency of regularization (r = .32, p <.05), lexicalization (r = .37, p <.05), and visual-phonologic errors (r = .41, p <.01) also increased, while the frequency of omissions (r = -.39, p <.01), and unrelated real word errors (r = -.55, p <.01) decreased. No significant associations were seen with semantic or unrelated nonword errors.

The phonology composite was not significantly associated with any of the alexia reading effects (i.e., regularity, lexicality or frequency effects). With regard to reading error types, the phonologic composite showed moderate, significant correlations with visual-phonologic, omission, and unrelated real word errors. Specifically, as phonology increased so did frequency of visual-phonologic errors (*r* = .39, $p < .01$), while frequency of omissions and unrelated real word errors decreased (*r* = -.39, $p < .01$; (*r* = -.31, $p < .05$, respectively). Only two of the phonologic tasks, minimal pairs and phoneme manipulation, significantly contributed to these associations. The other phonologic tasks, RW and NW rhyme judgment, were not significantly related. Moreover, no phonologic tasks were significantly associated with regularization errors, semantic errors, or unrelated nonword errors.

Table 13. Correlations between performance on non-orthographic semantic and phonologic tasks and alexia symptoms

		Alexia Symptoms									
		Regularity Effect	Lexicality Effect	Frequency Effect	Regularized Errors	Lexicalized Errors	Visual-Phonological Errors	Semantic Errors	Omission Errors	Unrelated RW Errors	Unrelated NW Errors
Semantics	Picture Association	-.07	.19	-0.31*	.35*	.29	.20	-0.08	-0.25	-.44**	-0.1
	Word-to-picture match	-0.40**	.07	-.39*	.20	.23	.31*	-0.06	-0.27	-.40**	-0.22
	Synonym Judgment	-.20	.18	-.23	.29	.39**	.25	-0.08	-.32*	-.37*	-0.27
	Comp. Verbs & Adj.	-0.35*	-.01	-.12	.21	.33*	.59**	-0.07	-.48**	-.64**	-.42**
	Semantic Composite	-0.30*	.13	-.31*	.32*	.37*	.41**	-0.08	-.39**	-.55**	-0.3
Phonology	Minimal pair discrimination	.14	.28	-.03	.14	.36*	.34*	0.07	-.48**	-0.14	-0.3
	RW rhyme judgment	-.13	-.14	-.01	.09	.01	.24	0.04	-0.14	-0.23	-0.21
	NW rhyme judgment	-.12	-.09	.03	.20	.10	.28	0.09	-0.27	-.34*	-0.1
	Phoneme manipulation	-.20	-.25	-.45**	.17	-.04	.31*	0.21	-0.26	-0.2	-0.27
	Phonologic Composite	-.11	-.07	-.15	.20	.14	.39**	0.13	-.39*	-.31*	-0.3

Regularity effect = Regular word accuracy - Irregular word accuracy; Lexicality effect = Real word accuracy - Nonword accuracy; Frequency effect = High frequency words - Low frequency words; RW = real word; NW = nonword

* $p < .05$, ** $p < .01$ (two-tailed).

RQ 3 Visual Analysis (Scatterplots)

In order to further understand the possible link between non-orthographic semantic and phonologic abilities and alexia subtypes, scatterplots (Figures 20 and 21) were created to visually analyze these relationships.

Figure 20 shows performance on the phonologic tasks (phonologic composite) on the x-axis and performance on the semantic tasks (semantic composite) on the y-axis. Each participant's position on the graph is labeled according to his/her alexia profile. Overlap among the reading groups is present; however, a pattern emerges that shows the less impaired readers (i.e., WNL and phonological alexia) tend to perform better than the more impaired readers (i.e., deep and global alexia) on both the semantic and phonologic tasks.

Specifically, on average the WNL group has the most intact semantics and phonology with 88% accuracy on semantics (*SD* = 5%; range =79%-94%) and 82% accuracy on phonology (*SD* = 11%; range =72%-97%). The average semantic performance for those with phonological alexia is 85% accurate (*SD* = 10%; range =61%-96%) and the average phonology performance is 77% accurate (*SD* = 10%; range =53%-91%). Participants with deep alexia demonstrate poorer semantic and phonologic abilities with average scores of 75% accuracy (*SD* = 4%; range =71%-80%) and 67% accuracy (*SD* = 6%; range =58%-71%), respectively. Finally, the individuals with global alexia have the poorest semantic and phonologic performance with average scores of 68% accuracy (*SD* = 8%; range =55%-75%) and 66% accuracy (*SD* = 7%; range =54%-70%), respectively.

Figure 20. Relationship between Alexia, Semantics, and Phonology (% correct)

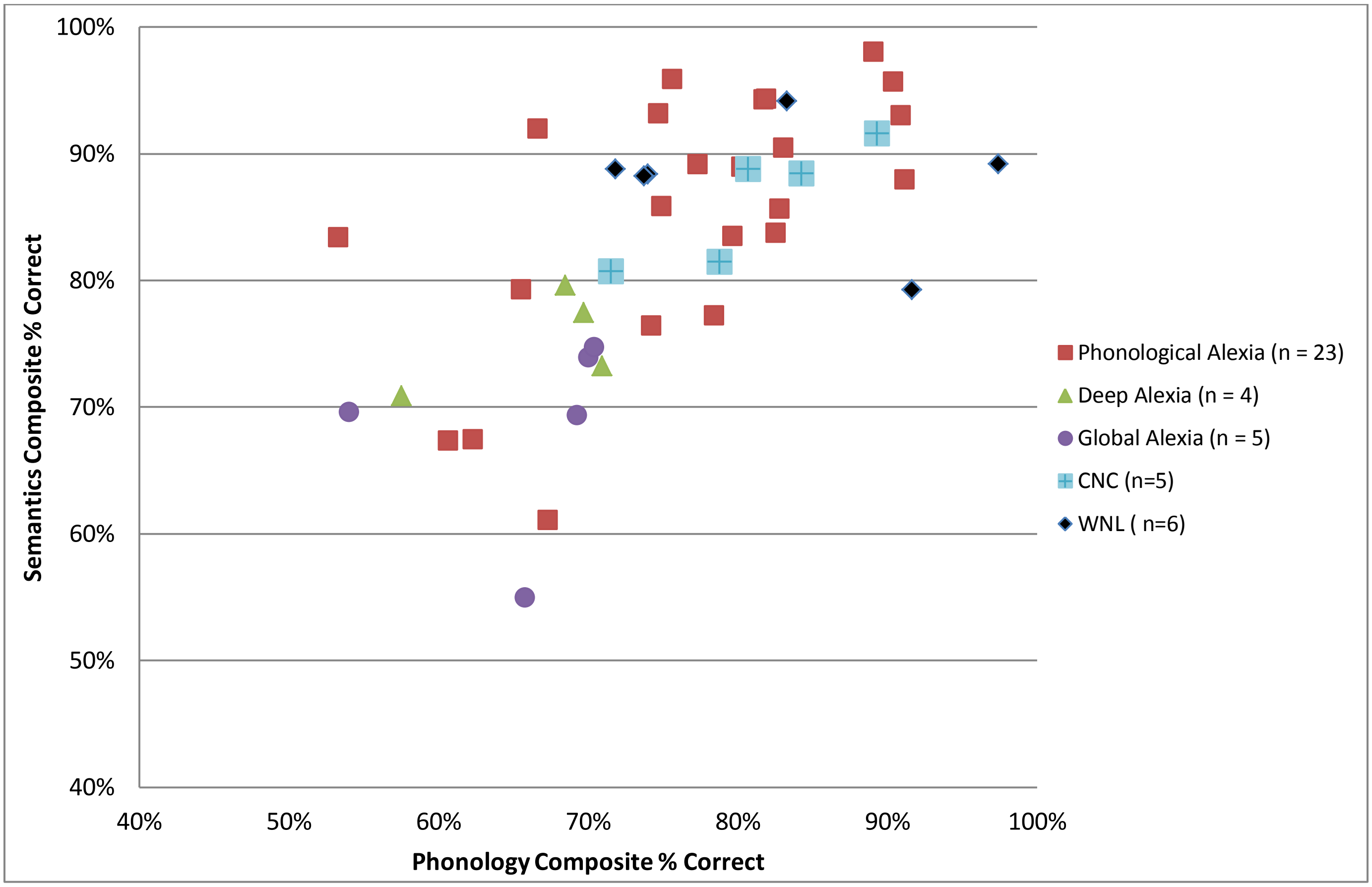


Figure 21 shows the same x- and y-axes as Figure 20, except performance is shown in z-scores instead of % correct. A z-score of "0" indicates the participant performed at the group mean. A z-score of +1 indicates the participant performed 1 SD above the group mean, and likewise a z-score of -1 indicates the participant performed 1 SD below the group mean. These data show the less impaired readers tend to perform above the group average on both non-orthographic language tasks, and the more impaired readers all perform below the group average. Specifically, the average phonologic z-score for those with deep alexia is -0.57 (*SD* = 0.56; range = -0.06- -1.37) and the average semantic z-score is -0.61 (*SD* = 0.36; range = -0.18 - -0.99). Those with global alexia demonstrate lower performance with an average phonologic z-score of -0.75 (*SD* = 0.48; range = -0.36- -1.56) and average semantic z-score of -1.17 (*SD* = 0.68; range =

-0.66- -2.34). The WNL group performed above average on phonology (average z-score = 0.35; SD = 0.79; range = 1.14- -0.31) and semantics (average z-score = 0.39; SD = 0.42; range = 0.92 - -0.37). The phonological alexia group showed the most diverse performance; however the average phonologic z-score was .11 (*SD* = 0.74; range = 0.96- -1.78) and the average semantic z-score was .20 (*SD* = 0.83; range = 1.03- -1.88). The percent correct and z-score data reported above are summarized in Table 14.

