

**SACCADIC EYE MOVEMENTS AND PAUSE/ARTICULATION
COMPONENTS DURING A LETTER NAMING SPEED TASK:
CHILDREN WITH AND WITHOUT DYSLEXIA**

by

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Abstract

Naming speed (NS) tasks that measure how quickly and accurately participants can name visual stimuli (e.g., letters) are commonly used to predict reading ability. However, the link between NS and reading is poorly understood. Three methods were used to investigate how NS relates to reading and what cognitive processes are involved: (a) changing stimulus composition to emphasize phonological and/or visual aspects (Compton, 2003); (b) decomposing NS times into pause and articulation components; and (c) analyzing eye movements during a NS task. Participants were in three groups: dyslexics (aged 9, 10), chronological-age (CA) controls (age 9, 10), and reading-level (RL) controls (aged 6, 7). We used a letter NS task and three variants that were either phonologically and/or visually confusing while subjects' eye movements and articulations were recorded, and examined how these manipulations influenced NS performance and eye movements.

For all groups, NS manipulations were associated with specific patterns of behaviour and saccadic performance, reflecting differential contributions of NS to reading. RL controls were less efficient, made more errors, saccades and regressions, and made longer fixation durations, articulation times, and pause times than CA controls. Dyslexics consistently scored in between controls, except for the number of saccades and regressions in which they made more than both control groups. Overall there were clear developmental changes in NS performance, NS components, and eye movements in controls from ages 6 to 10 that appear to occur more slowly for dyslexics.

Furthermore, pause time and fixation duration were key features in the NS-reading relationship, and increasing visual similarity of the letter matrix had the greatest

effect on performance for all subjects. This latter result was demonstrated by the decrease in efficiency and eye-voice span, increase in naming errors, saccades, and regressions, and longer pause times and fixation durations found for all subjects. We conclude that NS is related to reading via fixation durations and pause times; longer fixation durations reflect the greater amount of time needed to acquire visual/orthographic information from stimuli, and longer pause times in children with dyslexia reflect the greater amount of time needed to prepare to respond to stimuli.

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List of Abbreviations

ANOVA	Analysis of variance
CA	Chronological-age matched control group
NS	Naming speed
OS	Original naming speed task
PS	Phonologically similar naming speed task
RL	Reading-level matched control group
VPS	Visually and phonologically similar naming speed task
VS	Visually similar naming speed task

Chapter 1

Introduction

The ability to read is crucial for a child's overall academic, economic, and social success (Snow, Burns, & Griffin, 1998; Olitsky & Nelson, 2003; Norton & Wolf, 2012). A majority of children are able to learn to read with ease, and have normal reading ability that is characterized by fluent word identification and adequate comprehension (Vellutino & Fletcher, 2005). However, 10 to 15% of school-aged children have been found to have reading problems, and 2 to 4% of these children have been diagnosed with dyslexia (Snow et al., 1998; Vellutino & Fletcher, 2005; Shaywitz & Shaywitz, 2008; Vellutino, Fletcher, Snowling, & Scalon, 2004). Children with dyslexia have unexpected poor word reading ability that cannot be attributed to low intelligence or poor reading instruction (Cain, 2010). These children have repeatedly been found to be less likely to graduate from high school and are at a greater risk for unemployment, underemployment, and incarceration (Snow et al., 1998; Norton & Wolf, 2012; Grigorenko, 2006; Humphrey & Mullins, 2002; Svensson, Lundberg, & Jacobson, 2001). Providing the appropriate interventions to these children is crucial to their future outcomes and can change their overall trajectory (Snow et al., 1998; Norton & Wolf, 2012; Vellutino, Scanlon, & Tanzman, 1998). However, developing effective intervention methods requires diagnostic assessment which in turn requires understanding of the underlying nature of these reading problems.

Despite generations of research that has been conducted to explain the aetiology of reading disabilities, it is still unclear how or why some individuals develop dyslexia

whereas others do not. A key finding in the field of reading disabilities has been that phonological processing deficits are at the core of reading failure (Wolf, Bowers, & Biddle, 2000). However recent research has emerged that shows that a second core deficit is in naming speed (NS) (Kirby, Georgiou, Martinussen, & Parrila, 2010; Wolf et al., 2000; Norton & Wolf, 2012). It has been argued that because reading is a linguistic activity intimately tied to language processing, rapid labeling of visual stimuli would then be an effective way to measure language processing (Denckla & Cutting, 1999). Thus NS tasks, measuring how quickly and accurately subjects can name highly familiar stimuli (e.g., letters), were developed based on the hypothesis that rapid naming is a precursor of accurate and efficient reading (see Figure 1.1) (Denckla & Rudel, 1976; Wolf, Bally, & Morris, 1986; Wolf & Bowers, 1999; Kirby, Parrila, & Pfeiffer, 2003).

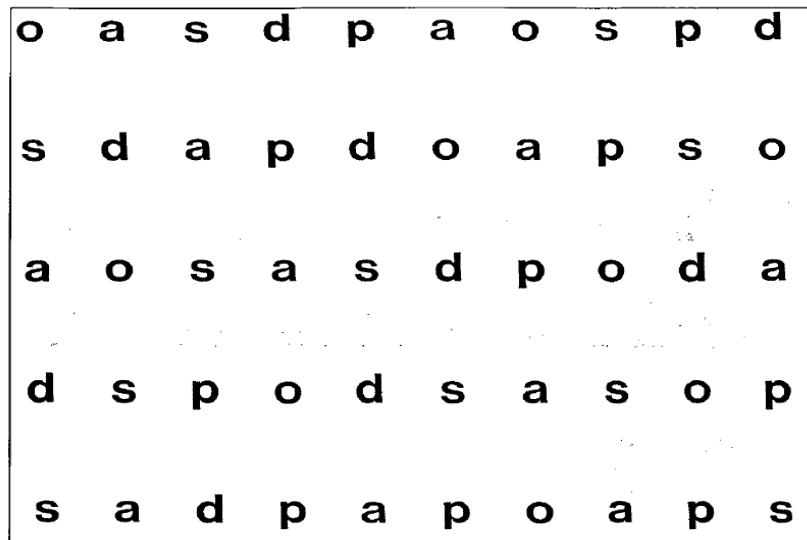


Figure 1.1. Original letter naming speed task (Denckla and Rudel, 1976). During this task subjects are instructed to name the letters out loud as quickly and accurately as possible from left to right starting at the top row. The time taken to do so and any errors are recorded.

Despite the consensus that NS and reading are related to one another, it is still unclear how they are related or what specific cognitive processes are involved (Kirby et al., 2010). One way to analyze this relationship is by changing the stimulus composition of a NS task to emphasize either visual and/or phonological aspects in order to examine the impact of orthographic and phonological processing. There are several ways to measure cognitive processes during these different tasks.

Eye movement recording has been used as a key tool to uncovering and understanding the cognitive processes that are involved in the reading process in normal readers (Rayner, 1997; Hyona & Olson, 1995). Eye movements may therefore be a useful tool to studying the underlying cognitive processes that are involved in NS tasks. This is because precise oculomotor control is required to visually scan the continuous array of letters in the visual display, and this same requirement is needed for reading lines of text. In addition to analyzing eye movement records, the total time to complete NS tasks can be separated into pause and articulation times, where an articulation time is the amount of time needed to name each stimulus, and pause time is the gap between the articulation of two successive stimuli (Neuhaus, Foorman, Francis, & Carlson, 2001). Analyzing pause times may provide insight into participants' on-line cognitive processing because it shows how long it takes for subjects to encode and process each stimulus, and prepare a response to that stimulus (Kirby et al., 2010).

The aim of this thesis is to investigate: (1) how NS and reading are related to one another, (2) how eye movements, NS performance, and NS components (pause and articulation times) are related to one another, (3) how these three measures are affected by single letter substitutions in a letter NS task designed to increase phonological and/or

visual processing, and (4) whether there are differences in task performance and NS-reading relations with increased reading development and between dyslexic and normal readers.

1.1 Reading Disabilities

Children with reading problems can be categorized into two groups – one in which these problems can be expected, and another in which they are not expected (Shaywitz, Mody, & Shaywitz, 2006; Vellutino et al., 2004). Children who have low general mental ability or who have had limited or inadequate reading instruction are expected and have been shown to have significant reading problems (Shaywitz, 2003). This group can be separated from children who would not be expected to develop a reading problem due to having the necessary intelligence, motivation, and instructional experiences that are normally associated with learning to read successfully, and do not have a non-neurological deficiency with vision or hearing (Shaywitz, 2003; Shaywitz et al., 2006; Vellutino et al., 2004). This latter group is referred to as having dyslexia.

1.1.1 A brief introduction to reading disabilities

Understanding how skilled readers process words provides a framework for studying reading development, and provides insight into possible causes of reading disabilities (Cain, 2010). Normal reading ability is characterised by having both fluent word identification and adequate language comprehension (Vellutino et al., 2004; Norton & Wolf, 2012). It has been proposed that there are four phases in which word reading develops, and successful completion of these four phases leads to normal reading ability (Ehri, 2005). In the pre-alphabetic phase, children have little or no knowledge of the alphabet and spoken words are arbitrarily associated with symbols such as pictures,

patterns, or letters. These children are not considered to be independent readers because they cannot read new words (Cain, 2010). In the partial alphabetic phase, knowledge of letter names and sounds is used to recognise words. In the full alphabetic phase, phonemic knowledge is applied in reading words from letter-sound correspondences. During this phase phonological processing, or the ability to use sounds in processing language, contributes to accuracy and fluency (Wagner & Torgesen, 1987; Gottardo, Stanovich, & Siegel, 1996; Torgesen, Wagner, Rashotte, Burgess, & Hecht, 1997). The consolidated alphabetic phase occurs between seven and nine years with words being recognized as chunks of familiar letter sequences, called orthographic representations, which allows for faster word recognition and improved literacy. This sequence for typical reading development has received empirical support for typical readers, but researchers are still unsure whether or not readers with dyslexia also follow this sequential reading development (Kerek & Niemi, 2009; Sprenger-Charolles, Siegel, Bechenec, & Serniclaes, 2003).

1.1.2 Clinical and diagnostic features of dyslexia

Dyslexia is a common neurobiological reading disability (Vellutino & Fletcher, 2005; Shaywitz & Shaywitz, 2005; 2008; Lyon, Shaywitz, & Shaywitz, 2003) that affects between 2 to 4% of children (Snowling, 2000; Cain, 2010; Shaywitz, Shaywitz, Fletcher, & Escobar, 1990). The symptoms of dyslexia are measured by reading achievement on standardized tests for reading accuracy, speed, and/or comprehension. The diagnosis of dyslexia is based on a discrepancy model in which individuals fall significantly below what is expected for their chronological age, measured intelligence, and age appropriate education (Shaywitz & Shaywitz, 2005; Shaywitz, 1996, 2003; Olitsky & Nelson, 2003;

Vellutino et al., 2004). Overall readers with dyslexia are characterized by having difficulties with accurate and/or fluent word recognition, and by having poor spelling and decoding abilities (Shaywitz & Shaywitz, 2005; Vellutino et al., 2004; Vellutino & Fletcher, 2005). This has been shown to significantly interfere with their academic achievement and with activities that require adequate reading skills, because these difficulties are associated with deficiencies in language comprehension, vocabulary knowledge, and/or syntactic competence (Vellutino & Fletcher, 2005).

Epidemiological research has shown that dyslexia fits a dimensional model, with reading ability and disability occurring on a continuum (Gilger, Borecki, Smith, DeFries, & Pennington, 1996; Shaywitz, Escobar, Shaywitz, Fletcher, & Makuch, 1992; Shaywitz & Shaywitz, 2005). Both prospective (Francis, Shaywitz, Stuebing, Shaywitz, & Fletcher, 1996; Shaywitz et al., 1995) and retrospective (Bruck, 1992; Felton, Naylor, & Wood, 1990; Scarborough, 1990) longitudinal studies have shown that over time, both poor readers and good readers maintain their relative positions along this continuum of reading ability (Shaywitz & Shaywitz, 2005). This demonstrates that dyslexia is not a ‘developmental lag’ that some children have with reading, rather it is a persistent and chronic condition (Shaywitz & Shaywitz, 2005). Studies have found that children who are at risk for developing a reading disability are more responsive to intervention programs, such as phonological awareness training programs, than children who are already failing to read (e.g. Ehri, Nunes, Stahl, & Willows, 2001; Bus and van Ijzendoorn, 1999). Therefore, if dyslexic readers do not receive the appropriate interventions during early language development, then they tend to maintain their relative position on this spectrum. This is typically seen in cases in which readers with mild

dyslexia receive the appropriate interventions they need as they are learning to read which results in few to no signs of having a reading problem in adulthood (Norton & Wolf, 2012). However, if readers have either severe dyslexia or do not receive the appropriate interventions then their reading disorders typically persist into adulthood (Norton & Wolf, 2012; Cain, 2010).

1.1.3 Psychological mechanisms

Multiple neurological, perceptual, and cognitive skills have been causally implicated with dyslexia. Currently, the most established theory is the phonological deficit hypothesis which proposes that dyslexia is caused by a deficit in the consolidation and/or retrieval of phonological or sound based codes (Brady & Shankweiler, 1991; Frith, 1985; Snowling, 1981; Snowling, 2000; Stanovich, 1988). This phonological deficit is then argued to impede the acquisition of alphabetic knowledge and decoding which affects the succession of development in: word recognition, fluent reading, and comprehension (Misra, Katzir, Wolf, & Poldrack, 2004; Bradley & Bryant, 1983; Catts, 1996; Wagner, Torgesen, & Rashotte, 1994).

Another established theory is the NS deficit hypothesis in which 60 to 75% of individuals with a reading disability have been found to have impaired timing mechanisms which affect reading fluency (Norton & Wolf, 2012; Katzir et al., 2008; Wolf et al., 2002; Waber, Wolff, Forbes, & Weiler, 2000). This deficit affects the acquisition of the associations between phonemic and orthographic information, which in turn impairs readers ability to fluently detect frequently occurring patterns in text (Cain, 2010). Researchers have found that phonological awareness and NS tasks are only moderately correlated ($r = 0.3$) in both reading impaired (Cornwall, 1992) and normally

achieving samples (Blachman, 1984; Mann, 1984). This indicates that even though NS has an influential phonological component that is needed when retrieving labels of presented items, it is still significantly different from phonology and contributes independent variance to reading fluency (Bowers, 1993; Bowers & Swanson, 1991; de Jong & van der Leij, 1999; Kirby et al., 2003; Young & Bowers, 1995; Kirby et al., 2010; Norton & Wolf, 2012; Cain, 2010; Swanson, Tainin, Neoechea, & Hammill, 2003; Manis, Seidenberg, & Doi, 1999). Furthermore, some children who perform poorly on NS tasks do well on phonological awareness tasks (Powell, Stainthorp, Stuart, Garwood, & Quinlan, 2007).