Figure 21. Relationship between Alexia, Semantics, and Phonology (Z-scores)

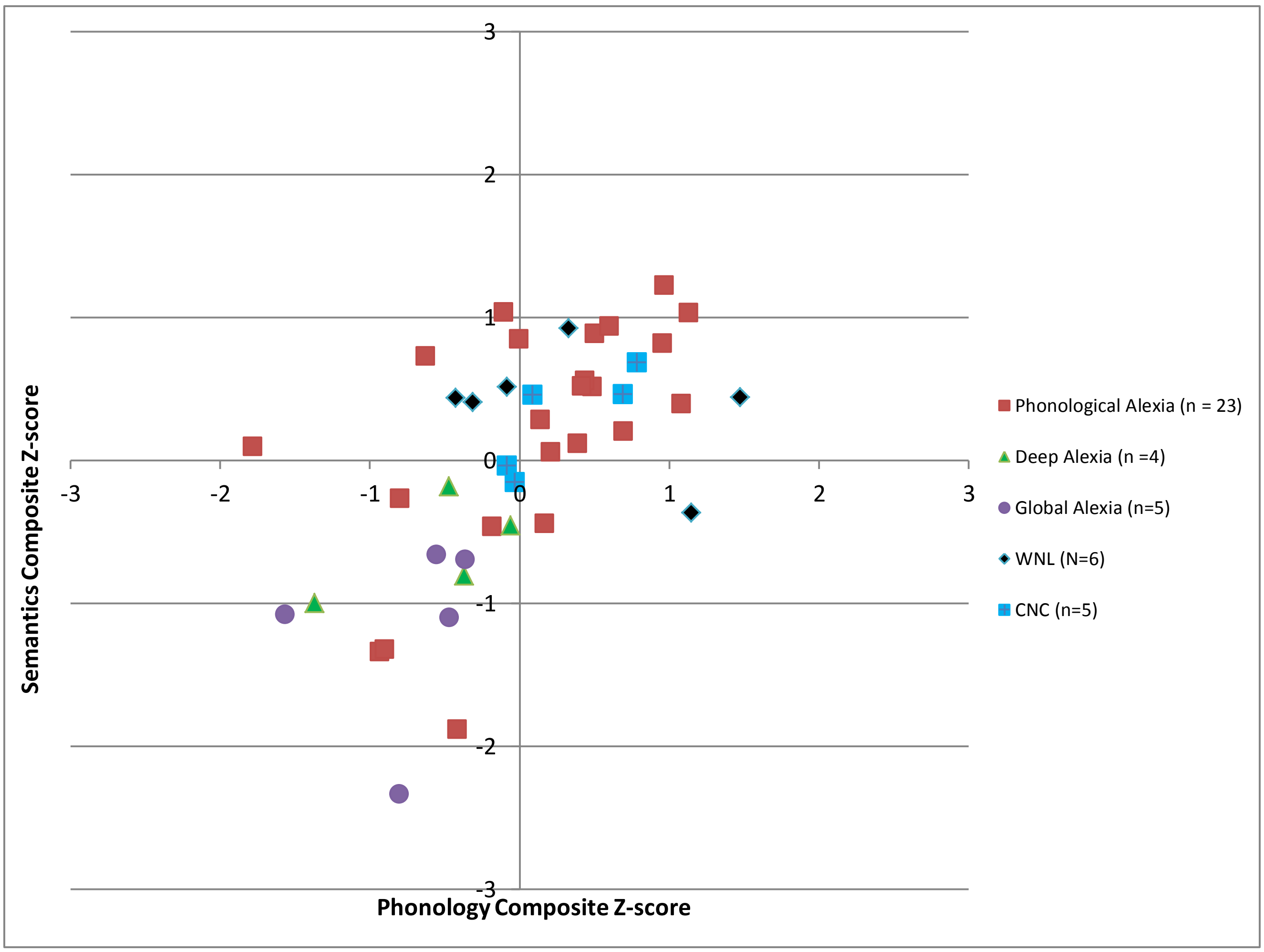


Table 14. Performance on semantics and phonology per reading profile

Reading Profile	***Avg. Semantic Composite***		***Avg. Phonologic Composite***	
	%	z-score	%	z-score
WNL	88% (5%)	0.39 (0.42)	82% (11%)	0.35 (0.79)
Phonological Alexia	85% (10%)	0.2 (0.83)	77% (11%)	0.11 (0.74)
Deep Alexia	75% (3%)	-0.61 (0.36)	67% (6%)	-0.57 (0.56)
Global Alexia	68% (8%)	-1.17 (0.68)	66% (7%)	-0.75 (0.48)

SD shown in parenthesis; WNL = within normal reading limits

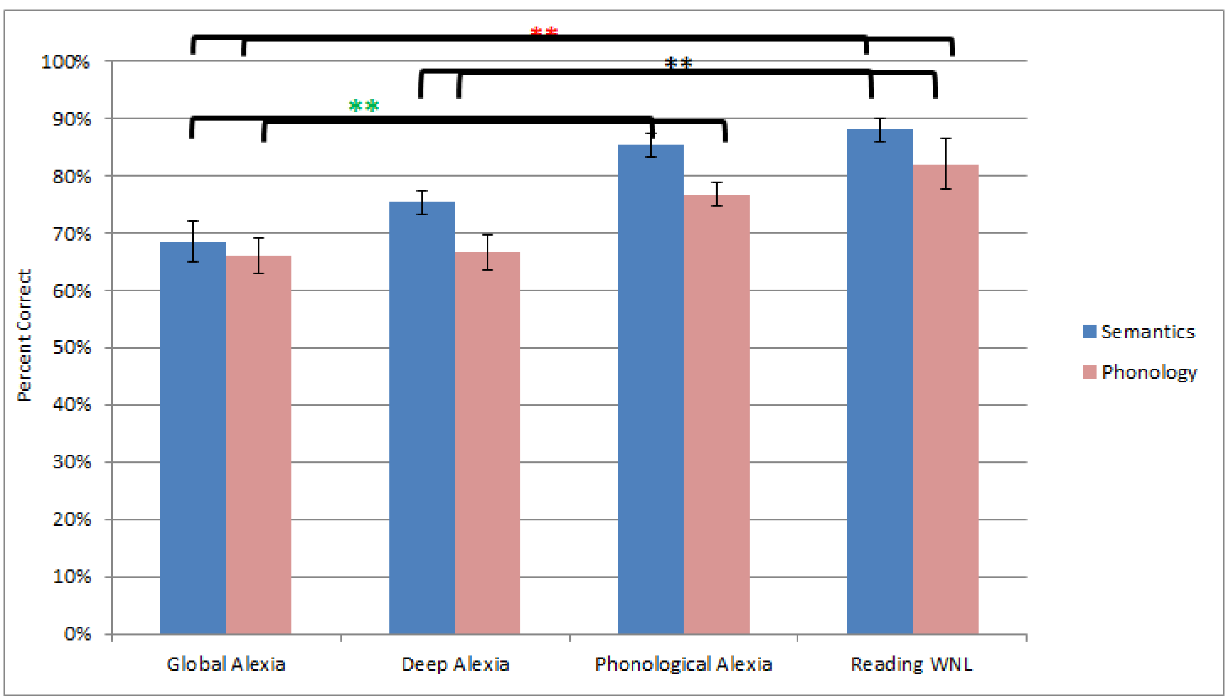
<u>Post hoc Analysis 1</u>

The scatterplots and descriptive data reported above show differences in semantics and phonology exist between, as well as within, the different reading groups. Those data do not reveal if these differences are statistically significant, however. Although not originally listed in the study proposal, post hoc ANOVA and t-test analyses were conducted in order to determine if differences in semantic and phonologic performance among the reading groups (i.e., WNL, phonological, deep, and global alexia) were statistically significant.

Between-group comparisons. A one-way ANOVA revealed semantic performance was statistically significantly different between the reading groups (F (3, 34) = 6.78, $p < .01$, η^2 = 0.37). Planned follow-up t-test comparisons showed that the WNL group demonstrated significantly better semantics compared to the deep alexia group (t (8) =4.36, p =.002) and global alexia group (t (9) = 5.02, p =.001). The phonological alexia group demonstrated significantly better semantics than the global alexia group (t (26) = 3.53, p =.002). The difference between semantic abilities among the phonological and deep alexia groups approached significance (t (25) = 1.97, p =.061). There were no significant semantic differences between the WNL and phonological alexia groups and no significant semantic differences between the deep and global alexia groups (See Figure 22).

A subsequent one-way ANOVA showed phonologic performance was also statistically significantly different between the reading groups (F (3, 34) = 3.78, p =.02, η^2 = 0.23). Planned follow up t-test comparisons revealed that the WNL group demonstrated significantly better phonology compared to the deep alexia group (t (8) = 2.57, p =.03) and global alexia group (t (9) = 2.89, p =.02). The phonological alexia group demonstrated significantly better phonology than the global alexia group (t (26) = 2.25, p =.03). The difference between phonological abilities among the phonological and deep alexia groups approached significance (t (25) = 1.90, p =.069). There were no significant phonological differences between the WNL and phonological alexia groups and no significant phonological differences between the deep and global alexia groups (See Figure 22).

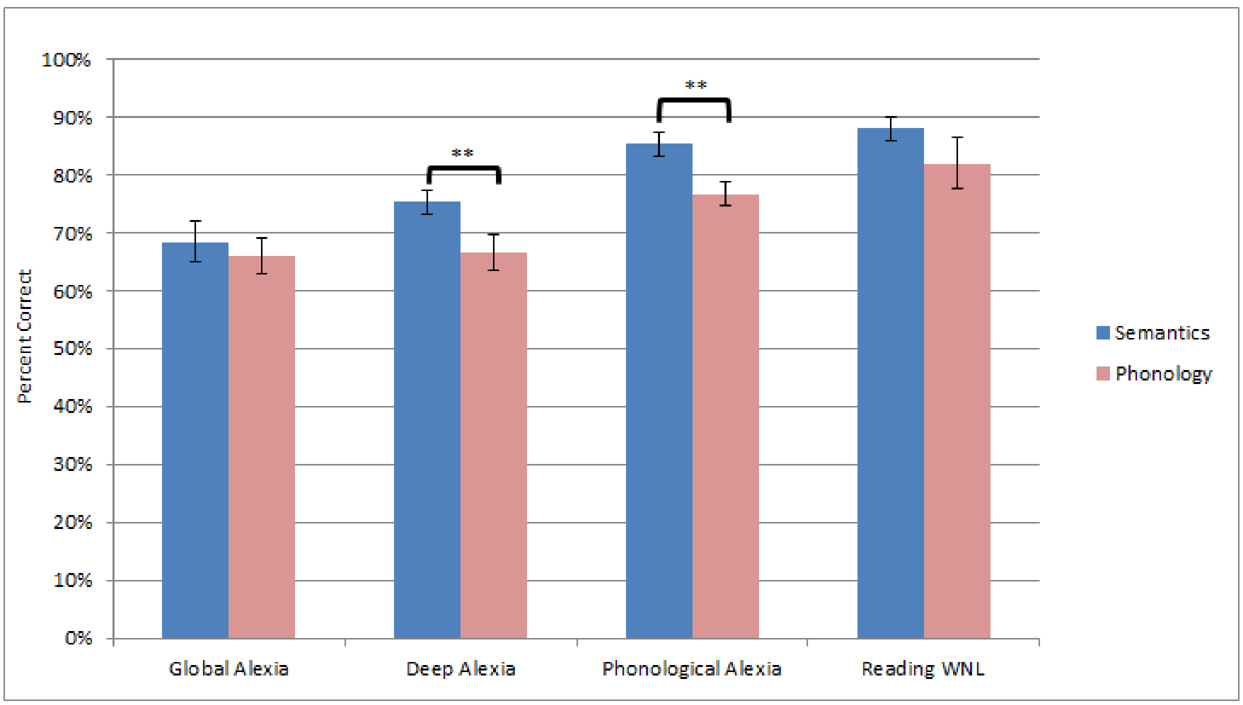
Figure 22. Between –group differences in semantic and phonologic performance



** = difference between WNL and global; ** = difference between WNL and deep; ** = difference between phonological and global; error bars represent standard error

Within-group comparisons. Paired t-tests were conducted to determine if semantic and phonologic abilities were significantly different within each reading group. For the WNL and global alexia groups, no significant within-group differences in semantic and phonologic performance were found (t (5) = 1.14, p =.30; t (4) = .61, p = .58, respectively). Within both the phonological alexia and deep alexia groups, semantic abilities were found to be significantly superior to phonologic abilities (t (22) =4.66, p = <.001; t (3) = 3.57, p =.04, respectively) (See Figure 23).

Figure 23. Within –group differences in semantic and phonologic performance

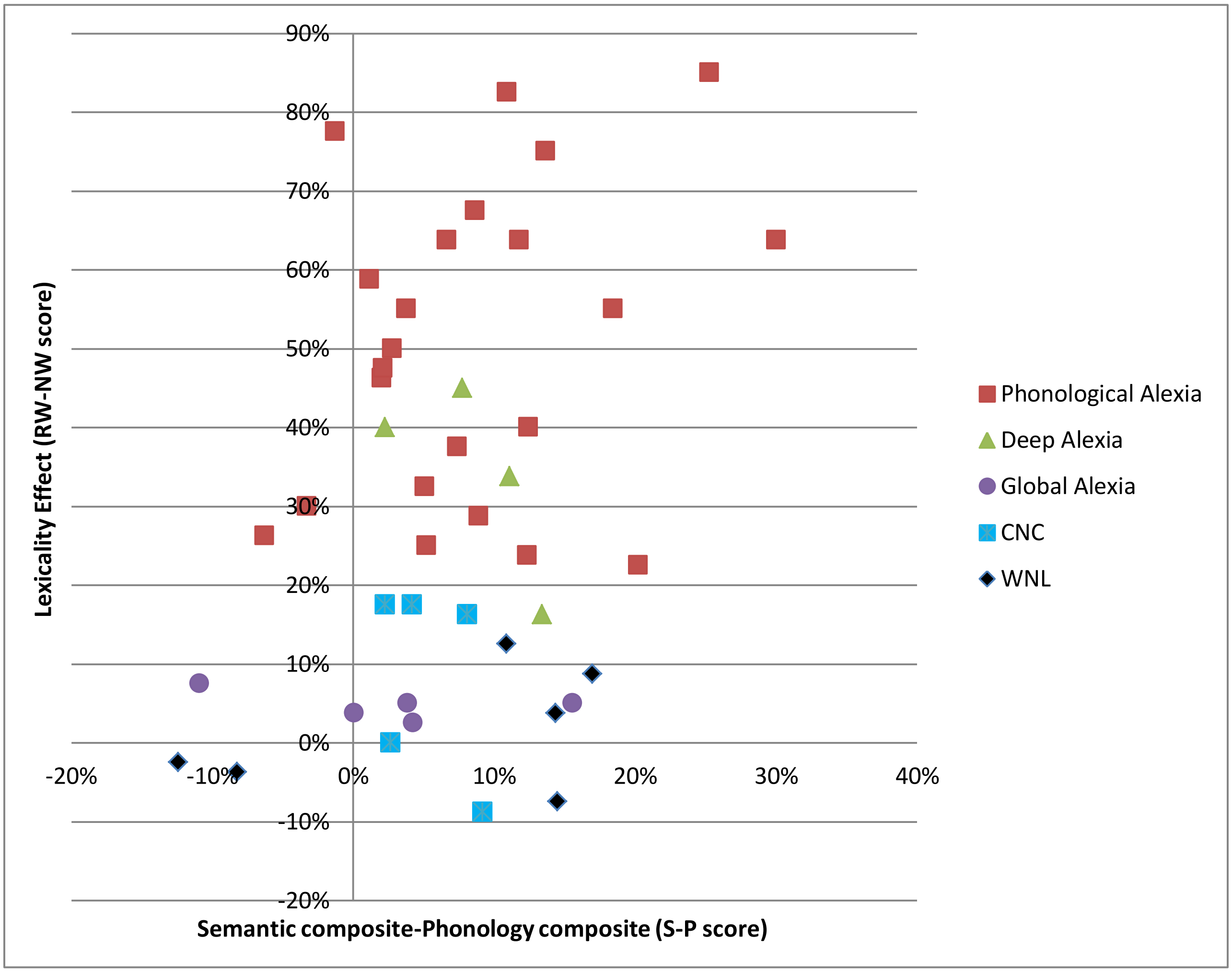


** = statistically significant within-group difference; error bars represent standard error

Post hoc Analysis 2

During visual analysis of the data, the author noticed that individuals with the largest discrepancy between semantic and phonologic abilities (S-P score) appeared to also have the largest discrepancy between real word and nonword reading ability (RW-NW score). A post hoc analysis was conducted to explore this observation and determine if larger S-P differences were related to larger lexicality effects (RW-NW scores). Specifically, a scatter plot was created to illustrate each participant's S-P and RW-NW scores (See Figure 24). Then, a simple linear regression was run to determine if S-P score was predictive of RW-NW score.

Figure 24. Relationship between S-P difference and size of lexicality effect



In figure 24, the key feature of phonological-deep alexia, the lexicality effect (RW-NW score), is shown on the y-axis and the difference in semantic and phonologic abilities (S-P score) is shown on the x-axis. These data illustrate that as the difference between semantic and phonologic abilities increases, an individual's lexicality effect tends to increase as well. This effect is seen more so in individuals with phonological alexia who by definition have the largest lexicality effects. The reading profiles associated with no or smaller lexicality effects (i.e., global and deep alexia, WNL, and CNC) show smaller discrepancies between semantic and phonologic performance. A simple linear regression model with S-P score predicting RW-NW score was found to approach statistical significance ($p = .06$). Thus, the discrepancy between semantic and phonologic abilities appears to have a trending positive relationship with the size of an individual's lexicality effect.

Chapter 4: Discussion

The primary systems hypothesis (PSH) proposes written language developed from and relies on the same linguistic representations and processing mechanisms that support spoken language. Therefore, all language abilities, both written (i.e., orthographic) and spoken (i.e., non-orthographic) are claimed to be supported by the same underlying, interconnected primary brain systems. Thus, the PSH postulates alexias (i.e., pure, surface, phonological, deep) are not reading-specific disorders, as traditionally viewed (Coltheart et al., 2001), but instead stem from varying degrees of impairment in primary semantic, phonologic, and visual systems (Patterson & Lambon Ralph, 1999; Woollam, 2014).

Motivated by the PSH, this study investigated how non-orthographic semantic, phonologic, and syntactic abilities inform reading performance in individuals with chronic, stroke-induced aphasia. Specifically, the current work 1) examined the relationship between non-orthographic language abilities and oral reading abilities, 2) investigated the relationship between non-orthographic language abilities and silent reading comprehension abilities, and 3) explored the relationship between alexia subtypes and corresponding degree of non-orthographic semantic and phonologic impairment. Non-orthographic language abilities were found to be statistically significantly related to oral reading and silent reading comprehension abilities, as well as alexia subtype, in a diverse sample of 43 PWA. These results will be expanded upon and interpreted individually (per RQ) before a general discussion of the overall study. Then, clinical implications, study limitations, and future directions will be addressed.

RQ 1: Semantics, Phonology, and Oral Reading

Research Question 1 aimed to understand the relationship between non-orthographic semantic and phonologic performance and the ability to read aloud regular words, irregular words, pseudohomophones, and nonwords in individuals with chronic aphasia.

Interpretation of overall performance. A wide range in performance on the semantic, phonologic, and oral reading tasks was observed. This finding is not surprising given the heterogeneous nature of the study sample. Despite variation in performance, no ceiling or floor effects occurred, which was one of the intended goals behind administering multiple measures within each language domain.

With regard to the four semantic tasks, average group performance was highest for word-to-picture match (93%), followed by auditory synonym judgment (82%), comprehension of verbs & adjectives (79%), and picture association (78%). It is likely the word-to-picture task was easiest because participants were able to benefit from simultaneous visual and auditory input, whereas the other three tasks had only one of these sensory supports.

With regard to performance on the phonologic tasks, minimal pair discrimination (92%) and phoneme in isolation identification (92%) were the most accurate followed by NW rhyme judgment (80%), RW rhyme judgment (79%), and lastly phoneme in syllable identification (37%). The phoneme in syllable identification task was the only task that required participants to parse sounds apart, albeit silent parsing due to the non-verbal nature of the task. This phoneme parsing task was inherently more demanding of verbal working and short-term memory than the other phonologic tasks, and this added complexity was likely responsible for the exaggerated lower performance. This finding agrees with work by Crisp and Lambon Ralph (2006), which also showed PWA performed more poorly on tasks involving phoneme manipulation compared to other phonological processing tasks, such as rhyme judgment.

When comparing phonologic to semantic abilities, on average the participants performed worse on the phonologic tasks (group composite score of 76%) than the semantic tasks (group composite score of 83%). This finding aligns with the common understanding that phonology is typically impaired in aphasia (Martin et al., 2006; Meier, Lo, & Kiran, 2016). Additionally, phonologic performance may have been lower than semantic performance because the phonologic tasks were comprised almost exclusively of nonword stimuli that contained novel phoneme sequences. These contrived tasks were, therefore, unfamiliar and taxed verbal short-term memory and the ability to access phonological words forms more so than the semantic tasks.

With regard to oral reading performance, overall accuracy was widely variable with individual performance ranging from 2%-97% accurate. This large range indicates that the full spectrum of reading abilities was represented in this sample (and will be discussed in detail later). Average reading performance was highest for regularly spelled words (74%), then irregularly spelled words (69%), pseudohomophones (45%), and nonwords (40%). This same word effect (regular > irregular > pseudohomophones > nonwords) has been documented in other work (Brookshire et al., 2014a) and reflects the PDP notion that statistically atypical orthographic items are more difficult to process (Ueno et al., 2014).

Interpretation of RQ 1 Correlation Analyses. Pearson correlation coefficients were calculated to determine the amount and strength of association between non-orthographic semantic and phonologic performance and oral reading performance (Refer to Table 7, pg.74). The semantic composite was highly related to oral reading evidenced by large and significant correlational values with the overall oral reading composite, as well as with each word type (i.e., regular, irregular, pseudohomophone, and nonword). Among the four tasks that comprised the semantic composite, comprehension of verbs & adjectives and auditory synonym judgment showed large correlations, whereas the word-to-picture match and picture association tasks showed only small to medium correlations. These results indicate that picture-based semantic tasks that primarily tap semantic-conceptual knowledge are not closely related to oral reading ability. This finding matches that of Crisp and Lambon Ralph (2006) who also found performance on auditory synonym judgment was highly correlated with oral reading while no significant correlations were found between oral reading and picture association tasks.

All four semantic tasks showed the largest correlation with irregular words, followed by regular words, pseudohomophones, and then nonwords. These results mostly align with the study predictions. It was expected that semantics would correlate the most with real word reading, particularly irregular words, given PDP theory proposes semantic knowledge acts as a mediating factor for words that have less consistent orthographic-phonologic connections (Ueno et al., 2014). It was also anticipated semantics would significantly correlate, although to a lesser extent, with pseudohomophone reading since the phonology of these words directly corresponds to semantic knowledge. It was unexpected, however, to find semantics significantly correlated with nonword reading, especially since the Crisp and Lambon Ralph (2006) study reported no significant relationship between these two variables in their sample of 12 PWA. Although unforeseen, this finding upholds the PDP assumption that connections between orthography and semantics cannot be selectively turned off in a parallel-distributed connectionist network, and therefore, nonwords will consequently engage semantic units to some extent (Welbourne & Lambon Ralph, 2007). Moreover, work with neurologically healthy individuals has demonstrated reading of nonwords is directly influenced by real word knowledge. These empirical findings further support the existence of an interconnected language system that involves simultaneous activation of phonology and semantics for all types of orthographic input, including nonwords (Glushko, 1979; Kay & Marcel, 1981; Rosson, 1983).