Wolf and Bowers (1999) proposed that there are multiple subtypes of dyslexia characterized by the presence or absence of phonological processing deficits, NS deficits, or both. Readers with a double deficit are considered to be the most at-risk for developing a reading disability and are the most impaired readers (Wolf & Bowers, 1999; Kirby et al., 2010; Vellutino et al., 2004; Norton & Wolf, 2012; Wolf et al., 2002). Four types of evidence support this double deficit hypothesis. First, letter and digit NS tasks have consistently been found to account for unique variance in reading performance after controlling phonological awareness (Manis, Doi, & Bhadha, 2000; Wolf et al., 2000). Wolf and Bowers (1999) argued that the functional independence of phonology and NS relies on the multi-componential nature of NS, and phonological skill cannot explain all of the variance found in reading measures. Second, studies have shown that readers who have a double deficit perform significantly below readers with neither deficit on independent measures of reading achievement (Vellutino et al., 2004; Wolf et al., 2000). Third, NS and phonological awareness are differentially related to reading subskills,

phonological awareness being more strongly correlated with accuracy in word identification and letter-sound decoding, and NS being more strongly correlated with speed of word identification and speed of letter-sound decoding (Vellutino et al., 2004; Manis et al., 2000; Wolf et al., 2000). Fourth, readers with double deficits are more severely impaired in reading compared to readers with single deficits (Morris et al., 1998). Therefore, there may be two independent causes of dyslexia: deficits in phonological awareness and NS, which can either occur independently of one another in a single deficit, or together in a double deficit.

1.1.4 What is the source of this deficit?

In order to understand the aetiology of dyslexia, it is important to consider the different potential levels of explanations. The behavioural expression of dyslexia is an inability or difficulty with reading, however the possible underlying causes for this symptom have been located at the cognitive, biological and the genetic levels.

Researchers have attempted to analyze dyslexia's aetiology by identifying and localizing the specific neural systems that are involved in reading by using functional magnetic resonance imaging (fMRI) (Vellutino & Fletcher, 2005; Shaywitz et al., 2006; Shaywitz & Shaywitz, 2005). fMRI is a “snapshot” imaging method of the brain that is sensitive to changes in the blood oxygenation level dependent (BOLD) signal that reflects neural activation (Shaywitz et al., 2003). During a cognitive task, such as reading, specific areas of the brain become activated which leads to an increase of oxygen being supplied to these regions. fMRI detects these subtle changes in blood flow providing real-time information about which brain areas are activated and inhibited during task performance (Price & McCrory, 2005). This can then be compared between different

conditions and/or different groups of subjects to evaluate the relative magnitudes of their different responses (Shaywitz et al., 2003; Frackowiak et al., 2004; Shaywitz et al., 2006).

There are three neural systems in the left hemisphere, one anterior and two posterior, that carry the majority of the workload for reading in normal readers (see Figure 1.2) (Price & Mechelli, 2005; Shaywitz & Shaywitz, 2005). In the anterior region the inferior frontal gyrus, commonly referred to as Broca's area, serves articulation and word analysis. The second and third neural systems are in the posterior region - the temporoparietal region also serves word analysis and integrates information across visual and auditory modalities, and the occipitotemporal region, or the word-form area, serves for the rapid, automatic, and fluent identification of words (Shaywitz et al., 2003; Norton & Wolf, 2012). Overall, normally-achieving readers show greater activation in these three neural systems compared to dyslexic readers (Shaywitz et al., 2006). As children become better readers, more brain activity takes place in the occipitotemporal region which allows word recognition to become more automatic and fluent. This growing efficiency in brain processing does not occur in readers who have dyslexia (Shaywitz et al., 2003), and the low activation in the occipitotemporal regions and overactivation in the anterior systems compared to normal readers has been referred to as the neural signature of dyslexia (Price & Mechelli, 2005; Shaywitz & Shaywitz, 2005). This low activation is thought to be a key reason readers with dyslexia cannot rapidly and effortlessly recognize familiar words (Dehaene, Cohen, Sigman, & Vinckier, 2005). However, fMRI studies have found that these three neural systems for reading are malleable and do respond to effective reading interventions (Shaywitz et al., 2006;

Shaywitz et al., 2004; Shaywitz & Shaywitz, 2005), which emphasizes the importance of early diagnosis and intervention (Shaywitz & Shaywitz, 2008).

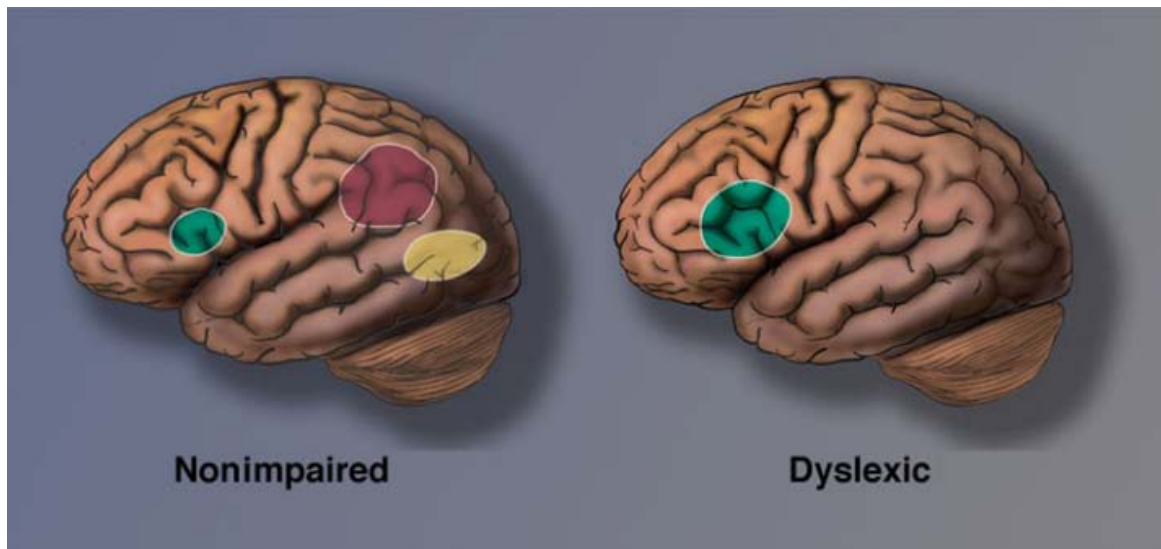


Figure 1.2. Neural systems of reading (Shaywitz, 2003). Studies have indicated three important systems in reading, all primarily in the left hemisphere. These include an anterior system and two posterior systems: 1. anterior system in the left inferior frontal gyrus or Broca's area; 2. dorsal temporoparietal system involving angular gyrus, supramarginal gyrus and posterior portions of the superior temporal gyrus; 3. ventral occipitotemporal system involving portions of the middle temporal gyrus and middle occipital gyrus. The low activation in the posterior systems and over activation in the anterior system compared to normal readers is referred to as the neural signature of dyslexia.

Currently, only one study has used fMRI to investigate the neural substrates that underlie performance during NS tasks. Misra et al. (2004) found that during a letter NS task average adult readers showed an increased activation in the left inferior frontal gyrus, left posterior middle frontal gyrus, bilateral inferior occipital areas, and left parietal and right frontal areas. These regions are consistent with areas that are involved in the reading networks and in tasks that require eye movement control and attention (Norton & Wolf, 2012). These findings indicate that NS tasks recruit the same network of

neural structures that are involved in reading, and demonstrate that letter NS tasks target key structures of this network. Researchers have yet to examine whether or not there is similar activation in readers with dyslexia during NS tasks.

The differences in neural activation between normal readers and readers with dyslexia have sparked theories that this may be influenced by genetic factors. Research has shown that dyslexia may be heritable (Pennington & Gilger, 1996), with heritability estimates ranging widely from 30 to 70% (Scarborough, 1990; Shaywitz & Shaywitz, 2005; Vellutino et al., 2004). Due to the different reading measures, diagnostic criteria, and the methods used in the literature it is difficult to ascertain the precise level of heritability of dyslexia (Norton & Wolf, 2012). The concordance of dyslexia has been reported to be higher in monozygotic than in dizygotic twins (Scerri & Schulte-Korne, 2010; Norton & Wolf, 2012). Researchers have found that phonological awareness, NS, and reading are affected by both common and separate genetic influences (Compton, Davis, DeFries, Gayan, & Olson, 2001; Petrill, Stainthorp, Stuart, Garwood, & Quinlan, 2006; Byrne et al., 2005). Eight chromosomes, with at least nine major candidate genes, have been identified and located as the genetic markers for dyslexia (Scerri & Schulte-Korne, 2010; Fisher & DeFries, 2002; Kibby & Hynd, 2001) and are mostly related to neuronal migration and axonal growth in utero (Galaburda, LoTurco, Ramus, Fitch, & Rosen, 2006).

Overall more research needs to be conducted to further understand these findings, especially the genetic markers, because it is still not clear whether the differences in the location of these genes account for polygenic inheritance, for different cognitive paths that lead to the same phenotype, or to the different sub-types of dyslexia (Shaywitz &

Shaywitz, 2005). It is also crucial for future research to link findings from fMRI and genetics to understand how biology and behavior interact with one another to affect reading ability (Norton & Wolf, 2012).

1.2 Naming Speed and Reading

The processes involved in the rapid naming of simple alphanumeric stimuli (e.g., letters) comprise a large subset of the same processes that are used during fluent reading of continuous text by skilled readers (Kirby et al., 2010). Thus, NS has been argued to be an earlier and a simpler approximation of the reading process (e.g., Denckla & Cutting, 1999), and has been shown to assess skills that are needed for fluent reading performance, word reading accuracy, and comprehension that is independent of phonological processing (Wolf et al., 2000; Kirby et al., 2010; Norton & Wolf, 2012; Kirby et al., 2003). Even though researchers have used different variations of NS tasks, such as the number of items to be named and the number of rows and columns of stimuli, there still exists a strong relationship between NS and reading (Norton & Wolf, 2012). This relationship is found as long as the factors that underlie the theoretical links between NS and reading are still intact, such as naming in a serial, left-to-right fashion, and subjects' familiarity with the presented stimuli (Norton & Wolf, 2012).

Furthermore, studies have found that continuous NS tasks (in which stimuli are presented in a serial list) are stronger and more consistent predictors of reading ability and discriminate task performance between dyslexics and controls compared with discrete NS tasks (in which stimuli are presented individually) (Denckla & Cutting, 1999). This indicates that the increased number of processes involved in serial naming tasks, such as visual scanning, saccadic eye movements, and sequencing of multiple

items, represent a 'microcosm' of the processes required for fluent reading (Wolf & Bowers, 1999).

1.2.1 Naming speed

NS is defined as the ability to quickly and accurately name a set of visually presented highly familiar stimuli (e.g., letters, digits, colors, or objects) randomly presented repeatedly in a left-to-right, top-to-bottom serial fashion (see Figure 1.1) (Kirby et al., 2010; Wolf & Bowers, 1999; Denckla, 1972; Denckla & Rudel, 1976; Wolf et al., 2000; Neuhaus et al., 2001; Norton & Wolf, 2012). NS tasks can be used to address the current controversy in reading research regarding whether reading ability and development are solely influenced by phonological skill, or if there are other non-linguistic processes such as visual processing, attention, and general timing capacity that are also involved.

1.2.1.1 Theories postulated to explain the naming speed- reading relationship

A number of theories have been proposed to explain the relationship that exists between NS and reading, based on the different conceptual analyses of the processes that are involved in either NS or reading (Kirby et al., 2010). However, these theories all share a similar view that NS and oral reading are similar because in both tasks subjects are required to move their eyes sequentially across the page, encode the stimulus that they are focusing on, access the mental representation of that stimulus, and then activate the associated motor instructions for naming that stimulus (Kirby et al., 2010). Overall, these theories are not mutually exclusive from one another but each targets different pieces of the puzzle of how NS is related to reading.

Some reading researchers have argued that NS is part of the realm of phonology because NS tasks require individuals to access rapidly phonological representations of stimuli. NS was initially referred to as "phonological recoding in lexical access" because it assesses the rate of access to and retrieval of stored phonological information from long-term memory (Schatschneider & Torgesen, 2004; Wagner, Torgesen, Laughon, Simmons, & Rashotte, 1993).

Researchers have also proposed that NS deficits are a reflection of deficits in general processing speed, which is the speed at which cognitive processing occurs (Kail, Hall, & Caskey, 1999; Kail & Hall, 1994; Norton & Wolf, 2012). Therefore, it is argued that NS and reading are related to one another because they both depend on fast and efficient cognitive processing (Kail et al., 1999; Cain, 2010). However, there has been little support for this theory in the field. Powell et al. (2007) and Cutting & Denckla (2001) found that even though children who had slower naming times also had slower global processing speeds, NS was significantly correlated with reading even after controlling for general processing speed. Thus, even though NS and reading are affected by general processing speed in terms of speed and fluency, NS builds on the existing architecture for more general processing speed (Norton & Wolf, 2012).

Other researchers have argued that NS should not just be classified as phonological because there are other non-phonological components, such as orthography, that are also important in this task (Schatschneider & Torgesen, 2004; Manis et al., 1999). During skilled reading, groups of letters or entire words are processed orthographically as single units instead of as sequences of grapheme-phoneme correspondences (Kirby et al., 2010; Ehri, 1997). This has been supported by evidence that shows that letter and digit

NS tasks account for more variance in orthographic processing than do phonological processing tasks (Manis et al., 2000). If individuals are too slow in identifying letters, which is reflected by slow naming times, then letter representations in words will not be activated quickly enough for individuals to become sensitive to commonly occurring orthographic patterns (Kirby et al., 2010).

Slow NS is a characteristic that has been found to differentiate between dyslexic readers and controls (Kirby et al., 2003; Papadopoulos, Georgiou, & Kendeou, 2009). It is argued that there are three ways in which slow NS may be contributing to dyslexics' problems with reading. First, slow NS prevents the appropriate amalgamation of the connections between phonemes and orthographic patterns at the subword and word levels of representations. Second, it limits quality of orthographic representations in long-term memory. Third, it increases the amount of practice needed before an orthographic code is learned as a lexical or a sublexical unit, and before representations of sufficient quality are achieved. Therefore, if dyslexics are slow in identifying individual letters in a NS task then single letters in a word will not be activated in sufficiently close temporal proximity to allow individuals to become sensitive to letter patterns that frequently co-occur in print (Wolf et al., 2000). The causes for NS deficits are still not known, but NS depends upon a complex system so slow NS may involve the breakdown of any one of the subsystems. Individuals may either have a breakdown in single or multiple components, or they may have a failure in being able to integrate information across subprocesses.