Similar to the semantic composite score, the composite phonology score also showed significant, positive correlations with the overall oral reading composite, as well as with each word type. However, the order of association was a near inverse of the semantic correlations. The largest phonology correlation was with pseudohomophones, followed by nonwords, and then regular and irregular words. Nonwords were hypothesized to have the largest correlation with phonology; however, it is likely the phonologic tasks were more highly correlated with pseudohomophone reading than nonword reading because the phonology of pseudohomophones is more familiar and stable (Patterson & Marcel, 1992) than the unfamiliar phonologic patterns of nonwords that require the language system to form and settle on new patterns of activation.

Of the phonologic tasks, the phoneme manipulation task showed the strongest correlations with pseudohomophone and nonword reading. This result supports work that has shown individuals with poor phonological processing, especially poor parsing/blending skills, also tend to have poor nonword reading abilities (Crisp & Lambon Ralph, 2006; Rapcsak et al., 2009). Overall, the phonologic correlational findings agree with the primary systems hypothesis and empirical work that proposes phonologic abilities play a key role in oral reading in aphasia (Crisp & Lambon Ralph, 2006; Patterson & Marcel, 1992; Rapcsak et al., 2009).

Interpretation of RQ 1 Regression Analyses. The correlation analyses discussed above measured the amount of linear association between two variables (i.e., semantics and oral reading; phonology and oral reading). The regression analyses conducted in this study also identified the association between these variables, and furthermore predicted the value of the dependent variables (i.e., regular, irregular, pseudohomophone, and nonword oral reading performance) given values for the independent variables (i.e., non-orthographic semantic and phonologic composite scores).

As expected, semantics and phonology together accounted for a significant amount of the variance in all five oral reading regression models (i.e., regular, irregular, pseudohomophone, nonword, and total oral reading models) (Refer to Table 8, pg. 76). This finding is similar to that of Henry et al. (2012) who showed semantics and phonology collectively accounted for a significant amount of the variance in oral reading and spelling in individuals with primary progressive aphasia. In the current work, when each predictor's individual contribution to the models was analyzed, it was found each predictor had unique effects. Specifically, improved semantic abilities predicted positive change in all word types, with the greatest estimated change for irregular reading, and conversely, enhanced phonologic abilities predicted significant change in pseudohomophone and nonword reading only.

It was anticipated, however, that phonology would significantly predict regular word reading, in addition to nonword and pseudohomophone reading. It has been proposed that individuals with phonological alexia rely heavily on meaning when reading due to impaired phonology (Woollams, 2014). Given that half of the participants presented with phonological alexia, it is possible many individuals in this study relied more on orthographic-semantic connections to process regularly spelled words and not as much on orthographic-phonologic connections. In other words, letter-sound translation may have been avoided and instead familiar words could have been directly associated with meaning. Similar to other visual items (i.e., +), written words can directly activate semantics (Harm & Seidenberg, 2004), although this connection is more arbitrary compared to the more systematic relationship between letters and sounds.

Additionally, since all of the phonologic tasks involved non-verbal responses, it is also possible that phonology was not significantly predictive of real word reading due to this task effect. Said another way, perhaps a phonologic composite comprised of performance on expressive phonologic tasks (e.g., participant says aloud the first or last phoneme in the target word) would have been more predictive of real word oral reading than the exclusively receptive phonologic composite utilized in this study. Some work has shown that only expressive phonologic tasks are predictive of oral reading (Woollam & Patterson, 2012), and moreover, studies that utilized receptive phonologic tasks also incorporated expressive phonologic tasks so the phonologic composite was a mixture of input and output phonologic performance (Crisp & Lambon Ralph, 2006; Henry et al., 2012, Jefferies et al., 2007; Rapcsak et al., 2009). Expressive phonologic tasks engage the same articulatory motor representations and speech motor planning and programming processes that are employed during oral reading, and this may explain why expressive, rather than receptive, phonologic tasks have more often been shown to be significantly related to oral reading.

Compared to the phonologic regression results, the semantic regression results were more in line with the study predictions and the PSH/PDP framework. It was hypothesized that semantics would be most predictive of real word reading, especially irregular word reading. The data match these predictions and support the PDP division of labor between semantics and phonology. In particular, the regression results showing semantics predict the greatest change in irregular words endorses the idea that semantics provide extra support when the processing between orthography and phonology is slow and laborious due to the statistical irregularities of the target word (Ueno et al., 2014). The expectation that semantics would be predictive of pseudohomophone reading was also confirmed. This may be explained by semantic knowledge helping to bind phonological elements (Woollams et al., 2014) and boost weak orthographic-phonologic connections (Crisp et al., 2011; Jefferies et al., 2007) which would be especially critical and useful when reading pseudohomophones.

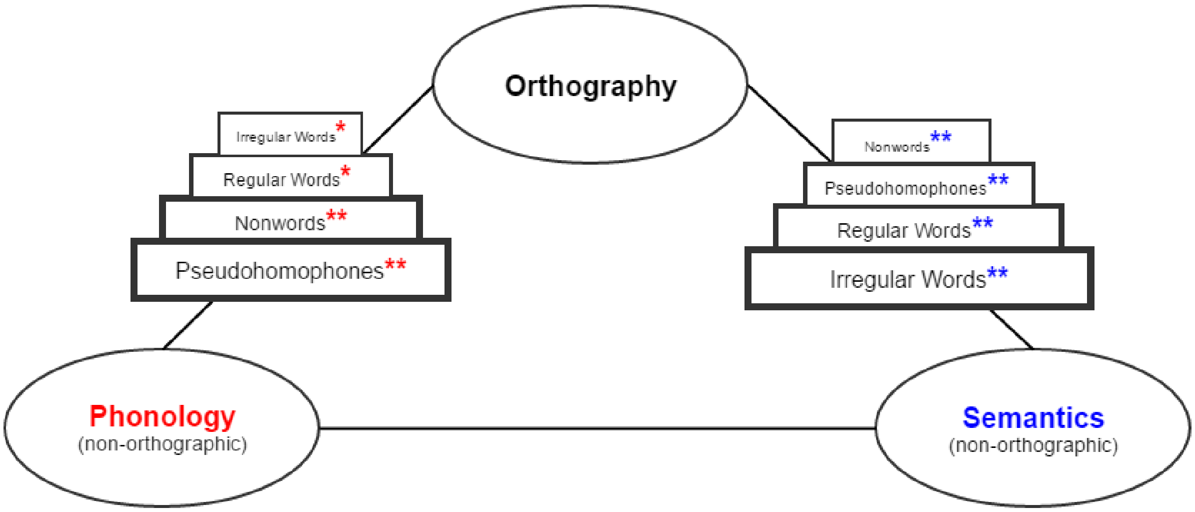
Finally, the finding that semantics significantly predicted nonword reading was initially a surprise since it is commonly thought that nonwords cannot benefit from semantic knowledge. As previously mentioned, it is actually fitting with PDP theory that semantics would be activated during nonword reading since semantic, phonologic, and orthographic units are always simultaneously engaged and the system's response depends on integrated information from all three of these sources. For example, Bourassa and Besner (1998) concluded nonwords that closely resemble real words can effectively prime real words (e.g., "deg" priming "cat"). The researchers explain this finding by proposing that the language network settles into the nearest attractor basin, and in this scenario, "dog" would be one likely settling point for the input of "deg". The nonwords used in the current study all closely resembled their parent real word, and therefore, it makes sense individuals with more intact semantic-orthographic connections may have benefited from the overlap in the orthography of the nonword (i.e., glope) and its parent word (i.e., globe).

An alternative explanation as to why semantics uniquely predicted nonwords concerns the tasks that comprised the semantic composite. Two of the four semantic tasks (i.e., auditory synonym judgment and comprehension of verbs & adjectives) were highly demanding of verbal working and short-term memory, which naturally involves phonologic processing (Baddeley, 2000). Consequently, semantic performance in this study inherently reflected some aspects of phonologic ability, and this confounding effect might further account for the significant relationship found between semantics and nonword reading.

Comparison and summary of RQ 1 correlation and regression findings. As outlined above, performance on the non-orthographic semantic tasks (i.e., semantic composite) was significantly correlated with *and* significantly predictive of oral reading of all four word types (i.e., regular, irregular, pseudohomophone, and nonwords). Overall performance on the non-orthographic phonology tasks (i.e., phonology composite) was also significantly correlated with all four word types; however, phonologic performance was only significantly predictive of two of the word types (i.e., pseudohomophones and nonwords). It is not unusual to find a variable is significantly correlated with, but not significantly predictive of another variable. This is especially true if the regression model contains more than one predictor, such as the multiple linear regression (MLR) models performed in this study. Semantics and phonology were both entered as predictors, and when there are multiple predictors, the total explanatory power of the MLR model reflects the overlapping contribution from both predictors. In addition to the shared contribution, a MLR model also reveals the distinctive contribution of each predictor to the dependent variable. As previously explained, this study found phonology only added independent information for pseudohomophone and nonword reading, whereas semantics provided unique information for all four word types.

Below in Figure 25, the correlation and regression findings from RQ1 have been visually summarized and superimposed on the PSH/PDP model. The size of the rectangles in this figure represents the size and strength of the relationship between phonology (or semantics) and a particular word type. Furthermore, one asterisk indicates phonology (or semantics) and a word type were statistically significantly correlated and two asterisks indicate phonology (or semantics) was significantly correlated with *and* predictive of reading aloud that particular word type.

Figure 25. RQ 1 findings superimposed on the PSH/PDP model



Note: * = significantly correlated; ** = significantly correlated and predictive; size of the rectangle represents size and strength of the relationship

To read any word, connectionist language theories, such as PSH/PDP, claim a unified language system synthesizes input from orthography, semantics, and phonology to arrive and settle at the final attractor pattern that allows the word to be correctly processed. When applied to the PSH/PDP model, it can be seen the current findings agree with this theory by demonstrating that non-orthographic semantics and phonology simultaneously contribute to orthographic processing. This is evidenced by both semantics and phonology being significantly correlated with oral reading of all word types. However, this contribution is not proposed to be all or none, but instead occurs along a gradient depending on the type of orthographic stimuli. The findings also support this division of labor and demonstrate that depending on the type of orthographic task, one primary systems pathway may have more influence on the final weight of the connections. In other words, certain connections may provide the majority of the input that helps the system to settle on the correct final attractor pattern. Specifically, the results from this study suggest that connections between non-orthographic semantic units and orthographic units (i.e., semantic-orthographic pathway) primarily support and impact processing of irregular and regular words, whereas connections between non-orthographic phonologic units and orthographic units (i.e., phonologic-orthographic pathway) primarily affect processing of pseudohomophone and nonwords in individuals with chronic aphasia.

RQ2: Semantics, Phonology, Syntax, and Silent Reading Comprehension

Research Question 2 aimed to understand the relationship between non-orthographic semantic, phonologic, and syntactic abilities and silent reading comprehension abilities in chronic aphasia.

Interpretation of overall performance. Participants completed several non-orthographic semantic, phonologic, and syntactic tasks, as well as silent reading comprehension tasks. (Refer to Tables 3 and 4, pg. 51 and 54). Average performance on the syntactic composite (67%) was lower than performance on the phonologic (76%) and semantic (83%) composites. The syntactic tasks involved processing at the phrase and sentence levels which is linguistically and cognitively more challenging than the semantic and phonologic tasks that involved only single word processing, so it is reasonable and expected that syntactic performance would be poorer.

Of the tasks that comprised the syntax composite, performance on comprehension of locative phrases (i.e., “boxes between buckets”) was lower and more variable than performance on the other two syntactic tasks that did not emphasize function words. Difficulty with function words has long been recognized in both the aphasia (Zurif, Green, Caramazza, & Goodenough, 1976) and phonological-deep alexia literature (Patterson & Marcel, 1977). The parallel impairment of function words in spoken language disorders (aphasia) and reading disorders (alexia) illustrates the primary systems view of language that posits similar patterns of breakdown will occur across language modalities due to impairment to central processing mechanisms that underpin all language activities.

With regard to performance on the silent reading comprehension measures, average performance was highest for paragraph-level reading comprehension (81%), followed closely by single word reading comprehension (79%) and then sentence-level comprehension (68%). It was surprising to find performance on paragraph-level comprehension comparable to single word comprehension; however, it is known that reading comprehension can be improved when more context is provided (Kim, Rising, Rapcsak, & Beeson, 2015). Therefore, additional context might account for the good performance on written paragraph comprehension. However, variability was seen for paragraph reading (ranging between 13%-100% accuracy) indicating that not all PWA in the study were able to benefit from the context offered in the paragraph stimuli.

Interpretation of RQ 2 correlation analyses. The composite semantic, phonologic, and syntactic scores were all positively and significantly correlated with reading comprehension at all levels (i.e., single words, sentences, and paragraphs) (Refer to Table 10, pg.84). The finding that all three non-orthographic language measures were significantly related to reading comprehension aligns with a developmental reading model known as the simple view of reading (Gough & Tunmer, 1986; Hulme & Snowling, 2014). The simple view of reading proposes reading comprehension is the product of decoding and oral language comprehension skills (i.e., reading comprehension = decoding x oral language comprehension). In this formula, decoding is represented by phonological ability, specifically orthography-phonology knowledge, and semantic and syntactic ability are encapsulated in oral language comprehension.

As predicted, semantics, phonology, and syntax varied in the strength of their relationships with reading comprehension. In comparison to the phonology and syntax composite scores, the semantic composite had the strongest correlation with overall reading comprehension, as well as with single word and paragraph reading comprehension. Similar to the oral reading correlation results, the synonym judgment and comprehension of verbs & adjective tasks were most strongly related to reading comprehension. This finding further indicates that these specific semantic tasks are closely associated with reading ability in chronic aphasia.

As expected, the non-orthographic syntactic tasks, especially the comprehension of locative phrases and spoken sentence-picture matching tasks from the PALPA, showed the highest correlations with sentence-level reading comprehension. The phonology tasks, on the other hand, consistently showed lower correlations than the semantic and syntactic tasks across all levels of reading comprehension.

The inferior relationship between phonology and reading comprehension is not all that surprising since it is known that successful written word comprehension can occur without full access to each phoneme in the target word (Crisp et al, 2011). Additionally, this lesser association might be attributed to the participants relying on whole word recognition by scanning the written stimuli for familiar words. Knollman-Porter et al. (2015) reported none of the PWA in their study read magazine articles word-by-word, but instead skimmed the text for key words that were easier to comprehend. Some participants in the current study anecdotally reported they were searching for key words. This scanning strategy could result in correct responses because many of the reading comprehension tasks involved a picture response. Essentially participants could create their own key word-to-picture matching task that bypassed grapheme-phoneme knowledge.

Overall, these correlational findings support the developmental literature that proposes oral listening comprehension ability is closely associated with written language comprehension ability (Compton et al., 2014). Additionally, and importantly, these data showing non-orthographic language performance was positively and significantly correlated with silent reading comprehension at the single word, sentence, and paragraph level suggests PSH/PDP assumptions can extend beyond oral reading of single words and may hold true for reading comprehension across multiple linguistic levels (i.e., single words, sentences, and paragraphs).

Interpretation of RQ2 regression analyses. Semantic, phonologic, and syntactic composite scores were entered simultaneously as predictors in four multiple linear regression models that estimated performance on overall reading comprehension, single word reading comprehension, sentence reading comprehension, and paragraph reading comprehension, respectively. As hypothesized, together the three non-orthographic language predictors accounted for a significant amount of the variance in all four reading comprehension models. When the sole contribution of each predictor was assessed, it was found semantics uniquely predicted performance at all levels of reading comprehension (i.e., single word, sentence, paragraph), and both phonology and syntax only uniquely predicted sentence-level reading comprehension. These results provided mixed support for the study predictions.

As expected, semantics was most predictive of single word reading comprehension. It was unanticipated, however, the semantic composite score would be more predictive of written paragraph comprehension than the syntactic composite. As previously postulated, it is feasible the participants in this study were scanning the written stimuli and therefore were likely filtering out most of the text and relying on familiar orthographic-semantic connections instead of reading the entire passage. In fact, this strategy may have been a direct result of the paragraph measures that were utilized. One of the paragraph tasks (RCBA 7) involved a picture response with picture options that corresponded with highly imageable content words in the paragraph. Therefore, to successfully complete this task, one only needed to match imageable words from the story with one of the picture choices. As a result, written syntactic knowledge was not heavily assessed. The other paragraph tasks (RCBA 8 and 9) involved pointing to one of three printed words to complete a sentence. Half of the correct words were found directly in the paragraph, and therefore one only needed to match two words (the word in the story and the word listed as an answer choice) to arrive at the correct answer. In other words, text-level reading could have been evaded and this may explain why semantics was more predictive of text reading than syntax.

As previously mentioned, phonology was anticipated to play a lesser role in reading comprehension since it is known that PWA can understand written words they are unable to fully decode and pronounce (Jefferies et al., 2007). However, it was still surprising phonology was not uniquely predictive of single word reading comprehension. In aphasia, it is possible phonology may have less involvement in written word comprehension than semantics due to weaker orthographic-phonologic connections that rely on a semantic boost to fully activate those connections and facilitate reading comprehension (Jefferies et al., 2007). Additionally, the degree of relationship between phonology and written word comprehension is likely to change depending on the type of word being read. For example, had comprehension of abstract words, which have weak semantic associations, been assessed than phonology may have been more predictive of single word reading comprehension as hypothesized.

Phonology was found to be significantly predictive of sentence-level reading comprehension, however, which was unexpected and seems like a contradicting finding. Although, most sentences contain some words (e.g., articles, function words, abstract words, and unfamiliar words) that do not benefit much from semantics, and in these cases, as alluded to above, it is conceivable orthographic-phonologic knowledge may play a part in helping to identify these words in a sentence. Moreover, phonology may also have been predictive of sentence reading comprehension because sentence processing, whether spoken or written, engages verbal short-term memory which inherently evokes phonologic processing (Baddeley, 2000). While phonology was found to be less predictive of sentence-level reading comprehension than semantics and syntax, this non-orthographic language ability does appear to have a small, yet significant influence on written sentence comprehension.

Of the three non-orthographic language measures, it was hypothesized that syntax would be the most predictive of sentence-level reading comprehension, and the regression results supported this prediction. Furthermore, the finding that non-orthographic syntactic performance was significantly predictive of written sentence comprehension corroborates the strong correlation found between these two variables. These findings together further support the notion that the primary systems featured in the PSH may perhaps extend beyond semantics, phonology, and single word processing to include syntax and sentence-level processing.

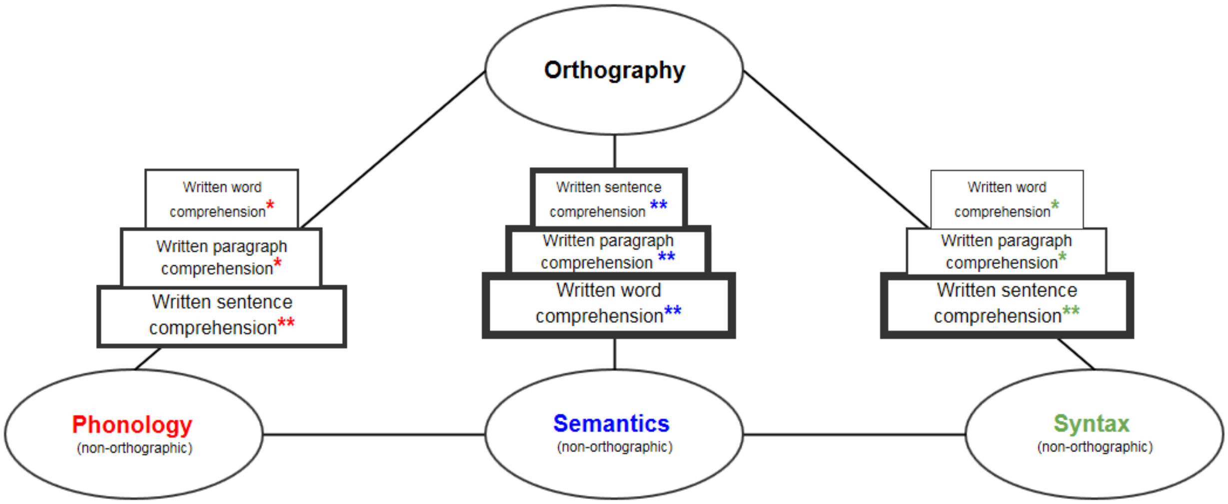
When results from the oral reading and silent reading comprehension regression models were compared, it was intriguing to find non-orthographic language performance accounted for more of the variance in overall silent reading comprehension (R^2 = .72) than in overall oral reading (R^2 = .57). There are two likely explanations for this finding. First, all of the non-orthographic language tasks and silent reading comprehension tasks were receptive in nature, whereas the oral reading tasks were expressive. Therefore, the higher variance accounted for in the reading comprehension model might reflect the fact that the predictor and outcome variables were both non-verbal. Second, and perhaps more pertinent, three predictors were included in the reading comprehension regression model compared to only two predictors in the oral reading regression model. The contribution of a third predictor likely increases the chances of accounting for more of the variance. Had a third oral reading predictor, such as a measure of letter-sound knowledge, been incorporated into the oral reading regression model, it is probable that more of the variance could have been explained. Despite the difference in the total amount of variance accounted for, the oral reading and silent reading comprehension regression models promote the PSH/PDP notion of an interconnected language system by showing performance on the same non-orthographic language tasks is significantly predictive of both oral reading and reading comprehension abilities.