1.2.1.2 Variations of NS tasks

Recent studies have sought to determine whether there are other important components of NS that are predictive of reading ability that are outside the realm of

phonology. For example, Compton (2003) compared the accuracy and letter NS performance of 383 first-grade dyslexic and non-dyslexic readers on NS tasks that were either visually and/or phonologically similar (see Figure 1.3). He reported four main findings. First, increasing visual similarity decreased NS speed and accuracy and overall had the greatest effect on performance compared to tasks with increased phonological similarity. Second, performance on tasks with increased phonological similarity was a better predictor of future word identification skill compared to tasks with increased visual similarity. Third, both accuracy and speed had similar predictive power for future word identification skill. Fourth, when controlling for initial reading skill, both speed and accuracy on the NS tasks predicted future word identification skill regardless of similarity.

Although the phonologically similar NS task was found to be a better predictor of future word identification in a dominance analysis, it was the visually similar task that significantly decreased speed and accuracy. This is not surprising because visual similarity will affect subjects' ability to distinguish between letters quickly. This finding was further supported by an eye-movement study conducted by Jones, Obregon, Kelly, and Branigan (2008) who found that dyslexics' performance was impaired by the increased visual-orthographic similarity of the letters which was shown with an increased fixation time and naming latency for target letters. Stainthorp, Powell, Stuart, Quinlan, and Garwood (2010) also found that 8 to 10 year olds with slow NS had a deficit in discriminating visual features of letters, and concluded that this may hamper some children's ability to learn letter-sound correspondences during reading acquisition.

Changing the stimulus composition of NS tasks, to emphasize either visual and/or phonological aspects, contributes to understanding the components that underlie NS and to understanding NS deficits that may be characteristic of individuals with reading difficulties. Compton's (2003) results show that, even in first grade children who are beginning to learn to read, NS performance can be significantly affected by single letter substitutions which affect the predictive relationship between NS and future word identification skill. However, the fact that subjects in Compton's study were in first grade may be tied to the finding that phonological similarity had a greater effect on the NS-reading relationship than visually similarity, because phonological factors dominate during early reading acquisition when readers are learning letter-sound correspondences. Overall, the results of these studies show that there are other non-phonological components, such as orthographic skill, that are also important in NS. They also show that there may be a partial dissociation between the effects of visual and phonological factors in NS and its relationship with reading ability.

Original (OR)

Letter matrix of **a, d, o, p, s**

o	a	s	d	p	a	o	s	p	d
s	d	a	p	d	o	a	p	s	o
a	o	s	p	s	d	p	o	d	a
d	a	p	o	d	s	a	s	o	p
s	o	d	p	a	p	o	a	d	s

Phonologically Similar (PS)

Replace o for v; **a, d, v, p, s**

d	a	p	v	d	s	a	s	v	p
s	v	d	p	a	p	v	a	d	s
v	a	s	d	p	a	v	s	p	d
s	d	a	p	d	v	a	p	s	v
a	v	s	p	s	d	p	v	d	a

Visually Similar (VS)

Replace o for q; **a, d, q, p, s**

a	q	s	p	s	d	p	q	d	a
d	a	p	q	d	s	a	s	q	p
s	q	d	p	a	p	q	a	d	s
q	a	s	d	p	a	q	s	p	d
s	d	a	p	d	q	a	p	s	q

Visually & Phonologically Similar (VPS)

Replace o for b; **a, d, b, p, s**

s	b	d	p	a	p	b	a	d	s
b	a	s	d	p	a	b	s	p	d
s	d	a	p	d	b	a	p	s	b
a	b	s	p	s	d	p	b	d	a
d	a	p	b	d	s	a	s	b	p

Figure 1.3. Variations of naming speed tasks. The Original NS Task was developed by Denckla & Rudel (1976). The Phonologically Similar (PS), Visually Similar (VS), and Visually and Phonologically Similar Task (VPS) were developed by Compton (2003).

1.2.2 Naming speed components

Researchers typically only measure overall naming times during NS tasks.

However, total naming time does not show important individual differences in reading-related processes, such as attentional control, and does not allow researchers to

adequately determine the underlying nature of these NS tasks (Neuhaus et al., 2001).

Therefore, as an attempt to understand the processes that underlie NS, researchers have separated naming times into the articulation times of stimulus names and pause times

between the articulation of names (Neuhaus et al., 2001; Jones et al., 2008; Norton & Wolf, 2012). This is important for both theoretical and practice reasons. From a theoretical stand point, it is important in allowing researchers to understand what processes underlie NS, what processes different NS tasks share, and what accounts for the relationship between NS and reading ability (Georgiou, Parrila, & Kirby, 2009; Clarke, Hulme, & Snowling, 2005; Georgiou, Parrila, Kirby, & Stephenson, 2008; Lervag & Hulme, 2009; Neuhaus & Swank, 2002). From a practical standpoint, decomposing NS provides researchers with more information regarding what happens during a NS task, and may help improve existing intervention programs by targeting specific interventions to the specific NS deficits that individuals have (Georgiou, Parrila, & Kirby, 2009).

Pause times, more so than articulation times, have been found to be significantly related to reading ability, perhaps because they indicate how long it takes individuals to process and prepare a response to stimuli (Kirby et al., 2010; Georgiou et al., 2006; 2008; 2009; Clarke et al., 2005; Neuhaus et al., 2001). Neuhaus et al. (2001) found that pause times during a letter NS task and the consistency of letter pause times (defined as the variance of the mean pause times of the 50 stimuli) consistently predicted decoding and reading comprehension compared to pause times during digits and objects NS tasks for a sample of 50 Grade 1 and Grade 2 subjects with no known learning disabilities. They concluded that pause times during a letter NS task predicted reading because of the unique speed of processing demands that are associated with retrieving letter knowledge, compared to the more general verbal processing speed demands needed during pause time of an object NS task (Neuhaus et al., 2001). These findings were also supported in a

follow-up study by Neuhaus and Swank (2002) who found that pause times during a letter NS task, and the consistency of pause and articulation times, were all significantly associated with reading in a large sample of Grade 1 students (N=221).

Anderson, Podwall, and Jaffe (1984) found, in a study with six 8-10 year old dyslexic children and six control children who were matched on age, sex, and IQ, that pause and articulation components of the dyslexic readers were slower than the component scores of control readers on letters, digits, colors, and objects NS tasks. Similarly, Obregon (1994) investigated the effects of time spent on errors, articulation time, pause time, and the end-of-line scanning time on color, object, and letter NS tasks by six adolescents with dyslexia and six controls. These two groups did not differ significantly on time spent on errors, articulation time, or end-of-line scanning time in any of the three NS tasks. Pause times were found to be significantly different for all three tasks, with the letter NS task pause times being the shortest and showing the largest differences between the groups. Georgiou et al. (2006) also found that only pause time in color and letter NS tasks was significantly related to Grade 1 word reading and reading fluency measures. Similarly, Clarke et al. (2005) found in a digit NS task that only articulation time was related to word and non-word reading ability, whereas pause and articulation times on a letter NS task were found to be related to word reading but not non-word reading. Pause times more so than articulation times may be the key to understanding the underlying mechanisms that drive the relation between NS and reading (Georgiou et al., 2006). This is supported by studies that report findings that variability that children show in NS tasks, especially between dyslexics and controls, is predominantly due to the length of pauses and not the length of articulations.

Wolf and Bowers (1999) postulated that the longer pause times that are generally found for dyslexic readers compared to non-dyslexic readers may reflect subjects' inability to disengage attention from an already-named stimulus and engage in processing the next stimulus. This was later termed by Hari and Renvall (2001) as a 'Sluggish Attentional Shifting' (SAS). Therefore, longer pause times found in dyslexic readers are thought to be due to difficulties in processing multiply presented items. However, this is mainly speculative because solely analyzing speech streams cannot identify which point during a pause time reflects a disengagement from one stimulus and an engagement and processing of the next stimulus (Jones et al., 2008); for that eye movements are required.

NS components have not yet been related to NS task variations, or to eye movements. Analyzing eye movement records during NS tasks, especially during NS components, should allow researchers to determine the extent to which reading disabilities can be solely attributed to faulty eye movements, or whether there are underlying neurological issues that are being manifested in these faulty eye movements.

1.3 Reading and Eye Movements

Researchers have found that eye movement records are valuable in being able to uncover the cognitive and perceptual skills of normal readers (Rayner, 1985; 1997; Starr & Rayner, 2001; Olitsky & Nelson, 2003; Rayner, Juhasz, & Pollatsek, 2005; Hyona & Olson, 1995). The variability that occurs in these eye movement measures is then a reflection of the variability that occurs in on-line processing (Rayner, 1997).

During reading, three primary characteristics occur. First, there is a series of eye movements, or saccades, in which the eyes move very rapidly. Second, these saccades are separated by periods of time in which the eyes are relatively still, called fixations. Due to

the high velocity of the saccade, no useful information is acquired when the eyes are moving; readers only acquire information from the text during the fixations (Rayner, 1997; Olitsky & Nelson, 2003). Third, 10-15% of the time readers move their eyes back in the text to look at material that has already been read – these are named regressions. Regressions are thought to be due to problems in comprehending the material, large forward saccades, semantic control, or inference making (Pavlidis, 1985; Rayner, 1997; Olitsky & Nelson, 2003).

Eye movement studies using normal readers have shown that there is generally an inverse relationship between age and the duration of fixations, and between age and the number of forward and regressive eye movements. Researchers have found a developmental trend in eye movements as reading skill increases and faster information processing occurs: fixation duration decreases, saccade length increases, and the frequency of regressions decreases (Buswell, 1922; Olitsky & Nelson, 2003). The most marked changes occur between beginner readers and readers who are in third or fourth grade: when children have had four years of reading experience, their eye movements are not too different from adults - the only exception being that the frequency of regressions is greater for children than for adults (Rayner et al., 2005). Conversely, as the difficulty of text increases, fixation duration increases, saccade length decreases, and regression frequency increases. Thus the variability in fixation time and saccade length that occurs between readers, and even within readers, has been thought to be related to cognitive processes that are associated with comprehension (Rayner, 1997).

Compared to normal readers, readers with dyslexia have been found to make longer and more fixations, shorter saccades, and more regressions (Rayner, 1985; Olitsky

& Nelson, 2003). These findings have led to three hypotheses to explain the differences in eye movements between these two groups (Olitsky & Nelson, 2003; Rayner, 1998). First, dyslexics' eye movements are a reflection of the problems that they have with the reading material; in other words, as they become more confused, their eye movements become more erratic. Second, erratic eye movements may sometimes be the cause of dyslexia. Third, erratic eye movements are the symptoms of one or more commonly shared or independent but parallel central deficits for readers with dyslexia. More research needs to be conducted to determine which, if any, of these three theories actually explains the atypical eye movements that are observed in readers with dyslexia.

The pattern of eye movements during NS tasks can be used to predict eye movements that may be found during reading, because these two tasks are very similar to one another. For example, in both tasks subjects are required to move their eyes sequentially across the page, encode the stimulus that they are focusing on, access the mental representation of that stimulus, and then activate the associated instructions for naming that stimulus (Kirby et al., 2010). Furthermore, precise oculomotor control is required in both tasks and aberrant eye movements and fixations in dyslexics have been theorized to contribute to reading disability (Stein & Walsh, 1997; Stein, 2003; Stein & Talcott, 2001). The magnocellular system is responsible for stabilizing readers' fixations and directing eye movements, thus impairments to this system lead to unstable fixations and poor control of eye movements. This further leads to information acquired during fixations being less than optimal, leading to more regressions required to go back and name words that have already been read (Stein, 2003). During NS tasks, this would lead to slower naming times and more errors. When analyzing dyslexics' performance a task

other than reading needs to be used, because if there are differences in their performance compared to controls it will not be clear whether this is due to their problems with reading or due to other underlying problems (Olson, Kliegl, & Davidson, 1983).

Therefore, the administration of NS tasks can help identify differences in performance between dyslexics and controls because it assesses the foundational subskills that are needed to develop more complex grapheme-phoneme knowledge (Kirby et al., 2010), while also controlling for stimulus familiarity so participants cannot be confused by the material that is presented to them.

1.4 Thesis Objectives

The objectives of this project are to understand: (1) how NS is related to reading, (2) how eye movements, NS performance, and NS components are related to one another, (3) how these three measures are affected by phonological and/or visual confusability, and (4) whether there are differences in performance with increased reading ability or between dyslexic and average readers. Overall, this study will contribute to understanding the components that underlie NS and to understanding NS deficits that individuals with reading difficulties may have. It will allow us to determine the extent to which NS performance can be significantly affected by single letter substitutions, and the extent to which these affect the predictive relationship between NS and reading ability. The results from this study may also inform the design of specific educational interventions that target these specific NS component deficits (i.e. visual, phonological, or both) that individuals with reading difficulties may have. Therefore, this study will contribute to a better interpretation of the aetiology of dyslexia in general, and to the

development of better assessment and intervention tools for dyslexia in both clinical and educational settings.

Chapter 2

Saccade characteristics and pause/articulation times during a letter naming speed task: Children with and without dyslexia

2.1 Introduction

A considerable amount of evidence in the field of reading disabilities has found that phonological processing deficits are at the core of reading failure. However, recent research has shown that a second core deficit is related to naming speed (Wolf, Bowers, & Biddle, 2000). Reading is a linguistic activity that is intimately tied to language processing, and so it has been argued that rapid labeling of visual stimuli is an effective way to measure this language processing (Denckla & Cutting, 1999). Naming speed (NS) tasks, in which subjects are asked to name highly familiar stimuli (such as letters) in a visual array as quickly and accurately as possible, were then developed based on the hypothesis that rapid naming is a precursor of both accurate and efficient reading.

NS tasks have been shown to be an independent source of variance in predicting concurrent and future reading ability in both developing readers and in poor readers (Georgiou, Parrila, Manolitsis, & Kirby, 2011; Neuhaus, Foorman, Francis, & Carlson, 2001; Compton, 2003). It has been argued that the processes that are involved in the rapid naming of these simple alphanumeric stimuli comprise a large subset of the same processes used during fluent reading of continuous text by skilled readers (Kirby, Georgiou, Martinussen, & Parrila, 2010; Denckla & Cutting, 1999; Wolf et al., 2000). Therefore, due to the similarities between these two tasks NS has been described as a “microcosm of reading” (Wolf & Bowers, 1999), and may be able to highlight problems

that readers have at an early stage (Georgiou et al., 2011). Early administration of this task can then be useful for screening for reading difficulties because it assesses some of the foundational subskills needed to develop more complex grapheme-phoneme knowledge (Kirby et al., 2010). However, even though NS tasks have been used for several decades to predict reading ability, it is still unclear what mechanisms or cognitive processes underlie this relationship (Kirby, Parrila, & Pfeiffer, 2003; Georgiou, Parrila, & Kirby, 2009).

A number of theories have been proposed to explain this NS-reading relationship. One of the theoretical positions has been that NS is fundamentally a phonological task because it assesses how rapidly subjects can access phonological codes from their lexical store (Torgesen, Wagner, & Rashotte, 1994; Torgesen, Wagner, Rashotte, Burgess, & Hecht, 1997). If this is the case then increasing the phonological difficulty of a NS task should negatively affect naming performance, and should strengthen the relationship between NS and reading. The phonological interpretation has been disputed by researchers who argue that there are other non-phonological components, such as orthography and speed, which are also important in this task. These researchers have argued that NS also assesses the automaticity of recognizing symbolic visual stimuli, which in turn contributes to orthographic processing (Bowers & Newby-Clarke, 2002; Bowers, 1993). If this is the case, then increasing the visual difficulty of a NS task should negatively affect naming performance and should strengthen the relationship between NS and reading. This leads to two key questions: (1) how is NS related to reading ability? and (2) are there other important components of NS that are predictive of reading ability outside the realm of phonology?

In this study, three methods were used to examine the impact of phonological and orthographic processing on this relationship. First, the stimulus composition of a letter NS task was manipulated to emphasize either phonological and/or visual processing (Compton, 2003). This was done to determine which component had the greater effect on NS performance and its relation with reading, and to determine whether there were differences in the ways that dyslexic and control subjects responded to these different stimuli. Second, naming times during the tasks were separated into components of pause and articulation times (Georgiou, Parrila, & Kirby, 2006). Analyzing pause times provides insight into subjects' on-line cognitive processing because it shows how long it takes for subjects to encode and process each stimulus, and prepare a response to that stimulus (Kirby et al., 2010). Third, eye position records during the tasks were analyzed to examine underlying cognitive processes and to determine which eye movement characteristics (e.g., fixation duration, and number of saccades and regressions) were most affected by the array manipulations and were most related to overall naming performance and reading ability.

To examine the impact of phonological and orthographic processing on the relationship between NS and reading, Compton (2003) adapted Denckla and Rudel's (1976) letter NS task to create three versions that were more phonologically and/or visually similar. He administered these four versions to first-grade children with and without dyslexia, and accuracy and naming time were used to predict word identification skill months later. He found that the visually similar NS task significantly impaired dyslexic reading on speed and accuracy compared with non-dyslexic reading, but it did not account for unique variance in predicting future word identification skill compared to

the other three tasks. It was the two tasks that increased phonological processing (PS and VPS tasks) that predicted unique variance in word identification skill.

A limitation of these results is that it is not clear whether these differences are due to the fact that most of the participants were at risk or already had a reading disability. Compton's results may also be affected by the age of the participants. Grade 1 is a period of time in which phonological processing dominates because children are learning how to read (Georgiou, Parrila, Kirby, & Stephenson, 2008; Kirby et al., 2003), which may explain why Compton found that the phonologically similar task was a better predictor of future reading.

To further understand the mechanisms that underlie the NS-reading relationship, naming times during these tasks have been separated into pause and articulation times. Articulation time is the amount of time needed to name a stimulus, and the pause time is the gap between the articulations of two stimuli (Neuhaus et al., 2001). Pause times are thought to measure the automaticity of retrieving phonological codes from the lexical store, recognizing stimuli, and shifting attention from one stimulus to the next. Articulation time has been shown to represent subjects' automaticity of generating a response to name stimuli once it has been recognized (Hulme, Newton, Cowan, Stuart, & Brown, 1999; Neuhaus et al., 2001). Pause times have been found to be significantly related to reading more so than articulation times (Neuhaus et al., 2001; Neuhaus & Swank, 2002; Georgiou et al., 2006). Variability in performance between average readers and dyslexics has been found to be due to the longer pause times in this latter group (Neuhaus et al., 2001). Therefore, decomposing naming times allows us to highlight important individual differences in reading-related processes, such as attentional control,

and understand the underlying cognitive processes that are involved in NS tasks and in its relationship to reading.

The last approach we used to understand the mechanisms that underlie the NS-reading relationship was by analyzing eye movement records during the NS tasks and how they relate to overall NS performance and reading ability. Eye movement research is a key tool to uncovering and understanding the mechanisms that are involved in the reading process (Hyona & Olson, 1995; Rayner, 1997). The variability that occurs in eye movement measures can then be thought of as a reflection of the variability that occurs in on-line processing (Rayner, 1997).

Eye movements during NS tasks may show many of the same characteristics found in reading tasks because these two tasks are very similar to one another (Kuperman & Van Dyke, 2011). For example, in both tasks subjects are required to move their eyes sequentially across a page, encode the stimulus that they are focusing on, access the mental representation of that stimulus, and then activate the associated instructions for naming that stimulus (Kirby et al., 2010). Eye movements during NS tasks may provide clues regarding the relationship between NS and reading. For example, longer fixation durations would implicate weaker orthographic processing as the basis of the relationship, whereas an increased number of saccades could implicate difficulties in eye movement control under speeded conditions. Furthermore, eye movements made during NS tasks such as those developed by Compton (2003) may provide greater detail regarding the phonological and orthographic explanations of the NS-reading relationship.

Even though a number of studies have attempted to analyze eye movements during NS tasks, it is difficult to compare their results. This is due to the different

methodologies, tasks or groups of participants that each study uses. For example, Jones, Obregón, Kelly, and Branigan (2008) used the traditional NS format (4 rows x 10 stimuli) and only phonologically or visually similar pairs of letter were analyzed within each condition for English-speaking adult dyslexics and controls. They found that increasing phonological or visual similarity between adjacent letters on the task slowed naming speed in both dyslexic and control adult groups, and this was worse for dyslexics.

This finding was not supported by Jones, Branigan, Hatzidaki, and Obregón (2010) who also used the traditional NS format with English-speaking dyslexics and controls but with a display-change paradigm in which the phonologically or visually similar letters appeared parafoveally. For example, in the visually similar condition, when a participant fixated the target item q (in position n), the visually-similar letter p appeared in the parafovea (in position $n + 1$). They found that increasing phonological similarity of parafoveal information did not affect performance for either dyslexic or control adult groups, and increasing orthographic similarity of parafoveal information only negatively affected the dyslexic group. Jones, Ashby, and Branigan (2013) also found that foveal processing for controls was significantly affected by orthographically-similar parafoveal letters, but was affected by phonologically-similar parafoveal letters for dyslexics. They also found that controls had longer fixation durations when parafoveal letters were orthographically similar, but dyslexics had longer fixation durations when parafoveal letters were phonologically similar.

Lastly, Yan, Pan, Laubrock, Kliegl, and Shu (2013) used a gaze-contingent moving paradigm, in which the amount of parafoveal information was manipulated (full preview, no preview), with Chinese-speaking dyslexic and control children to examine

whether inefficiency of parafoveal processing leads to slow naming times that are typically found for dyslexics. Yan et al. (2013) found that dyslexics extracted less parafoveal information than controls, indicating that dyslexics may allocate more attentional resources towards mapping visual symbols to orthographic representations during the foveal stage of processing. This is thought to be due to the fact that translating visual symbols into phonological output is not an automatic process for dyslexics, and this reduces their perceptual span which leads to an inefficient preactivation of parafoveal information and more difficulty in processing the next foveal item.

2.1.1 Present study

The goal of this present study is to use stimulus manipulations, NS components, and eye-movement methodology to: (1) analyze how NS is related to reading, (2) determine whether NS performance, NS components, and eye movements are affected by increasing visual and/or phonological similarity, (3) determine whether visual or phonological similarity contributes more to the NS-reading relationship, and (4) investigate whether there are difference in NS performance and eye movements between dyslexics and average readers or with increased reading ability. We investigate three groups of participants: dyslexics, chronological-age (CA) matched controls, and reading-level (RL) matched controls. This experimental design aims to isolate causal variables which may be important for explaining why reading fails to develop normally. The design does this by comparing dyslexics (a) with normal younger readers (the RL matched controls) reading at the same developmental level as the dyslexics, and (b) with children who have average reading ability and are of the same age and IQ (the CA matched controls). The importance of doing this is because if there are differences in

performance between dyslexics and CA controls then it will not be clear whether this difference is due to dyslexic's reading disability. Therefore, both control groups are necessary to establish a causal argument and any differences found between dyslexics and RL controls in NS and/or eye movement performance point towards potential causal factors involved with dyslexia because these two groups have the same reading ability (Cain, 2010).

We use a letter NS task and three variants that are either phonologically and/or visually similar (Compton, 2003) while subjects' eye movements and articulations are recorded. Studies using a priming paradigm to examine letter naming processes have reported that substituting a letter that was visually similar to a letter in the matrix had the greatest influence on speed and accuracy, and this was worse for dyslexics compared to controls (e.g., Arguin & Bub, 1995; Compton, 2003). These findings suggest that for all three groups, visually similar substitutions should negatively affect performance more so than phonological substitutions, and CA controls will perform better than dyslexics and RL controls.

With respect to the NS components, based on Georgiou et al.'s (2006) findings we hypothesize that variability in NS performance, especially between dyslexics and CA controls, will be due to dyslexics' longer pause times more so than articulation times. We further hypothesize, based on the results of Neuhaus et al. (2001) and Neuhaus and Swank (2002), that reading ability, both in terms of group and individual reading scores, will be more related to pause time than articulation time.

Lastly, with respect to eye movements, and based on the work by Jones et al. (2008; 2013) and Yan et al. (2013), we hypothesize that the CA controls will have shorter

fixations, longer saccades, and fewer regressions compared to dyslexics and RL controls, and that these same variables will be related to individual reading scores. We further hypothesize that all three groups will have longer fixations, and more saccades and regressions in the visually similar task compared to the phonologically similar task.

2.2 Methods

2.2.1 Participants

Experimental procedures were approved by the Queen's University Research and Ethics Board, and complied with the principles of the Canadian Tri-council Policy Statement on Ethical Conduct for Research Involving Humans and the principles of the Declaration of Helsinki (1964). Participants were recruited through the Kingston community or through Kingston Reading Clinics, and parents gave their written and informed consent prior to testing. Three groups of 15 participants each took part in this study: one dyslexic group (ages 8.1 - 10.9 years, 11 males, mean age = 9.8 years, $SD = .75$) and two control groups – a chronological-age (CA) matched group (ages 8.1 - 10.9 years, 6 males, mean age = 9.7 years, $SD = .68$), and a reading-level (RL) matched group (ages 6.9 - 7.9 years, 7 males, mean age = 7.3 years, $SD = .34$). The two control groups were formed based on raw scores of reading ability on the Woodcock Reading Mastery Test – Revised Form G, Word Identification Subtest. Figure 2.1 portrays how these three groups were distributed on reading level and age. Participants from the dyslexic group were either formally diagnosed as having dyslexia or they scored in the same range that an individual with dyslexia would score on the Woodcock Word Identification test.

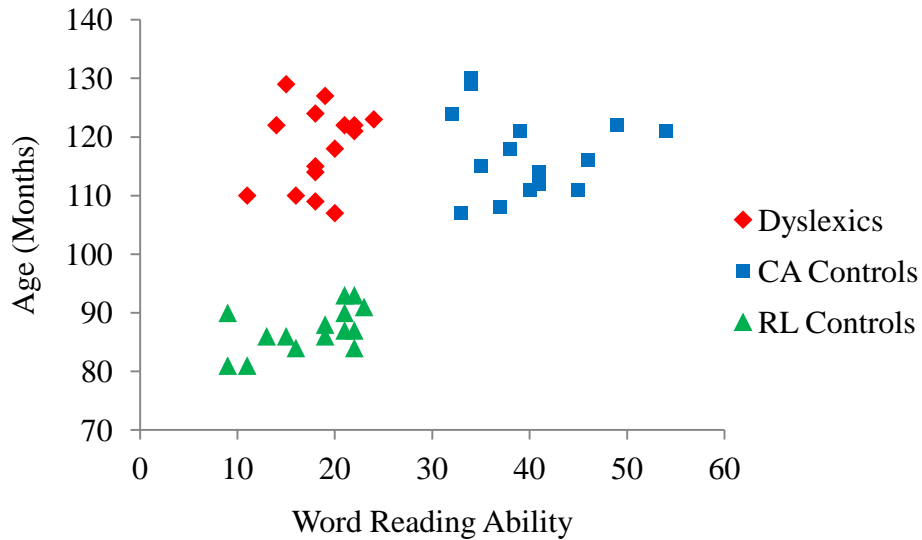


Figure 2.1. Participants' age and word reading ability. Reading ability was based on scores on the Woodcock Reading Mastery Test – Revised Form G, Word Identification Subtest.

2.2.2 Measures

Letter Naming Speed

Four versions (2 trials/version) of a letter NS task were administered: the original (OR) task developed by Denckla and Rudel (1976) with the letter matrix composed of *a*, *d*, *o*, *p*, *s*, and three adaptations to this task developed by Compton (2003) – tasks with (a) increased visual similarity (VS) (*o* replaced with *q*), (b) increased phonological similarity (PS) (*o* replaced with *v*) or (c) both increased visual and phonological similarity (VPS) (*o* replaced with *b*) (see Figure 1.3). Each NS task presented 50 letters simultaneously visible with ten repetitions of the five letters arranged semi-randomly in five rows of ten. Participants were instructed to name all the letters as quickly and accurately as possible from left to right and top to bottom, and their articulations and eye movements were recorded. Prior to the presentation of the tasks, two practice trials were administered. In

the first practice trial participants were asked to name the eight letters that were going to be used (i.e., *a, d, b, p, s, q, o, v*) in order to assess their familiarity with the letter names; participants who were not able to name all eight letters accurately were to be taken out of the data analysis. All participants recruited for this study were able to accurately name all 8 letters. In the second practice trial, a NS task consisting of 20 letters in four rows with a random assortment of the eight letters was administered to ensure adequate familiarity with the letters and an understanding with the requirements of the task. Wolf and Denckla (2005) reported test-retest reliability to be .92 across ages. Participants' efficiency scores on these tasks were defined as the number of letters correct/ second and were calculated by dividing total naming time by the number of letters named correctly.

Tests of Reading Ability

Reading ability was assessed with three tasks: Word Identification, Sight Word Efficiency, and WordChains. In Word Identification (taken from the *Woodcock Reading Mastery Test-Revised Form G (WRMT-R)*) participants were asked to read aloud 106 words that increased in difficulty until they either attempted all the words or made six consecutive errors. Participants' scores were the number of words read correctly. Sight Word Efficiency was taken from the Test of Word Reading Efficiency (TOWRE; Wagner, Torgesen, & Rashotte, 1999). Participants were presented with a list of 104 words divided into four columns of 26 words each that increased in difficulty and were asked to read the words out loud as quickly as possible. A short eight-word practice list was presented before the test. Participants' scores were the number of words read correctly within the 45-s time limit. Test-retest reliability coefficients have been reported to range from .82 to .87 (Wagner et al., 1999). In WordChains, participants were asked to

identify words that were presented as a continuous line of print without inter-word spaces by inserting a slash between the words (e.g., *boygomeet* → *boy/go/meet*). The test included 17 rows of words of increasing length. The first two rows consisted of two words put together and the last three rows consisted of seven words put together. Participants' scores were the number of correctly placed slashes minus the number of errors and slashes omitted (up to the last inserted slash) within the one minute time limit.