Comparison and summary of RQ 2 correlation and regression findings. As described above, all three non-orthographic language composite scores (i.e., semantic, phonologic, and syntactic composites) were significantly and positively correlated with performance at all three reading comprehension levels (i.e., single words, sentences, and paragraphs). In addition to significant correlations, the semantic composite was also found to be significantly predictive of all three reading comprehension levels; whereas, the phonologic and syntactic composites were only significantly predictive of one reading comprehension level (i.e., sentence-level). As previously explained, it is not unusual to find a variable is significantly correlated with, but not significantly predictive of another variable. This is especially true if the regression model contains more than one predictor, such as the multiple linear regression (MLR) models performed in this study. Semantics, phonology, and syntax were all entered as predictors, and therefore the overall explanatory power of the MLR models came from the collective and overlapping input of all three predictors. However, the MLR models also revealed the unique contribution of each predictor to the dependent variables. This study found that only sentence-level reading comprehension performance was predicted by unique contributions from all three predictors. Single word and paragraph reading comprehension performance, on the other hand, was predicted solely by semantics. Said another way, the contributions from phonology and syntax to single word and paragraph reading comprehension were not adding any new information not already accounted for by semantics.

Below in Figure 26, these correlation and regression findings have been visually summarized and superimposed on a proposed expanded version of the PSH/PDP model that illustrates additional connections between non-orthographic syntactic processing units and orthographic processing units. Similar to Figure 25, the size of the rectangles in this figure represents the size and strength of the relationship between a non-orthographic language ability (i.e., semantics, phonology, or syntax) and a reading comprehension ability (i.e., word, sentence, or paragraph comprehension). Furthermore, one asterisk indicates the variables were significantly correlated, and two asterisks indicate the non-orthographic language measure was both significantly correlated with and significantly predictive of reading performance at that particular reading comprehension level.

When applied to the PSH/PDP model, the findings suggest that in aphasia, connections between semantic and orthographic processing units (i.e., semantic-orthographic pathway) heavily influence processing at all reading comprehension levels, most especially for written word reading comprehension. Sentence-level reading comprehension appears to be supported by more equally distributed input from all three pathways (i.e., syntactic-orthographic, semantic-orthographic, and phonologic-orthographic). However, syntax demonstrates the greatest influence on sentence-level reading comprehension. Finally, written paragraph comprehension seems to be primarily supported by semantics.

Figure 26. RQ 2 findings superimposed on the PSH/PDP model



Note: * = significantly correlated; ** = significantly correlated and predictive; size of the rectangle represents size/strength of the relationship

These findings indicate that non-orthographic language abilities not only predict single word oral reading abilities in PWA, as demonstrated in RQ1 and previous work (Crisp & Lambon Ralph, 2006; Henry et al., 2012; Patterson & Marcel, 1992; Rapcsak et al., 2009), but they also significantly inform and contribute to reading comprehension abilities beyond the single word level. Furthermore, the results illustrated above suggest the same PSH/PDP assumptions about how oral reading occurs at the single word level (i.e., graded division of labor between non-orthographic and orthographic language processing pathways) also apply to reading comprehension at the word, sentence, and paragraph level. This notion is supported by the finding that all three non- orthographic language measures were significantly related to reading comprehension, but they demonstrated different degrees of relatedness depending on the level of reading comprehension. Said another way, depending on the type of orthographic task (i.e. reading comprehension of words, sentences, or paragraphs) one pathway within the interconnected language system (i.e., semantic-orthographic, phonologic-orthographic, or syntactic-orthographic) may have more influence, yet, the final attractor is still established by synthesizing varying degrees of input from all of the language pathways.

RQ 3: Alexia, Semantics, and Phonology

Research Question 3 investigated the relationship between alexia subtype and corresponding semantic and phonologic abilities. First, each participant's reading profile (i.e., surface, phonological, deep, global alexia, or within normal limits) was determined. Then, correlations between hallmark alexia symptoms and performance on the non-orthographic semantic and phonologic measures were calculated to explore the relationship between alexia symptoms and non-orthographic language ability. In addition, the degree of semantic and phonologic impairment associated with each reading profile was examined.

Interpretation of reading profiles. It is well-known that alexia commonly co-occurs with stroke-induced aphasia (Brookshire et al., 2014a; Webb & Love, 1983), and that phonological-deep alexia is the most frequent subtype of alexia found in aphasia (Crisp & Lambon Ralph, 2006; Luzzatti et al., 2006; Rapcsak et al., 2009). Therefore, it is fitting with the literature, and the study predictions, that the vast majority of PWA in the current study presented with alexia, and furthermore, most of these individuals fell somewhere on the phonological-deep alexia continuum. In fact, 27 out of the 37 (73%) individuals with alexia were identified with either phonological or deep alexia, and this finding aligns closely with that of Rapcsak et al. (2009) who found 21 out of 27 (78%) PWA to be on the phonological-deep alexia continuum.

Other reading profiles, in addition to phonological or deep alexia, were also identified in this sample of 43 PWA. Six (14%) individuals read within two standard deviations of the normal control reference data, and therefore were not assigned an alexia subtype, but instead were classified as reading within normal limits (WNL). At the other extreme, five individuals (12%) had almost no ability to read aloud and were determined to have global alexia. Global alexia is seen by some as the absolute lowest end of the phonological-deep alexia continuum (Rapcsak et al., 2009). The presence of both global alexia and reading WNL indicates that the full range of reading ability in chronic aphasia was assessed in this study.

There were five PWA (12%) who presented with reading profiles that could not be classified (CNC) into a familiar alexia type. Three of these individuals (P6, P8, P11) likely presented with a very mild phonological alexia and fell somewhere between WNL and pure phonological alexia on the reading continuum. This was evidenced by their small lexicality effects, which precluded a phonological alexia classification; yet, their reading was still outside of normal limits. Rapcsak et al. (2009) reported two similar cases of mild phonological alexia in their study of alexia in 27 PWA. The other two individuals in the CNC group (P26 and P27) met the deep alexia criteria in terms of reading accuracy (i.e., poor RW and very poor NW reading), but not in terms of reading errors, as neither participant produced semantic errors. Both of these individuals previously had speech therapy focused on grapheme-phoneme correspondences, and due to this training they explicitly attempted to sound out each word in the oral reading lists. This reading strategy likely prevented semantic errors from occurring. Jefferies et al. (2007) described a similar performance by an individual with severe alexia who did not make semantic reading errors due to unsuccessful "persistent attempts to generate phonology from orthography" as a response to a grapheme-phoneme therapy.

It is not unusual no PWA in this study were identified to have surface alexia since surface alexia is more often associated with semantic dementia and damage to the left anterior frontal lobe (Woollams et al., 2007; Woollam, 2014). The participants tended to demonstrate less accurate irregular word reading than regular word reading, which is characteristic of surface alexia. Irregular word errors were mostly visual/phonologic in nature, and very few regularization errors were made on mispronounced irregular words, however. This same finding was reported by Crisp and Lambon Ralph (2006) who indicated that PWA may have more difficulty reading irregular words than regular words, but they do not make the same type and/or amount of errors as individuals with surface alexia.

In sum, the entire phonological-deep alexia continuum was present in this large, diverse sample of PWA. At the high end of the reading continuum, there were six individuals with normal reading and likely two participants with mild phonological alexia. Most of the sample (23) fell in the middle with a more pure phonological alexia profile. On the more impaired side of the spectrum there were four participants with deep alexia, and six individuals with global alexia at the very low end of the reading continuum.

The alexia literature promotes the notion that there are no clear dividing lines between alexia subtypes on the phonological-deep alexia continuum (Crisp & Lambon Ralph, et al., 2006; Rapcsak et al., 2009). The data from this study support the existence of a phonological-deep alexia continuum due to difficulty with nonword reading and similar types of reading errors being present among all participants. However, differences in the size of the lexicality effect (Refer to Figure 18, pg. 93) and type and amount of reading errors produced by PWA in this study (Refer to Figure 19, pg. 94) may offer some insight as to where an individual will fall on the reading continuum. For example, individuals with small lexicality effects are likely to be on either extreme end of the continuum depending if the small lexicality effect is due to very poor reading of both RWs and NWs (global alexia) or good reading of both RWs and NWs (mild phonological or WNL). Individuals with large discrepancies between RW and NW reading are likely to represent the middle of the phonological-deep continuum. It is known that lexicality effects vary in size in phonological-deep alexia (Farah et al., 1996); however data from this work suggest that the relative size of the lexicality effect may be one indication of alexia severity.

Furthermore, the relative frequency, instead of mere presence, of oral reading errors, may be yet another way to estimate the severity of phonological-deep alexia. Individuals with phonological, deep, and global alexia all made the same type of oral reading errors, but the frequency of these errors varied greatly. The data suggest individuals higher on the phonological-deep alexia continuum (e.g., mild and pure phonological alexia) will make overall less oral reading errors and errors will tend to be visual-phonologic and lexicalizations with few omission errors. Conversely, individuals lower on the phonological-deep continuum (e.g., deep and global alexia) will likely produce errors on the majority of reading attempts, with omission and unrelated reading errors being the most common error types.

It was surprising to find semantic errors occurred across all three alexia subtypes with 22 (51%) participants producing at least one semantic error. However, semantic errors accounted for a very small amount of the proportion of the total reading errors for all participants, even among individuals with deep alexia. This finding of semantic errors (rarely) occurring across the alexia continuum agrees with the suggestion by Jefferies and colleagues (2007) that presence of semantic errors should not be solely responsible for distinguishing alexia subtypes on the phonological-deep continuum.

Interpretation of RQ 3 correlation analyses. Non-orthographic semantic and phonologic abilities showed significant correlational relationships with some of the hallmark reading symptoms associated with alexia (Refer to Table 13, pg. 99). As predicted, semantic performance was negatively correlated with the regularity reading effect, omission reading errors, and unrelated real word errors, and was positively correlated with visual/phonological and lexicalized reading errors. It was unexpected, however, to find semantic ability was not significantly associated with semantic reading errors. Although, despite being small in size, all of the correlations between the semantic tasks and proportion of semantic errors were negative indicating a trend towards a decrease in semantic reading errors as semantic abilities improve, which aligns with findings from other phonological-deep alexia work (Crisp & Lambon Ralph, 2006).

It was hypothesized that phonology would be negatively correlated with oral reading errors. This result was seen for omission and unrelated errors; however, unexpectedly phonology was positively correlated with visual/phonologic reading errors indicating that more visual-phonologic errors occur as phonology improves. It is possible improved phonology allows for strengthened, although not perfect, orthographic-phonologic knowledge and therefore more visual/phonologic reading errors will occur when the orthographic-phonologic connections are only partially enhanced. The finding that phonology was not significantly related to semantic reading errors was unexpected, yet in agreement with results from Crisp and Lambon Ralph (2006).

The correlational findings discussed above support the primary systems framework by demonstrating alexia reading errors are significantly associated with non-orthographic semantic and phonologic performance. Furthermore, semantic and phonologic abilities have been shown to have similar correlations with both reading and naming errors in aphasia. For example, semantic abilities have been found to be negatively correlated with semantic errors in naming (Lambon Ralph et al., 2002; Martin et al., 2006) and semantic errors in reading (Crisp & Lambon Ralph, 2006). Similarly, phonologic abilities have been shown to be negatively associated with omission errors in naming (Lambon Ralph et al., 2002; Minkina et al., 2015) and omission errors in reading (current study). These parallel cross-linguistic correlation findings provide strong support for the PSH by indicating multiple language activities (e.g., naming and reading) have similar relationships with general semantic and phonologic abilities.