Decoding ability was assessed with two measures: Phonemic Decoding Efficiency and Word Attack. Phonemic Decoding Efficiency was taken from the Test of Word Reading Efficiency (TOWRE; Wagner et al., 1999). Children were asked to read as fast as possible a list of 63 pseudowords that increased in difficulty. A short eight-word practice list was presented before the test. Participants' scores were the number of pseudowords read correctly within the 45-s time limit. Word Attack was taken from the WRMT-R. Children were asked to read aloud 45 pseudowords that increased in difficulty until they either attempted all the words or made six consecutive errors. Participants' scores were the number of pseudowords read correctly.

Tests of Mental Ability

Both verbal and nonverbal ability were assessed by measures taken from the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999). Verbal ability was assessed with the Vocabulary subtest in the WASI. Participants were asked to provide definitions of 29 words that were presented both orally and visually. All items were scored 2, 1, or 0 points depending on participants' definitions. 2-point responses showed a good understanding of the word's meaning, 1-point responses were essentially correct showed only a vague understanding of the word's meaning, and 0-point responses were

incorrect. Following standardized administration procedures, testing began from item five for all participants and ended upon completion of the test or after four consecutive scores of 0. Nonverbal ability was assessed with the Matrix Reasoning subtest of the WASI. Thirty-five incomplete visual patterns each with five possible pieces to complete the patterns were shown to participants one at a time. Participants were asked to point to the piece that would best complete the pattern. Participants were either scored 1 for a correct answer, or 0 for an incorrect answer. Following standardized administration procedures, testing began from item seven and ended upon completion of all items or after five consecutive errors. Both raw scores and T scores were recorded, the latter being age-standardized scores (mean = 50, SD = 10) as defined in the test manual.

2.2.3 Procedure

Testing took one hour and was divided into two sessions with each lasting approximately 30 minutes. In the first session the reading and mental ability tests were administered. In the second session the four NS tasks with two trials/task were administered, while eye movements and articulations were recorded; the four NS tasks were counterbalanced for order. The order of tasks was otherwise fixed across participants so that individual differences would not be confounded with differences in task presentation. Upon completion of the study, participants received \$20 compensation for their participation.

2.2.4 Eye-tracking and visual display

Eye position was recorded during the NS tasks by using the Eyelink 1000 head free eye tracking system (SR Research Ltd, Mississauga, ON). The 17" LCD monitor and mounted infrared camera were at a distance of 600mm from the right eye. All recordings

and calibrations were done monocularly based on the right eye; viewing was binocular. The position of the right pupil was digitized in both the vertical and the horizontal axes at a sampling rate of 500Hz and average gaze position error of $<0.5^{\circ}$. Before administration of the NS tasks, the eye movements of each participant were calibrated using nine target locations on the screen (eight around the periphery and one central). The targets were flashed sequentially around the screen and the participant fixated on each one. After calibration, the process was repeated to validate that the average error between fixation and target was $<2^{\circ}$ and that no loss of eye tracking occurred.

For the NS tasks, each trial started with illumination of a central fixation point (FP) for 800ms. The FP then disappeared and the array of letters appeared on the monitor. The letters were presented in black print (Century Gothic font, size 28) on a white background, with a 2.98° viewing distance between each letter and 1.85° viewing distance between each row. Participants were requested to remain as still as possible while they named the letters on the screen, and the system recorded their saccades and fixation durations. Participants' vocal responses were recorded by a microphone attached to the infrared camera of the eye tracker. After naming the last letter on the visual array subjects were told that the next NS task will be presented. No feedback was given on performance. After every two NS trials a picture appeared on the monitor to indicate a break.

2.2.5 Analysis of sound files

The sound files containing the letter naming responses for each subject were analyzed using custom software developed in MatLab (Version R2011a; MathWorks Inc., Natick, MA, USA). Data extraction was completed following the procedure

described in detail by Georgiou and colleagues (2006). Before estimating the means for NS pause and articulation times, four types of data cleaning took place. First, if there was an incorrect articulation, then the preceding pause time, the incorrect articulation, and the following pause time were removed. Second, if there was a self-correction, then everything between the two correct articulations were removed. Third, if a stimulus was skipped then the pause time between the two correct articulations and the articulation time that followed the skip were removed. Fourth, if off-task behavior (e.g., coughing, self-encouragement) was observed between two articulations, the specific pause time was removed. Therefore, articulation time in this study represented the mean of those articulation times that were correctly verbalized and were not preceded by a skipped stimulus. Pause time in this study represented the mean of the pause times between two correctly articulated stimuli.

2.2.6 Data analysis

Eye-movement data and articulations were marked and analyzed using custom software developed in MatLab (Version R2011a; MathWorks Inc., Natick, MA, USA). Eye position and articulations were recorded continuously from the start to end of each trial. For the eye tracking data, the variables of interest were: fixation durations, total number of saccades and regressions, and the eye-voice span at the beginning of the task. Fixation duration was defined as the average duration (in milliseconds) of all fixations in the trial. The cutoffs for determining both the onset and termination of a saccade were determined by using the saccade parameters of velocity threshold, 30 deg/sec, and acceleration threshold, 8000 deg/sec². When the parameters were above these thresholds it marked the beginning of a saccade, and when they dropped below these thresholds it

marked the end of a saccade. Regressions were defined as leftward saccades that were within 30 degrees of visual angle from the horizontal and were less than 10 degrees in amplitude (so as to ignore blinks and eye movements to the next line). The eye-voice span was defined as the distance between the position of the eyes at the beginning of articulation of the first letter of each task and the first letter, specified in numbers of letters. For example, if the eyes were on the first letter when articulation began, the eye-voice span would be 1. The beginning of each task was chosen to simplify the analysis because it avoided the need to identify what letter came before the eye-voice span and whether this had an impact on performance, and whether participants had made mistakes. Eye tracking data that were associated with skips or errors were manually removed from the data analyses. Eye-movement measures reported are the means calculated for the two trials/task.

2.2.7 Statistical analysis

Statistical analysis of data was completed using SPSS Statistics v19.0 (IBM, Chicago, IL, USA). Differences between groups on the tasks were analyzed using two-way repeated measures analyses of variance (ANOVA). The between-subjects factor had three levels representing the three groups (CA controls, RL controls, and dyslexics), and the within-subjects factor had four levels representing the four tasks (OR, PS, VS, and VPS). Separate analyses were conducted for NS performance (NS efficiency and number of errors), NS components (articulation and pause times), eye movement measures (fixation durations, and number of saccades and regressions), and the eye-voice span. A one-way ANOVA coupled with Bonferroni post hoc tests for multiple comparisons was conducted to determine whether the three groups differed significantly on the above

measures. Bivariate correlations were calculated to describe the relationships between the dependent variables. Lastly, paired sample *t*-tests were calculated to compare the four tasks with one another to test whether the versions were significantly different.

Significant differences across Groups (CA controls, RL controls and dyslexics) and task (OR, PS, VS, and VPS) will be explicitly highlighted in the Results section and Figures.

2.3 Results

2.3.1 Reading and cognitive measures performance

The descriptive statistics on all reading and cognitive measures are presented by group in Table 2.1. A MANOVA, with the reading measures as the dependent variables and group as the between-subjects factor, revealed a significant main effect of group, Wilk's $\lambda = 0.30$, $F(8, 148) = 5.26$, $p < .001$. Subsequent univariate ANOVAs (shown in Table 2.1) revealed that the groups differed significantly on all reading measures ($ps < .001$). Bonferroni post hoc tests indicated that CA controls obtained significantly higher scores than RL controls and dyslexics on all reading measures ($p < .001$), and that dyslexics performed better than the RL controls on Word Attack ($p < .001$). The groups were also compared on Vocabulary and Matrix Reasoning raw and T scores (see Table 2.1). For Vocabulary Raw Score ($p < .001$), CA controls performed better than RL controls and dyslexics ($p < .05$). For Vocabulary T Score, the only significant difference was between CA controls and dyslexics ($p < .01$). For Matrix Reasoning, the only significant difference was between the two control groups ($p < .05$), and for Matrix T Score, there was no significant difference among the three groups ($p > .05$).

Table 2.1.

Descriptive statistics of dyslexic and control groups on reading and cognitive measures.

	CA Control (<i>n</i> = 15)		RL Control (<i>n</i> = 15)		Dyslexics (<i>n</i> = 15)		<i>F</i> (2,44)	η_p^2
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>		
Word Identification	39.87	6.35	17.53	4.98	18.40	3.40	93.97**	.82
TOWRE SWE	67.93	10.44	28.47	14.74	38.73	15.55	33.21**	.61
WordChains	31.54	6.78	.31	11.52	7.43	14.26	27.04**	.59
TOWRE PDE	38.00	12.78	15.80	8.42	18.07	7.41	23.22**	.53
Word Attack	25.67	2.72	8.13	3.54	15.13	6.09	61.43**	.75
WASI	21.33	5.52	14.73	5.26	18.87	5.60	13.61**	.39
Vocabulary								
WASI	58.20	9.44	54.80	7.60	48.13	8.67	5.32**	.20
Vocabulary T Score								
Matrix Reasoning	40.60	7.57	28.33	4.70	33.87	6.74	5.59*	.21
Matrix Reasoning T Score	51.93	11.31	54.13	8.52	48.33	9.01	1.37	.06

Note. TOWRE=Test of Word Reading Efficiency; SWE=Sight Word Efficiency; PDE=Phonemic Decoding Efficiency; WASI= Wechsler Abbreviated Scale of Intelligence. * $p < .05$; ** $p < .001$.

2.3.1.1 Factor analysis of reading measures

To simplify the analyses of the relationship of NS performance and eye movement measures with reading ability, an overall reading ability measure was formed by conducting a factor analysis based on principal axis factoring (PAF) for the five reading measures (see Table 2.2). PAF was chosen in order to select the least number of factors which can account for the correlation between the reading measures. This analysis extracted one factor which was identified as overall reading ability. Regression factor scores were calculated for this factor, and a univariate ANOVA with Bonferroni post hoc comparisons revealed that the three groups differed significantly from one another on overall reading ability ($p < .001$). All subsequent reading analyses refer to the factor score for overall reading ability.

Table 2.2.

Factor analysis based on principal axis factoring.

Variables	Factor 1: Reading Measures
Word Identification	.84
Sight Word Efficiency	.95
Word Attack	.91
Phonemic Decoding Efficiency	.84
WordChains	.80
Eigenvalue	4.03
% of Total Variance	80.63

2.3.1.2 Implications of group differences

Groups were originally formed so that they would differ appropriately on age and Word Identification. The only reading measure that varied from this pattern was Word

Attack, on which dyslexics performed better than RL controls. We interpret this to mean that dyslexics have had considerably more instruction in phonics than the younger children, and decided not to take this difference into account in subsequent analyses. The groups did not differ on Matrix Reasoning T score, from which we conclude that they had the same overall mental ability. The differences on both the raw and T scores for Vocabulary are more of a concern, in that the low scores of the dyslexics could cause other differences that are not specifically due to dyslexia. However, vocabulary is affected by reading, because a considerable amount of vocabulary is learned through reading and dyslexics read less than non-dyslexics (Scarborough & Parker, 2003; Shaywitz et al., 1995). Furthermore it would be difficult to control for vocabulary when only two of the groups differed, and controlling vocabulary could have different effects in the different groups. We decided to carry out subsequent analyses without controlling for vocabulary differences.

2.3.2 Naming speed efficiency and naming errors

Correlations, means, and standard deviations for naming speed efficiency and the number of errors for each naming speed task are presented in Table 2.3. The correlations between efficiency scores on the four tasks ranged from .80 to .88, and from .50 to .57 for the number of errors. The correlations between efficiency and errors ranged from .34 to .73. To analyze how efficiency was correlated with number of errors across the tasks and to make further analyses easier to present, the versions were collapsed by calculating the mean of the z-scores of the four tasks (see Table 2.3). Across groups, efficiency and number of errors were strongly correlated ($r = -.67, ps < .01$).

Table 2.3.

Correlations, means, and standard deviations for overall reading ability and naming speed performance (naming efficiency scores and number of errors).

	1	2	3	4	5	6	7	8	9	10	11
1. Reading Ability	-										
2. Average Efficiency	.41**	-									
3. Average Errors Efficiency	-.35*	-.67**	-								
4. OR	.35*	.96**	-.62**	-							
5. PS	.38*	.95**	-.63**	.88**	-						
6. VS	.46**	.93**	-.72**	.86**	.84**	-					
7. VPS	.37*	.93**	-.57**	.86**	.84**	.80**	-				
8. OR	-.20	-.44**	.80**	-.49**	-.39**	-.43**	-.36*	-			
9. PS	-.31*	-.47**	.82**	-.42**	-.54**	-.48**	-.34*	.57**	-		
10. VS	-.34*	-.58**	.81**	-.50**	-.51**	-.73**	-.44**	.50**	.56**	-	
11. VPS	-.31*	-.71**	.83**	-.61**	-.63**	-.71**	-.71**	.55**	.56**	.60**	-
<i>M</i>	-	-	-	1.32	1.27	1.03	1.02	2.23	2.46	5.40	5.71
<i>SD</i>	-	-	-	.38	.35	.33	.32	2.61	2.43	5.80	3.64

Note. OR = Original NS Task; PS= Phonologically Similar NS Task; VS = Visually Similar NS Task; VPS = Visually and Phonologically Similar NS Task. Efficiency Scores represent the number of letters correct/second. $N = 45$. * $p < .05$; ** $p < .01$.

2.3.2.1 The influence of letter composition on naming speed efficiency and naming errors

Two two-way repeated measure ANOVAs were used to examine the effects of letter composition (the four NS tasks) and group (CA controls, RL controls, and dyslexics) separately for efficiency and number of errors (see Figure 2.2, A and B).