Interpretation of RQ 3 visual analyses. Scatterplots were created to visualize relationships between reading profiles (i.e., phonological, deep, global alexia, or WNL) and non-orthographic semantic and phonologic abilities. Given that many studies have reported phonological-deep alexia stems from a fundamental impairment of phonology (Crisp & Lambon Ralph;, 2006; Jefferies et al., 2007; Patterson & Marcel, 2002; Rapcsak et al., 2009), it was not surprising to find non-orthographic phonologic performance declined as location on the phonological-deep alexia continuum declined. It was interesting, however, that this same pattern was observed for semantics. As non-orthographic semantic performance declined so too did location on the phonological-deep alexia continuum. Said another way, alexia severity was seen to increase as semantic performance decreased. The influence of semantic ability on oral reading performance in phonological-deep alexia has remained relatively unexplored (Rapcsak et al., 2009), and this work suggests that the phonological-deep alexia continuum is not only characterized by severity of phonological deficit, but also by degree of semantic impairment. With that said, it is critical to acknowledge and keep in mind that the semantic tasks inherently involved phonologic processing, as previously discussed.

When the interplay between semantics, phonology, and alexia type was examined (Refer to Figures 20 and 21, pgs. 101 and 102), the different alexia subtypes did not wholly separate; yet, despite some degree of overlap between them, a pattern emerged that showed severity of alexia reflected severity of semantic and phonologic impairment. In particular, individuals reading WNL performed almost half a standard deviation above the group average for both semantics and phonology. Those with phonological alexia tended to demonstrate semantic and phonologic abilities that were near the group average. Deep alexia was associated with performance about half a standard deviation below the semantics and phonology group mean, and those with global alexia tended to perform a full standard deviation or more below the rest of the group in phonology and semantics. Moreover, between-group comparisons found the semantic and phonologic abilities of the WNL group were statistically significantly better than those in the deep and global alexia groups, and the phonological alexia group demonstrated statistically significantly better semantic and phonologic performance compared to the global alexia group. Within-in group comparisons revealed the phonological and deep alexia groups demonstrated statistically significant discrepancies between semantic and phonologic performance with semantics being superior to phonology.

The findings described above support the study predictions and strongly imply that a person's non-orthographic semantic and phonologic abilities will indicate what type of reader he or she is. Specifically, these results suggest that an individual with aphasia who demonstrates relatively intact semantic and phonological abilities is likely to present with mild reading difficulties and may even perform WNL on some reading tests. Whereas, an individual with superior semantic to phonologic abilities is likely to fit a phonological-deep alexia profile. Lastly, someone with severely impaired semantics and phonology will probably present with a reading profile consistent with global alexia.

To further explore how differences in semantic and phonologic abilities may impact reading ability, a simple liner regression model was conducted with the discrepancy between semantic and phonologic abilities (S-P score) entered as the predictor variable and size of lexicality effect (RW-NW score) as the outcome variable. This post-hoc analysis revealed S-P score was approaching a significant, positive relationship with the RW-NW score. This finding hints that the hallmark feature of phonological-alexia, the lexicality effect, may reflect more than just an imbalance of real word and nonword reading ability. In addition, a lexicality effect may imply an imbalance of semantic and phonologic abilities exists.

This finding suggests individuals with normal reading abilities are good at reading both real words and nonwords (i.e., no lexicality effect) due to equally strong semantic and phonologic abilities (i.e., no S-P discrepancy); whereas, individuals with phonological-deep alexia may be better at reading real words and poorer at reading nonwords (i.e., large lexicality effect) due to stronger semantic than phonological abilities (i.e., large S-P discrepancy). Finally, those with global alexia may have no significant difference between real word and nonword reading (i.e., no lexicality effect) due to severely impaired semantics and phonology (i.e., no S-P difference). This notion proposes that in addition to size of lexicality effect, size of S-P discrepancy may also be indicative of alexia severity and may offer an explanation as to why real word and nonword reading abilities differ so widely across the phonological-deep alexia continuum.

In sum, results from RQ 3 support the PSH by providing evidence that alexia severity is directly related to the status of non-orthographic semantic and phonologic abilities. Moreover, findings suggest alexia subtypes may be described based on degree of underlying central language impairment instead of being described solely by traditional reading symptoms (i.e., lexicality effect and types of oral reading errors). Based on these findings, it appears that alexia in aphasia may be interpreted from a primary systems perspective, and conversely, these results do not support the traditional, dual route notion of alexia being a reading-specific disorder.

General Discussion

This study found non-orthographic language abilities to be significantly related to oral reading and silent reading comprehension abilities, as well as alexia subtype, in a large diverse sample of 43 individuals with chronic stroke-induced aphasia. In regard to oral reading abilities, semantic ability was found to be significantly and positively correlated with and predictive of reading *all* word types (i.e., regular, irregular, pseudohomophones, and nonwords) while phonology was most highly correlated with and predictive of pseudohomophone and nonword reading only. These results suggest that the PDP division of labor between orthographic, semantic, and phonologic connections has changed in chronic aphasia. Instead of having efficient processing from both primary semantic and phonologic pathways, left-hemisphere stroke appears to have resulted in a greater reliance on input from the semantic pathway (i.e., semantic-orthographic connections) than the phonologic pathway (i.e., phonologic-orthographic connections). This conceivable change in the division of labor would result in the phonologic pathway being dependent on semantics to boost the more impaired orthographic-phonologic connections. This notion agrees with the claim by Crisp et al. (2011) that semantic representations become more essential to reading when phonological impairment is present.

Semantic knowledge was also found to significantly impact silent reading comprehension. Specifically, semantic performance was predictive of reading comprehension at all levels (i.e., single word, sentence, and paragraph). Comparatively, phonology and syntax were only uniquely predictive of sentence reading comprehension. The greater influence of semantics than phonology on reading comprehension agrees with research that has shown PWA are able to extract meaning from orthography more efficiently than they can decode, or process phonology from orthography (Jefferies et al., 2007). In comparison to non-orthographic semantic and phonologic abilities, the finding that non-orthographic syntactic ability was most highly correlated with and significantly predictive of sentence-level reading comprehension seems to extend the PSH beyond single word processing and provides preliminary evidence that the ability to comprehend spoken sentences is closely related to the ability to comprehend written sentences in chronic aphasia.

Skilled reading comprehension undoubtedly involves more than just intact semantic, phonologic, and syntactic abilities. Successful and enjoyable comprehension of written material relies on many other abilities, such as attention, working memory, and inference making, to name a few (Compton et al., 2014; Hulme & Snowling, 2014). The multi-component nature of text-level reading comprehension likely explains why the three non-orthographic language predictors used in this study accounted for less of the variance in paragraph reading comprehension compared to single word and sentence reading comprehension.

Acquired reading impairment (alexia) was prevalent in this large sample of PWA. The entire phonological-deep-global alexia continuum was represented evidenced by great variability in real word and nonword reading accuracy, as well as in types and frequency of reading errors produced. Severity of alexia was shown to be related to the status of non-orthographic phonologic and semantic abilities suggesting that the alexia continuum may reflect a semantics-phonology continuum. Specifically, individuals on the lower end of the reading continuum (i.e., global and deep alexia) demonstrated more impaired semantics and phonology than individuals higher on the continuum (i.e., phonological alexia and WNL). Moreover, semantics and phonology were significantly correlated with hallmark alexia reading errors further indicating that reading performance in aphasia is linked to non-orthographic language performance.

Viewed collectively, results from all three research questions in this study provide strong support for the PSH/PDP view of language processing that proposes spoken and written language are intimately related and supported by the same interconnected primary language systems. This study endorses the PSH by confirming findings from previous work (Crisp & Lambon Ralph, 2006; Henry et al., 2012) that showed non-orthographic semantic and phonologic abilities are predictive of oral reading abilities (RQ1). In addition, this work provides evidence that the PSH/PDP framework extends beyond oral reading of single words by demonstrating that non-orthographic language abilities are also significantly related to silent reading comprehension at the word, sentence, and paragraph levels (RQ 2). Finally, in accordance with the PSH, data from this work implies that alexia may reflect underlying central language impairment with severity of non-orthographic semantic and phonologic impairment corresponding to severity of alexia (RQ 3). These findings not only contribute to our understanding of reading theory, but also have the potential to inform clinical practice.

Clinical Implications

Results from this study hold clinical relevance and will hopefully be applied to the development of novel aphasia assessment and treatment protocols in the future. Currently, treatment for an individual with aphasia and co-occurring alexia is often focused on the reading impairment and neglects the spoken language impairment or vice versa. This separation of alexia from aphasia likely reflects the traditional dual route belief that spoken and written language systems are functionally unrelated, and therefore need to be treated individually. However, this study has shown that acquired reading impairment is closely connected to non-orthographic language impairment in aphasia. Thus, this work supports integrated treatment of acquired written and spoken language impairments since these deficits are believed to stem from damage to the same underlying primary language systems. Relatively recent reading treatments for PWA (Beeson et al., 2010; Brookshire et al., 2014b; Conway et al., 1998; Kendall, Conway, Rosenbek, Gonzalez Rothi, 2003; Yampolsky &Waters, 2002) have started to treat the primary system of phonology in an effort to improve reading ability. Results from this study provide support for these newer treatment approaches and encourage the treatment of semantics, in addition to phonology, in future reading treatment protocols since semantic ability was found to be strongly predictive of both oral and silent reading abilities. Lastly, findings from this study promote using performance on non-orthographic semantic and phonologic tasks to aid in the diagnosis of alexia subtype instead of relying solely on single word oral reading accuracy and types of oral reading errors produced, as is commonly practiced.

Limitations

Despite being carefully selected, the participants and outcome measures included in this study limit the interpretation and generalization of the study findings. Even though individuals with various types and severity of aphasia were permitted to participate, aphasia was restricted to the chronic phase and must have been the result of a left-hemisphere stroke. Therefore, the study findings only apply to this specific aphasia population. To truly test the PSH, the participant inclusion/exclusion criteria should be widened to include individuals with aphasia and alexia secondary to right hemisphere stroke, bilateral stroke, traumatic brain injury, or progressive language impairment, for example.

The independent (non-orthographic language measures) and dependent (oral reading and silent reading comprehension measures) variables were also restricted in some regards. Specifically, the non-orthographic language tasks utilized were all non-verbal and therefore the influence of expressive semantic, phonologic, and syntactic abilities on oral reading and silent reading comprehension cannot be inferred from this study and should be explored in future work. In addition, the tasks comprising the phonologic composite were weakly correlated with one another compared to the highly correlated tasks within both the semantic and syntactic composites. This is likely the result of using tasks that targeted various phonological skills (i.e., RW and NW rhyme judgment and phoneme identification and manipulation). Using phonologic tasks that were more strongly correlated may have altered the relationship between phonology and reading in this study.

Oral reading was narrowly measured as the ability to read aloud regular words, irregular words, pseudohomophones, and nonwords. Linguistic variables known to influence reading, such as imageability, frequency, concreteness/abstractness, and grammatical class, were not examined. In addition, direct orthography to phonology translation was only measured via nonword reading. However, alternative measures, such as spoken nonword to written nonword matching or written nonword rhyme judgment, could be used in follow-up work to further assess grapheme-phoneme correspondence knowledge, especially in those individuals who were unable to read aloud nonwords (Crisp et al., 2011). In addition to the oral reading stimuli, it might also be argued that the silent reading comprehension stimuli were lacking, particularly the paragraph-level tasks that were relatively easy for most participants. Perhaps, more complex and more functional reading stimuli, such newspaper articles, should be used to measure text-level comprehension in future work.