For efficiency, the results showed significant main effects of group, $F(2, 42) = 9.64, p < .001, d = .32$, and task, $F(3, 126) = 57.90, p < .001, d = .58$, but no significant interaction effect, $F(6, 126) = .88, p = .51, d = .04$. The group effect was examined with a one-way ANOVA coupled with Bonferroni post hoc tests using the average z-score of the four tasks. Overall, CA controls were significantly more efficient than the RL controls and dyslexics ($p < .01$), and these latter two groups were not significantly different from one another ($p > .05$). To examine the task effect, paired-samples t -tests revealed that the OR and PS tasks were not significantly different from one another, $t(44) = 1.92, p > .05, r = .88$, and neither were the VS and VPS tasks, $t(44) = .58, p > .05, r = .80$. The OR and PS tasks as well as the VS and VPS tasks were combined, and a paired-samples t -test revealed that OR-PS efficiency was higher than VS-VPS efficiency, $t(44) = 12.85, p < .001, r = .92$, suggesting that efficiency is a function of the visual similarity of the letters and not of the phonological similarity.

For number of errors, the results showed significant effects for group, $F(2, 42) = 5.69, p = .01, d = .21$, task, $F(3, 126) = 20.90, p < .001, d = .33$, and the group x task interaction, $F(6, 126) = 2.40, p = .03, d = .10$. The group effect was examined with a one-way ANOVA using the average z-score of the four tasks; the CA controls made significantly fewer errors than the RL controls ($p < .01$), and there was no significant

difference between dyslexics and RL controls ($p > .05$). The task and group x task effects were further analyzed with paired-samples t -tests. The OR and PS tasks were not significantly different from one another, $t(44) = .64, p > .05, r = .57$, and neither were the VS and VPS tasks, $t(44) = .45, p > .05, r = .66$. The OR and PS tasks as well as the VS and VPS tasks were combined, and a paired-samples t -test revealed that these two combinations were significantly different from one another, $t(44) = 6.76, p < .001, r = .68$, suggesting that the task effect is a function of the visual similarity of the letters and not of the phonological similarity. With respect to the interaction, dyslexics were similar to the CA controls on the OR-PS score ($p > .05$), but made fewer errors than the RL controls ($p < .05$), whereas they were similar to the RL controls on the VS-VPS score ($p > .05$) but made more errors than the CA controls ($p < .05$).

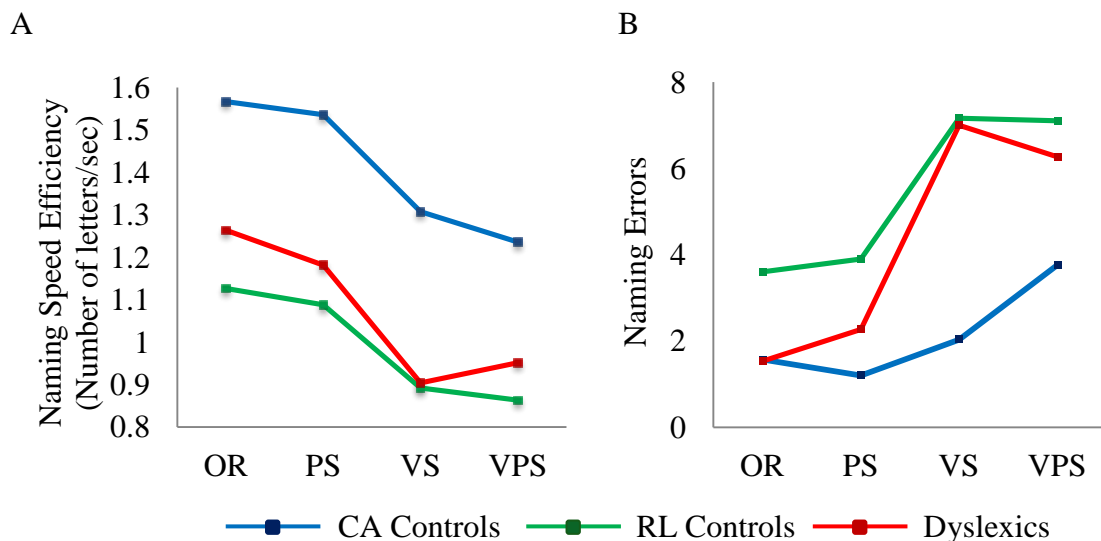


Figure 2.2. Group by version effect on NS performance. (A) Efficiency score. (B) Errors. Note. OR = Original NS Task; PS = Phonologically Similar NS Task; VS = Visually Similar NS Task; VPS = Visually and Phonologically Similar NS Task.

2.3.2.2 NS-reading relationship

Having established that both efficiency and errors are affected by single letter substitutions and that there were significant group differences across the tasks, the next

step was to determine whether NS performance was related to overall reading ability. Average efficiency scores were positively correlated with overall reading ability ($r = .41$, $p < .01$), and errors were negatively correlated with overall reading ability ($r = -.35$, $p < .05$). Further analyses revealed that efficiency on all four tasks was significantly positively correlated with overall reading ability, and errors on all tasks except for OR were significantly negatively correlated with overall reading ability ($p < .05$) (see Table 2.3). The VS task was the best correlate with overall reading ability for both efficiency and number of errors (see Table 2.3).

2.3.3 Naming speed components

Correlations, means, and standard deviations for articulation and pause times for each task are presented in Table 2.4. All correlations were significant ($p < .05$). The correlation between articulation times on the four tasks ranged from .62 to .88, and from .77 to .88 for pause times. The correlations between articulation and pause times were more modest, ranging from .42 to .65. To simplify subsequent analyses, the versions were collapsed by calculating the mean of the z-scores of the four tasks (see Table 2.4). Across groups, articulation and pause times were strongly correlated ($r = .57$, $ps < .01$).

Table 2.4.

Correlations, means, and standard deviations for overall reading ability and naming speed components (articulation and pause times).

	1	2	3	4	5	6	7	8	9	10	11
1. Overall Reading Ability	-										
2. Average Articulation Time	-.31*	-									
3. Average Pause Time	-.31*	.57**	-								
4. OR	-.34*	.91**	.58**	-							
5. PS	-.31*	.93**	.60**	.88**	-						
6. VS	-.18	.84**	.41**	.62**	.70**	-					
7. VPS	-.26	.90**	.44**	.77**	.75**	.68**	-				
8. OR	-.32*	.55**	.94**	.65**	.62**	.29	.42**	-			
9. PS	-.33*	.54**	.95**	.52**	.62**	.38*	.39**	.88**	-		
10. VS	-.22	.45**	.91**	.42**	.44**	.48**	.27	.77**	.84**	-	
11. VPS	-.28	.58**	.93**	.58**	.56**	.38*	.55**	.87**	.84**	.78**	-
<i>M</i>	-	-	-	18.7	19.2	19.1	19.0	17.8	17.8	19.2	19.5
<i>SD</i>	-	-	-	2.5	2.6	2.2	2.4	7.7	7.4	6.4	7.2

Note. OR = Original NS Task; PS = Phonologically Similar NS Task; VS = Visually Similar NS Task; VPS = Visually and Phonologically Similar NS Task. Time is in seconds. $N = 45$. * $p < .05$; ** $p < .01$.

2.3.3.1 The influence of letter composition on naming speed components

Two two-way repeated measures ANOVAs were used to examine the effects of group (CA controls, RL controls, and dyslexics) and letter composition (the four NS tasks) separately on articulation and pause times (see Figure 2.3, A and B).

For articulation time there was only a significant main effect for group, $F(2, 42) = 4.27, p = .02, d = .17$, but no significant task effect, $F(3, 126) = 1.68, p = .18, d = .04$, or interaction effect, $F(6, 126) = 1.90, p = .09, d = .08$. The group effect was analyzed through a one-way ANOVA with Bonferroni comparisons using the average z -score of the four tasks; CA controls made significantly shorter articulation times than the RL controls ($p < .05$), and there was no significant difference between the dyslexics and the two control groups ($p > .05$).

For pause time, there were significant effects for group, $F(2, 42) = 5.19, p < .01, d = .20$, and task, $F(3, 126) = 4.23, p = .01, d = .09$, but no significant interaction effect, $F(6, 126) = .99, p = .43, d = .05$. The group effect was analyzed with a one-way ANOVA with Bonferroni post hoc tests using the average z -score of the four tasks; CA controls made significantly shorter pause times than the RL controls and dyslexics ($p < .05$), with no significant difference between dyslexics and RL controls ($p > .05$). To further analyze the task effect, paired-samples t -tests demonstrated that the OR and PS task pause times did not differ from one another, $t(44) = .04, p > .05, r = .88$, and neither did the VS and VPS, $t(44) = .37, p > .05, r = .78$. The OR-PS tasks and the VS-VPS tasks were combined, and a paired-samples t -test revealed that VS-VPS pause times are longer than OR-PS pause times, $t(44) = 3.50, p < .001, r = .91$, indicating that it is visual similarity and not phonological similarity that increases subjects' pause times.

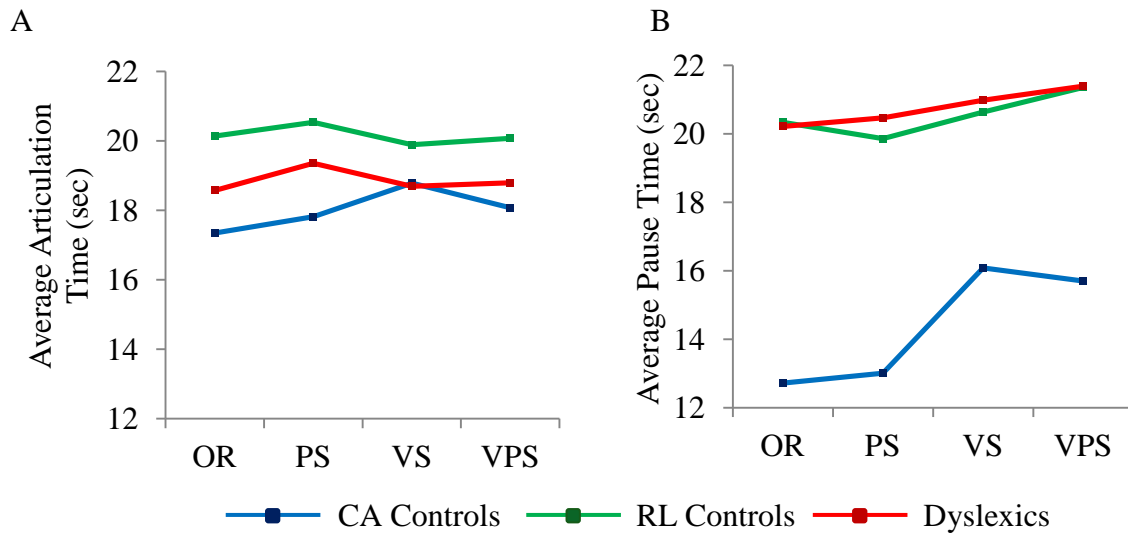


Figure 2.3. Group by version effect on NS components. (A) Articulation time. (B) Pause time. *Note.* OR = Original NS Task; PS = Phonologically Similar NS Task; VS = Visually Similar NS Task; VPS = Visually and Phonologically Similar NS Task.

2.3.3.2 NS components and reading

Having established that both articulation and pause times can be affected by single letter substitutions and that there were significant group differences across the tasks, the next step was to determine whether these components are related to overall reading ability. Average articulation and pause time across the four tasks were negatively correlated with overall reading ability ($p < .05$) (see Table 2.4). Further analyses revealed that overall reading ability is only correlated with the OR and PS tasks for both articulation and pause time ($p < .05$).

2.3.4 Eye movement measures

Correlations, means, and standard deviations for fixation duration, saccade count, and regression count in the four NS tasks are presented in Table 2.5. All correlations within a measure across tasks were significant ($p < .01$). The correlation between fixation duration on the four tasks ranged from .80 to .88, from .44 to .69 for saccade count, and

from .71 to .75 for regression count. Saccade count and regression count are the only measures that are significantly correlated with one another ($p < .05$), and ranged from .41 to .83. To simplify subsequent analyses, the versions were collapsed by calculating the mean of the z-scores of the four tasks (see Table 2.5). Across groups, saccade count and regression count were strongly correlated ($r = .81, ps < .01$).

Table 2.5.

Correlations, means, and standard deviations for overall reading ability and eye movement measures.

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.
1. Overall Reading Ability	-															
2. Average Fixation Duration	-.39**	-														
3. Average Saccade Count	-.13	-.05	-													
4. Average Regression Count	-.16	.08	.81**	-												
5. OR	-.47**	.93**	-.01	.12	-											
6. PS	-.33*	.95**	-.04	.08	.87**	-										
7. VS	-.39**	.92**	-.10	-.01	.80**	.83**	-									
8. VPS	-.29	.95**	-.03	.12	.84**	.88**	.83**	-								
9. OR	-.08	.00	.87**	.71**	.01	.03	-.04	.00	-							
10. PS	-.17	.00	.81**	.68**	.04	-.01	-.11	.07	.60**	-						
11. VS	.00	-.18	.85**	.71**	-.15	-.16	-.26	-.10	.69**	.63**	-					
12. VPS	-.18	.01	.75**	.56**	.07	.00	.07	-.08	.56**	.44**	.47**	-				
13. OR	-.07	.09	.73**	.89**	.07	.10	.05	.13	.80**	.51**	.66**	.45**	-			
14. PS	-.23	.09	.72**	.88**	.13	.06	-.01	.14	.59**	.83**	.54**	.41**	.71**	-		
15. VS	-.11	-.02	.71**	.91**	.03	-.02	-.11	.02	.56**	.56**	.77**	.45**	.75**	.74**	-	
16. VPS	-.16	.13	.71**	.89**	.19	.14	.03	.12	.57**	.53**	.56**	.67**	.72**	.70**	.74**	-
<i>M</i>	-	-	-	-	429.5	449.5	470.3	459.1	85.8	86.2	93.3	95.8	16.8	16.3	19.9	20.6
<i>SD</i>	-	-	-	-	95.1	110.4	91.0	94.3	18.2	14.9	22.0	20.7	6.5	5.7	8.3	8.0

Note. OR = Original NS Task; PS = Phonologically Similar NS Task; VS = Visually Similar NS Task; VPS = Visually and Phonologically Similar NS Task. Fixation Duration is measured in milliseconds. $N = 45$. * $p < .05$; ** $p < .01$.

2.3.4.1 The influence of letter composition on eye movement measures

Three two-way ANOVAs with repeated measures were used to examine the effects of letter composition (the four NS tasks) and group (CA controls, RL controls, and dyslexics) separately for fixation duration, saccade count, and regression count (see Figure 2.4, A, B, and C).

For fixation duration, there were significant main effects for group, $F(2, 42) = 6.02, p < .01, d = .22$, and task, $F(3, 126) = 8.42, p < .001, d = .17$, but no significant interaction effect, $F(6, 126) = .69, p = .66, d = .03$. The group effect was investigated with a one-way ANOVA and Bonferroni post hoc tests comparing the average z-scores of the four tasks; CA controls made significantly shorter fixation durations than RL controls ($p < .01$), with no significant difference between the dyslexics and the two control groups ($p > .05$). The task effect was further analyzed with paired-samples t -tests which revealed that all the tasks were significantly different from one another ($p < .05$) except for the PS-VPS tasks and the VS-VPS tasks ($p > .05$). The PS-VPS tasks and the VS-VPS tasks were combined, and a paired-samples t -test revealed that VS-VPS fixation durations are longer than PS-VPS fixation durations, $t(44) = 2.24, p < .05, r = .95$, suggesting that it is visual similarity of the letters that increases fixation duration.

Similarly, for saccade count there were significant effects for group, $F(2, 42) = 3.67, p = .03, d = .15$, and task, $F(3, 126) = 6.94, p < .001, d = .14$, but no significant interaction effect, $F(6, 126) = 1.17, p = .33, d = .05$. To analyze the group effect, a one-way ANOVA with Bonferroni post hoc tests was conducted and indicated that CA controls made significantly fewer saccades than dyslexics ($p < .05$), but did not make fewer saccades than the RL controls ($p > .05$). To analyze task effect, paired samples t -

tests revealed that the OR and PS tasks were not significantly different from one another, $t(44) = .208, p > .05, r = .60$, and neither were the VS and VPS tasks, $t(44) = .760, p > .05, r = .47$. Conducting another paired samples t -test after combining the OR-PS tasks and the VS-VPS tasks revealed that there were a greater number of saccades on the VS-VPS tasks than the OR-PS tasks, $t(44) = 4.80, p < .001, r = .76$, suggesting that increasing visual similarity of the letters in the matrix increased number of saccades.

For regression count there were significant main effects for group, $F(2, 42) = 4.43, p = .02, d = .17$, and task, $F(3, 126) = 13.77, p < .001, d = .25$, but no significant interaction effect, $F(6, 126) = 1.58, p = .16, d = .07$. To examine the group effect, one-way ANOVAs with Bonferroni post hoc tests revealed that CA controls made significantly fewer regressions than dyslexics ($p < .05$) but not RL controls ($p > .05$). Furthermore, paired samples t -tests were conducted to analyze the task effect and indicated that the OR and PS tasks were not significantly different from one another, $t(44) = .76, p > .05, r = .71$, and neither were the VS and VPS tasks, $t(44) = .80, p > .05, r = .74$. The OR-PS tasks and the VS-VPS tasks were combined to further analyze these results, and a paired-samples t -test revealed that number of regressions was higher on the VS-VPS task than the OR-PS task, $t(44) = 5.82, p < .001, r = .84$, indicating that it is visual similarity and not phonological similarity that increases number of regressions.

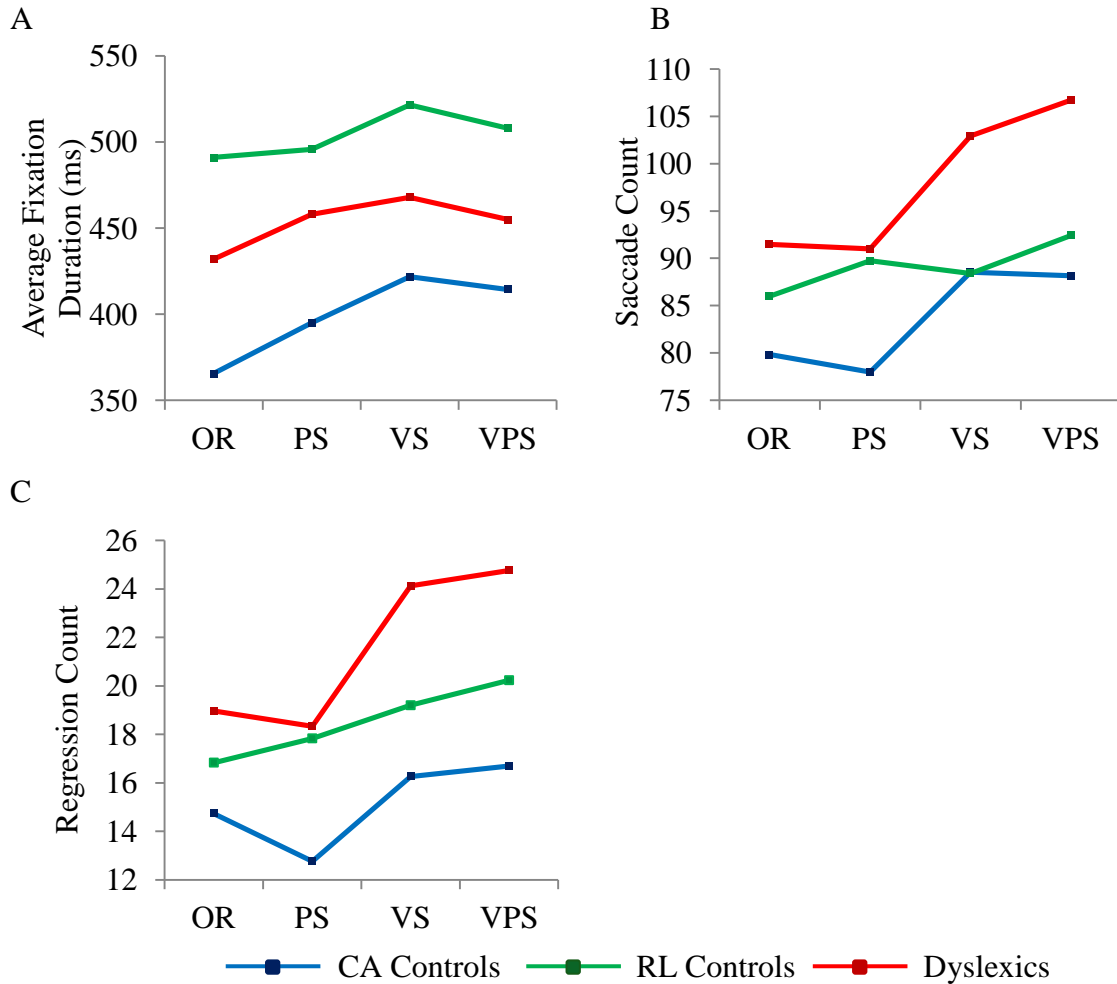


Figure 2.4. Group by version effect on eye movement measures. (A) Fixation duration. (B) Saccade Count. (C) Regression Count. *Note.* OR = Original NS Task; PS = Phonologically Similar NS Task; VS = Visually Similar NS Task; VPS = Visually and Phonologically Similar NS Task.

2.3.4.2 Eye movements and reading

Having established that eye movement measures are affected by single letter substitutions and that there were significant group differences across the tasks, the next step was to determine whether performance was related to reading ability. The correlations between the eye movement variables (collapsed across tasks by averaging z-scores) and overall reading ability are shown in Table 2.5. Average fixation duration is the only eye movement measure that was significantly correlated with overall reading

ability ($r = -.39, p < .01$) (see Table 2.5). Further analyses (see Table 2.5) revealed that OR, PS, and VS fixation durations were significantly correlated with overall reading ability ($p < .05$).

2.3.5 Eye-voice span

The eye-voice span is the distance between the position of the eyes at the beginning of articulation of the first letter of each task and the first letter, measured in numbers of letters; thus it evaluates coordination between eye movements and articulations. Correlations, means, and standard deviations for each the eye-voice span in each task are presented in Table 2.6. Correlations ranged from .29 to .65, and all were significant ($p < .05$), except for that between the OR and PS tasks ($p > .05$).

Table 2.6.

Pearson correlations for eye-voice span on all NS tasks.

Eye-Voice Span	1.	2.	3.	4.
1. OR	-			
2. PS	.29	-		
3. VS	.42**	.65**	-	
4. VPS	.33*	.58**	.44**	-
<i>M</i>	1.35	1.23	1.09	1.10
<i>SD</i>	.53	.40	.37	.31

Note. OR = Original NS Task; PS = Phonologically Similar NS Task; VS = Visually Similar NS Task; VPS = Visually and Phonologically Similar NS Task. Eye-Voice span represents the number of letters subjects' eyes are ahead of the articulation of the first letter in each NS task. $N = 45$. * $p < .05$; ** $p < .01$.

2.3.5.1 Influence of item composition on eye-voice span

A two-way ANOVA with repeated measures was used to examine the effects of letter composition (the four NS tasks) and group (CA controls, RL controls, and dyslexics) on eye-voice span (see Figure 2.5). The results revealed a significant main effect for task, $F(3, 126) = 6.92, p < .0001, d = .14$, but no significant group effect, $F(2,$

42) = 1.62, $p = .21$, $d = .07$, or interaction effect, $F(6, 126) = .29$, $p = .94$, $d = .01$. To examine the task effect, paired-samples t -tests revealed that the OR and PS tasks were not significantly different from one another, $t(44) = 1.50$, $p > .05$, $r = .29$, and neither were the VS and VPS tasks, $t(44) = .21$, $p > .05$, $r = .44$. The OR-PS tasks as well as the VS-VPS tasks were combined, and a paired-samples t -test revealed that the eye-voice span was smaller for the VS-VPS tasks than the OR-PS tasks, $t(44) = 4.95$, $p < .001$, $r = .70$, suggesting that it is visual similarity that decreases eye-voice span.

Despite the nonsignificant group effect, there is an apparent trend in Figure 2.5 that CA controls have larger eye-voice spans than RL controls and dyslexics. A one-way ANOVA demonstrated that the three groups are not significantly different from one another ($p > .10$), but the two controls groups are approaching significance ($p = .06$). To examine this, the RL controls and dyslexics were combined and compared with CA controls by using a univariate ANOVA on the average z -score of the four tasks. This test revealed that CA controls made significantly bigger eye-voice spans than RL controls-dyslexics combined, $F(1, 44) = 7.15$, $p = .01$, $d = .14$.

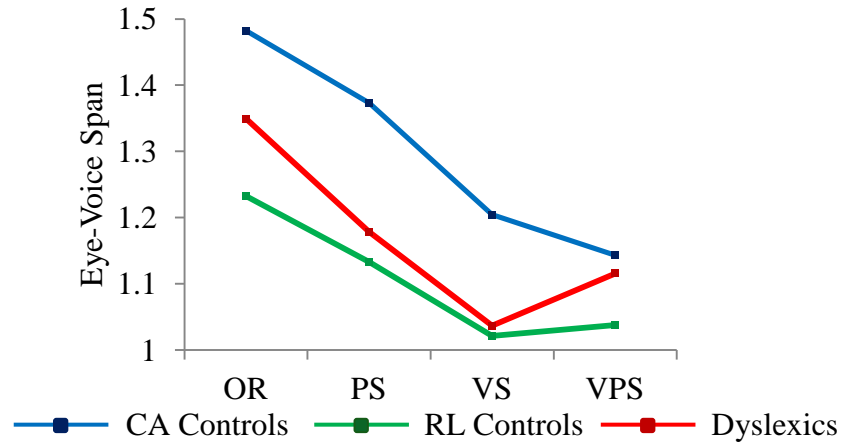


Figure 2.5. Group by version effect on eye-voice span. Eye-Voice span represents the number of letters subjects’ eyes are ahead of the articulation of the first letter in each NS task. On the y-axis, 1 indicates that subjects’ eyes are on the letter they are articulating, and 1.5 indicates that their eyes are a half letter ahead of the letter they are articulating. *Note.* OR = Original NS Task; PS = Phonologically Similar NS Task; VS = Visually Similar NS Task; VPS = Visually and Phonologically Similar NS Task.

2.3.5.2 Relationship of eye-voice span to NS performance, eye movements, and reading measures

To analyze how eye-voice span was related to overall reading ability, naming efficiency, errors, articulation times, pause times, fixation duration, saccade count, and regression count, an overall score for the four eye-voice span measures was calculated by averaging their z-scores (see Table 2.7). Overall reading ability was not significantly correlated with average eye-voice span ($p > .05$). Of the other NS variables, eye-voice span was positively correlated with naming efficiency ($p < .01$), and negatively correlated with number of errors, articulation time, and pause time ($p < .05$) (see Table 2.7).

Table 2.7.

Correlations between eye-voice span, overall reading ability, NS performance, and NS components.

	1.	2.	3.	4.	5.	6.	7.	8.	9.
1. Eye-Voice Span	-								
2. Overall Reading Ability	.27	-							
3. Efficiency	.42**	.41**	-						
4. Errors	-.31*	-.35*	-.67**	-					
5. Articulation Time	-.31*	-.31*	-.68**	.33*	-				
6. Pause Time	-.41**	-.31*	-.80**	.23	.57**	-			
7. Fixation Duration	-.27	-.39**	-.71**	.41**	.67**	.67**	-		
8. Saccade Count	-.24	-.13	-.49**	.17	.23	.50**	-.05	-	
9. Regression Count	-.29	-.16	-.62**	.37*	.33*	.54**	.08	.81**	-

Note. $N = 45$. * $p < .05$; ** $p < .01$.

2.3.6 Cognitive measure relationships

Pearson correlations between the cognitive measures and the other dependent variables analyzed in this study are presented in Table 2.8. Both Vocabulary and Matrix Reasoning were significantly positively correlated with overall reading ability ($p < .01$). When analyzing the average z-scores of the four tasks, pause time and fixation duration were the only measures that were significantly negatively correlated with Vocabulary ($p < .05$). Matrix Reasoning was not significantly correlated with any of the other dependent variables ($p > .05$).

Table 2.8.

Correlations of cognitive measures with naming performance and eye movement measures.

	1	2	3	4	5	6	7	8	9	10	11
1. Vocabulary	-										
2. Matrix Reasoning	.31*	-									
3. Overall Reading Ability	.71**	.53**	-								
4. Efficiency Scores	.29	.14	.41**	-							
5. Errors	-.15	-.27	-.35*	-.67**	-						
6. Articulation Time	-.25	-.23	-.31*	-.68**	.33*	-					
7. Pause Time	-.30*	.04	-.31*	-.80**	.23	.57**	-				
8. Fixation Duration	-.41**	-.09	-.39**	-.70**	.41**	.67**	.67**	-			
9. Saccade Count	-.07	.02	-.13	-.49**	.17	.23	.50**	-.05	-		
10. Regression Count	-.01	.06	-.16	-.62**	.37*	.33*	.54**	.08	.81**	-	
11. Eye-Voice Span	.16	.07	.27	.42**	-.31*	-.31*	-.41**	-.27	-.24	-.29	-

Note. $N = 45$. * $p < .05$; ** $p < .01$.

2.3.7 Regression analyses

Hierarchical regression analyses were conducted to investigate if any of the NS components and eye movement variables were unique predictors in the NS-reading relationship after controlling for general mental ability (measured by Matrix Reasoning). Three series of regression analyses were conducted with either NS efficiency or overall reading ability as the outcome measure. The results of the regression analyses are presented in Table 2.9. In each model, Matrix Reasoning was entered first. In the second step, NS components (articulation time and pause time) or eye movement variables (fixation duration, saccade count, and regression count) were entered together. This sequence of predictors was selected to control first for general mental ability, and then for either NS components or eye movement variables. The third model (2b in the table) used the better component predictor (Pause Time) and the best eye movement predictor (fixation duration).