As previously mentioned, there is more contributing to reading ability than semantics, phonology, and syntax; however this study limited the predictors to these three language measures. Future work is needed, therefore, to investigate the impact of other possible reading predictors. In particular, the influence of attention and working memory on reading comprehension in aphasia needs to be addressed given these cognitive abilities are known to be impaired in aphasia (McNeil, Odell, Tseng, 1991; Sung et al., 2009). Moreover, attention and working memory deficits have been linked to reading impairment in children with developmental dyslexia (Bosse, Tainturier, & Valdois, 2007; Germano, Gagliano, & Curatolo, 2010; Smith-Spark & Fisk, 2007) and this same relationship is likely to exist in adults with acquired alexia. Using performance on the cognitive tests that were collected for descriptive purposes only for this study (i.e., Corsi block, Raven's Matrices, and CLQT symbol trails), as predictive measures of reading in a follow-up study would be a likely next step to further investigate causes of acquired reading impairment in aphasia.

A final limitation to acknowledge concerns the conservative method used to determine the lexicality effect. In this study, a lexicality effect was defined as non-overlapping real word and nonword 95% CIs. Had a more liberal method been used to establish the presence of a lexicality effect, it may have been possible to identify alexia subtypes for the individuals who were not able to be classified (CNC). Currently, there is no agreed upon way to measure a lexicality effect, and therefore researchers have adopted several approaches. For example, some researchers have vaguely proposed a "dramatic difference" between real word and nonword reading ability is required (Patterson & Marcel, 1992) while others have used statistical tests, such as the Fischer's exact test (Rapcsak et al., 2009) or chi square test (Farah et al., 1996; Kim & Russo, 2015) to identify if a significant difference between real word and nonword reading ability is present. It remains to be determined how best to measure and quantify a lexicality reading effect. Until a standard method is adopted, the use of different methods will directly alter findings between studies and limit generalizability.

Future Directions

In addition to addressing the limitations outlined above, there are several directions to consider for future work aimed at investigating the primary systems hypothesis. The current study could be extended to include spelling tasks, in addition to reading tasks, to have both input and output written language measures. Then, the relationship between spoken language (expressive and receptive) and written language (expressive and receptive) could be fully examined. Additionally, oral reading error profiles could be compared with spelling and naming error profiles to investigate the similarity between type and frequency of spoken vs. written language errors. Furthermore, reading and spelling abilities in PWA could be compared to understand similarities and differences among acquired written language impairments (i.e., alexia and agraphia). It would also be interesting to examine reading comprehension abilities associated with alexia and agraphia since these disorders are traditionally characterized by expressive, and not receptive, written language impairment. Finally, the current findings along with results from other PSH studies could be used to inform the design of PSH-motivated written language treatment that would target non-orthographic language abilities shown to be predictive of reading, in addition to orthographic skills, in an effort to improve written language processing.

Conclusion

The results of this work offer promising support for the primary systems view of language processing by showing that non-orthographic language abilities are closely linked to oral reading and silent reading comprehension performance in chronic aphasia, and furthermore that alexia severity in PWA can be described by severity of semantic and phonologic impairment. However, these findings are preliminary and therefore this work needs to be replicated and extended to further understand the connection between acquired spoken and written language impairment in aphasia. It is important to note the findings from this study do not imply a causal relation between improvement in non-orthographic language abilities and reading abilities. This work showed statistically significant positive relationships exists between these variables, and as non-orthographic language performance improves reading performance is also expected to improve. It remains to be determined if this relationship may be reciprocal in nature, however.

It also remains to be determined if these findings have any validity in a treatment setting. The significant relationships revealed between reading performance and performance on non-orthographic language measures suggest that targeting non-orthographic language skills in treatment may be one reading rehabilitation approach worth exploring. It is the author's goal to continue to investigate the relationship between spoken and written language impairment and apply these findings to the systematic design and implementation of a written language treatment protocol for individuals with chronic aphasia.

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Appendix I: Correlation Tables for Each Language Domain

Semantic Tasks

	CCT	PALPA 47	PALP49	PALPA57
CCT	--			
PALPA 47	.51**	--		
PALPA 49	.68**	.67**	--	
PALPA 57	.45**	.57**	.71**	--

CCT = Camel and Cactus Test (Adlam et al., 2010); PALPA = Psycholinguistic Assessment of Language Processing in Aphasia (Kay et al., 1992)

* *p* < .05, ** *p* < .01, *** *p* < .001 (two-tailed).

Phonologic Tasks

	SAPA min pairs	SAPA RW rhyme	SAPA NW rhyme	LAC
SAPA min pairs	--			
SAPA RW rhyme	.41**	--		
SAPA NW rhyme	.35*	.74**	--	
LAC	.26	.36*	.33*	--

SAPA = Standardized Assessment of Phonology in Aphasia (Kendall et al., 2010); LAC = Lindamood Auditory Conceptualization Test (Lindamood & Lindamood, 1988)
* *p* < .05, ** *p* < .01, *** *p* < .001 (two-tailed).

Syntactic Tasks

	PALPA55	PALPA58	CAT 9
PALPA 55	--		
PALPA58	.76**	--	
CAT 9	.85**	.71**	--

PALPA = Psycholinguistic Assessment of Language Processing in Aphasia (Kay et al., 1992); CAT = Comprehensive Aphasia Test (Swinburn et al., 2004)

** p < .05, ** p < .01, *** p < .001 (two-tailed).*

Oral Reading Tasks

	ABRS regular	ABRS irregular	ABRS nonwords	SAPA pseudo
ABRS regular	--			
ABRS irregular	.98**	--		
ABRS nonwords	.69**	.70**	--	
SAPA pseudo	.78**	.81**	.87**	--

ABRS = Arizona Battery for Reading and Spelling (Beeson et al., 2010); SAPA = Standardized Assessment of Phonoloy in Aphasia(Kendall et al., 2010)

* *p* < .05, ** *p* < .01, *** *p* < .001 (two-tailed).

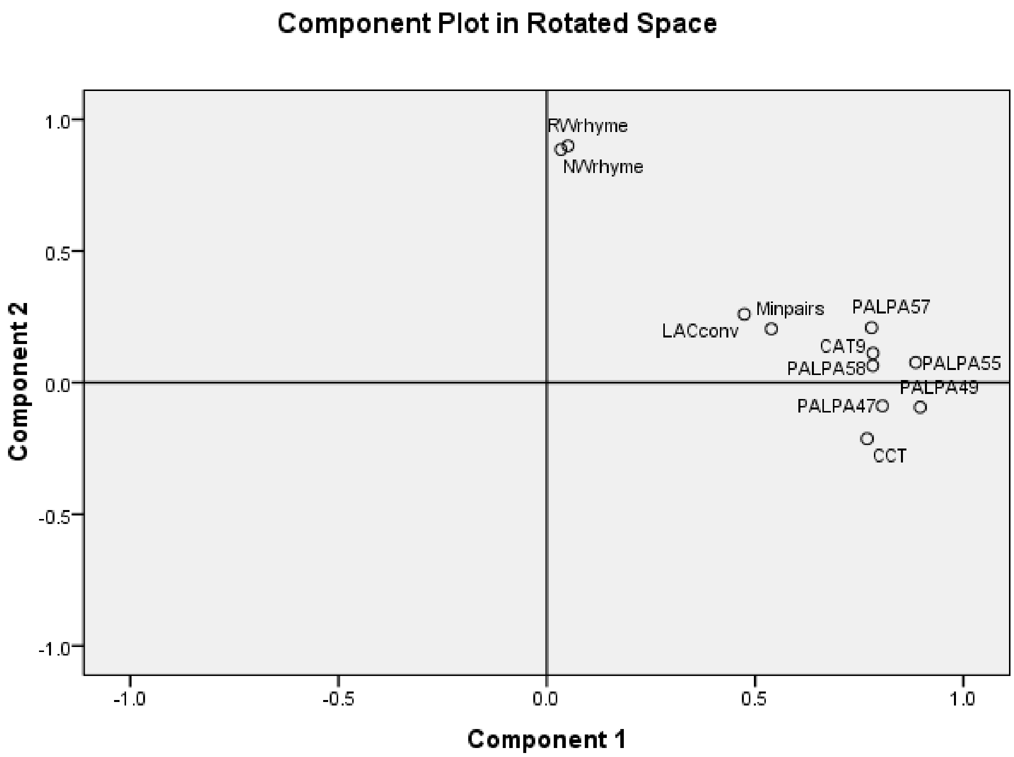
Silent Reading Comprehension Tasks

	Single Words			Sentences			Paragraphs		
	CAT 8	PALPA 50	PALPA 51	CAT 10	PALPA 59	RCBA 4	RCBA 7	RCBA 8	RCBA 9
CAT 8	--								
PALPA 50	.64**	--							
PALPA 51	.63**	.81**	--						
CAT 10	.67**	.75**	.66**	--					
PALPA 59	.69**	.62**	.60**	.78**	--				
RCBA 4	.60**	.67**	.75**	.55**	.54**	--			
RCBA 7	.59**	.59**	.62**	.62**	.71**	.57**	--		
RCBA 8	.64**	.78**	.82**	.66**	.60**	.73**	.64**	--	
RCBA 9	.68**	.76**	.75**	.75**	.72**	.76**	.68**	.87**	--

CAT = Comprehensive Aphasia Test (Swinburn et al., 2004); PALPA = Psycholinguistic Assessment of Language Processing in Aphasia (Kay et al., 1992)RCBA = Reading Comprehension Battery for Aphasia (LaPointe & Horner, 1982)

* *p* < .05, ** *p* < .01, *** *p* < .001 (two-tailed).

Appendix II: Principal Components Analysis (PCA) Component Plot



Appendix III: Standard Error of Measurement (SEM) and 95% Confidence Interval (CI) Calculations

Real Words (Regular and Irregular):

SEM = SD √ (1-r)

= 0.331 √ (1-.990)

= 0.331 √0.01

= 0.331 (.1)

= 0.0331

95% CI: 1.96 (.0331) = +/- 0 .0648

Regular words:

SEM = SD √ (1-r)

= .326 √ (1-.980)

= .326 √.02

= .326 (.1414)

= .0461

95% CI: 1.96 (.0461) = +/- 0.0904

Irregular words:

SEM = SD √ (1-r)

= .339 √ (1-.979)

= .339 √.021

= .339 (.1449)

= .0491

95% CI: 1.96 (.0491) = +/- 0 .0963

Nonwords:

SEM = SD √ (1-r)

= .352 √ (1-.951)

= .352 √.049

= .352 (.2213)

= .0779

95% CI: 1.96 (.0779) = +/- 0 .1527

Pseudohomophones:

SEM = SD √ (1-r)

= .331 √ (1-.895)

= .331 √.105

= .331 (.3240)

=.1073

95% CI: 1.96 (.1073) = +/- 0.2102