Table 2.9.

Summary of hierarchical regression analyses predicting NS efficiency and overall reading ability.

Step, predictor	NS Efficiency				Overall Reading Ability			
	ΔR^2	β	t	p	ΔR^2	β	t	p
1. Matrix Reasoning	.02	.14	.90	.38	.28**	.53	4.08	.00
2. NS Components	.71**				.11*			
Articulation Time		-.31	2.95	.01		.01	.08	.94
Pause Time		-.63	6.21	.00		-.34	2.21	.03
2a. Eye Movements	.83**				.15*			
Fixation Duration		-.67	10.53	.00		-.34	2.79	.01
Saccade Count		-.18	1.70	.10		-.07	.35	.73
Regression Count		-.43	3.96	.00		-.10	.49	.63
2b.	.69**				.14*			
Pause Time		-.62	5.40	.00		-.17	1.06	.29
Fixation Duration		-.28	2.45	.02		-.23	1.42	.16

Note. β coefficients are from the step at which the predictor entered the model. * $p < .05$; ** $p < .001$.

General mental ability, as measured by Matrix reasoning, accounted for only 2% of the variance for predicting NS efficiency. The NS components and the eye movement variables added a further 71 to 83% of the variance, the higher being for the eye movement variables. For the NS components, both articulation time and pause time predicted NS efficiency significantly, but pause times played a larger role ($\beta = .63$) than articulation time ($\beta = .31$). All three eye movement variables also predicted NS efficiency significantly, with fixation duration playing the largest role ($\beta = .67$). To further analyze these results, another hierarchical regression analysis was conducted with pause time and fixation duration as predictors, after controlling matrix reasoning in the first step, and NS efficiency as the outcome variable (Table 2.9, model 2b). Pause time and fixation

duration accounted for a significant proportion of the variance. Even though both pause time and fixation duration significantly predicted NS efficiency, pause time plays a much larger role than fixation duration, $\beta = .62, p < .001$ vs. $\beta = .28, p = .02$.

The second set of regression analyses used the same set of predictors but with reading ability as the outcome. As indicated in Table 2.9, matrix reasoning accounts for 28% of the variance in overall reading ability. NS components and the eye movement variables added a further 11 to 15% of the variance than that accounted for by matrix reasoning, the higher being for the eye movement variables. Of the variables, only pause time and fixation duration significantly predicted overall reading ability. To analyze this further, another hierarchical regression analysis was conducted with pause time and fixation duration as predictors, after controlling matrix reasoning (Table 2.9, model 2b). Pause time and fixation duration together added an additional 14% of the variance to that accounted for by only matrix reasoning but did not individually contribute significantly to overall reading ability, $ps > .16$ (see Table 2.9).

2.4 Discussion

The aim of this study was to use eye movement methodology, stimulus manipulations, and NS components to: (1) analyze how NS is related to reading, (2) determine whether eye movements, NS performance, and NS components are affected by increasing phonological and/or visual similarity, (3) determine whether phonological or visual similarity contributes more to the NS-reading relationship, and (4) investigate whether there are differences in NS performance with increased reading ability or between dyslexic and average readers. The results of this study indicate that pause time and fixation duration are key features in the NS-reading relationship, and increasing

visual similarity of the letter matrix had the greatest effect on performance for children with and without dyslexia. This latter result was demonstrated by the decrease in efficiency and eye-voice span, increase in naming errors, saccades, and regressions, and longer pause times and fixation durations found for all subjects. There also appeared to be clear developmental changes in NS performance and eye movements in normally-achieving children from ages six to 10 that seemed to occur more slowly for dyslexics. The remainder of this discussion focuses on three questions: (1) what determines NS? (2) what distinguishes dyslexics from controls? and (3) what predicts reading ability?

2.4.1 What determines NS?

Extensive developmental behavioural studies have shown that NS is a strong predictor of both concurrent and future reading ability, independent of the effects of other predictors such as phonological awareness, IQ, attention deficit disorder, socioeconomic status, articulation rate, and prior reading skills (Kirby et al., 2010; Misra, Katzir, Wolf, & Poldrack, 2004; Norton & Wolf, 2012; Wolf & Bowers, 1999). It has been argued that naming speed is an earlier and a simpler approximation of the reading process, that NS tasks assess critical subskills that are needed for fluent reading performance (Denckla & Cutting, 1999; Wolf et al., 2000), and that NS tasks would assist in the early identification of children who are at-risk for developing a reading disability (Neuhaus et al., 2001). However in spite of this evidence it is still unclear why NS is related to reading, or what specific cognitive processes are involved in NS (Georgiou et al., 2006; 2009; Kirby et al., 2010). Therefore, one of the primary goals of this study was to understand the cognitive process or processes that are involved in NS. The present results show several clear patterns indicating that NS efficiency was mostly affected by the

visual similarity of the letters in the matrix, and is largely a function of pause time and fixation duration.

Visual similarity of the letter matrix significantly affected NS efficiency and number of errors, and led to dyslexics behaving more like RL controls than CA controls (see Table 2.3 and Figure 2.2 A and B). This suggests that the ability to discriminate between the visual forms of letters influences NS performance, and supports Bowers, Golden, Kenny, and Young's (1994) argument that rapidly accessing the visual forms of letters is an important predictor for NS performance. These findings also support those by Best and Howard (2005) who found higher rates of visual confusion and errors in dyslexics compared to controls. To explain these findings it has been suggested that dyslexics may heavily rely on visual codes when they are processing written material to compensate for their phonological deficits, whereas average readers re-code written verbal information into phonological form (Snowling & Hulme, 1989). Therefore, the speeded conditions of this task coupled with the visual similarities negatively impacted dyslexics' pre-existing deficit in accurately accessing the letter forms for the stimuli from their lexical store, and led to them performing more like the RL controls than the CA controls.

Furthermore, NS efficiency was largely a function of pause time and fixation duration. In terms of the NS components, both articulation time and pause time had a significant effect in predicting NS efficiency after controlling for general mental ability, but pause time was substantially stronger (see Table 2.9) which is consistent with findings in the literature (e.g. Georgiou et al., 2006; Neuhaus et al., 2001; Neuhaus & Swank, 2002; Anderson, Podwall, & Jaffe, 1984; Obregon, 1994). This reflects the longer

pause times taken by dyslexics and RL controls to encode and process each stimulus, and prepare a response to that stimulus (Kirby et al., 2010).

In terms of the eye movement variables, even though both fixation duration and regression count predicted NS efficiency significantly after controlling for general mental ability, fixation duration was substantially stronger (see Table 2.9). It is also worth noting that overall the eye movement variables accounted for 85% of the variance in predicting NS efficiency after controlling for general mental ability. Wolf and Denckla (2005) reported NS tasks test-retest reliability to be .92 across ages. This demonstrates that the eye movement variables are predicting almost as much of NS as it can predict of itself. However, when both pause time and fixation duration were used as predictors of NS efficiency after controlling for general mental ability, pause time was a stronger predictor than fixation duration. This indicates that pause time plays the largest role in predicting NS performance (see Table 2.9).

2.4.2 What distinguishes dyslexics from controls?

The second goal of this study was to understand what separated dyslexics from controls. The experimental design of this study allowed us to do this because it controlled for reading experience and instruction and isolated causal variables which may be important for explaining why reading fails to develop normally. The RL matched controls did this by comparing dyslexics with normal younger readers reading at the same developmental skill level as the dyslexics, and the CA matched controls did this by comparing dyslexics with children who have average reading ability and are of the same IQ and age and have had the same amount of reading instruction. Both control groups are necessary to establish a causal argument, and when dyslexics behave worse than RL

controls in NS and/or eye movement performance this points towards causal factors involved with dyslexia. However, this experimental design only provides insight into what may be causing this reading disability – other factors may be causing dyslexics to perform worse than RL controls. Furthermore, even if dyslexics performed like RL controls this does not indicate that they do not have a reading disability.

Compared to CA controls, dyslexics performed more like RL controls and were less efficient, had longer articulation times, pause times, fixation durations, and eye-voice spans, and made more errors, saccades, and regressions. These differences may be causal factors responsible for making them dyslexic or may be the consequences of the problems that they have with reading. The only areas where dyslexics performed worse than RL controls were on saccade count and regression count which may indicate difficulties that this group has in eye movement control under the speeded conditions of these tasks (Yan et al., 2013). Based on the experimental design of this study, this may suggest causal factors of what causes dyslexia. However, it also may be that RL controls do not make as many regressions because they are less concerned about whether they have made a mistake in naming a letter and keep moving along. Dyslexics on the other hand know they have a reading disability, and know that they are participating in this study because of their difficulties with reading. This may have led them to be much more cautious in naming the letters, and so they are ensuring that they name the letters correctly by going back in the matrix. This indicates that dyslexics may also regress more in reading, and simply use this same process in naming letters.

In average readers, the magnocellular system is dominant in directing eye-movements and stabilizing brief fixations on word (Stein, 2003). The finding that

dyslexics make longer fixations and more saccades and regressions than CA controls may then suggest an impairment to a certain degree in dyslexics' magnocellular systems which is leading to poor oculomotor control across the tasks (Pammar & Vidyasagar, 2005). As a result, the information acquired during fixations is less than optimal which leads to dyslexics needing to go back in the task and re-fixate on the letters resulting in an increase in the number of saccades and regressions (Stein, 2003). Furthermore, the longer fixations found for dyslexics across the tasks indicate that they may have weaker orthographic processing compared to CA controls, which implies that recognizing symbolic visual stimuli is not an automatic process and so longer fixations are required in order to recognize the stimuli (Hung, 2012; Bowers & Newby-Clark, 2002). These longer fixation durations imply a slower visual processing speed which is related to the decrease in efficiency that is found for dyslexics compared to CA controls. These two measures (NS efficiency and fixation durations) were significantly correlated with one another ($r = -.71, p < .01$) which implies that shorter fixations are associated with increased NS efficiency, and faster visual processing speed (see Table 2.7). Therefore, poor oculomotor control as a result of magnocellular systems impairments would impact the relationship between NS and reading by: (1) impairing the connections between phonological and orthographic units, (2) preventing the development of clear orthographic representations, and (3) increasing the amount of exposures required to automatize the orthographic representations (Hung, 2012; Bowers & Newby-Clark, 2002). A longitudinal study with an at-risk sample and average readers that started before reading instruction began is required to determine if this is a causal factor, and whether children with dyslexia have less controlled eye movements than average readers.

This delay at the visual stage also explains our finding of longer pause times for dyslexics. We found a positive correlation between pause times and fixation duration for the three groups combined ($r = .67, p < .01$) (see Table 2.7), indicating that longer fixation durations are associated with longer pause times. This is not surprising because if it takes subjects a longer amount of time to acquire the information they need from a stimulus, then they will take longer to process the stimulus and prepare a response to name that stimulus (Wolf & Bowers, 1999). This would then lead to less fluent naming performance, which is portrayed by the significantly negative correlations between pause times and efficiency as well as between fixation duration and efficiency (see Table 2.7).

However, less fluent naming may also be due to a dispersed allocation of visual attention which leads to a reduced ability to discriminate a fixated letter from its surrounding information (Whitney & Cornelissen, 2005). Dyslexics may have a disrupted perceptual analysis of target letters because they focus too much of their attention on parafoveal items, which leads to a decreased attentional capacity available to process the target letter on which they are currently fixating. For example, studies have found that dyslexics have a more parallel distribution of attention in their visual field compared to controls, which leads to a broader distribution of attention across their visual field (Geiger & Lettvin, 1987; Geiger, Lettvin, & Fahler, 1994; Facoetti, Paganoni, & Lorusso, 2000; Lorusso et al., 2004). This was reflected in the finding that both children and adults with dyslexia were much better at identifying items that were presented in their periphery compared to controls (Geiger et al., 1994). A broader distribution of attention may also be due to more attentional resources being allocated towards mapping visual symbols to

phonological representations compared to controls during the foveal stage of processing (Yan et al., 2013).

More research needs to be conducted to determine if this parallel distribution of attention is what is driving the difference in performance between dyslexics and CA controls. The multi-componential processes that are required during these tasks may make the task more laborious for dyslexics and their poor performance may simply reflect their difficulty in performing tasks simultaneously (Nicolson & Fawcett, 1990). Also, if dyslexics have not automatized the rapid activation and integration of phonological and visual stimuli, then NS tasks may tax limited executive processes to a greater extent compared to controls who have already automatized them (Wolf & Bowers, 1999).

2.4.3 What predicts reading ability?

Our last goal was to determine what processes tapped by the NS tasks predict reading ability. As previously mentioned, NS efficiency was found to be largely a function of pause time and fixation duration. These two variables also distinguished dyslexics from CA controls, though less so from RL controls. These three groups were combined in a series of hierarchical regressions to determine overall reading ability, and pause time and fixation duration remained to be the main predictors after controlling for general mental ability (see Table 2.9).

Researchers have suggested that articulation time reflects subjects' automaticity of generating a response to name stimuli once it has been recognized, and pause times reflect the process of retrieving its verbal labels which includes recognition of the stimulus and attentional processes regarding eye movements (Kirby et al., 2010; Neuhaus

et al., 2001; Balota & Abrams, 1995; Wolf & Bowers, 1999). Both articulation time and pause time were equally correlated with overall reading ability ($r = -.31, p < .05$) (see Table 2.4). However, in a series of regression analyses pause time, and not articulation time, was a significant predictor in predicting overall reading ability after controlling for general mental ability (see Table 2.9). This may be due to the speed of processing demands associated with retrieving letter knowledge that are involved in both pause times and reading (Neuhaus et al., 2001).

To visually scan the continuous array of letters in the visual display subjects need to have precise oculomotor control, and this same requirement is needed for reading lines of text. Fixation duration was the only eye movement variable that was significantly correlated with overall reading ability ($r = -.39, p < .01$) (see Table 2.5), and the only one to predict reading ability after controlling for general mental ability (see Table 2.9). This suggests that the greater amount of time needed to acquire or encode stimuli is an important factor in predicting reading ability and thus in understanding the NS-reading relationship. This also implies that CA controls may have more automatic or efficient foveal processing, which is demonstrated by their shorter fixation durations, than dyslexics which allows for more attentional resources to be devoted to parafoveal processing (Yan et al., 2013). However, when both pause time and fixation duration were used as predictors of overall reading ability after controlling for general mental ability, neither pause time or fixation duration were significant unique predictors even though together they accounted for a significant amount of variance (see Table 2.9). This suggests that they are strongly related and that the same factors underlie both.

Lastly, to determine whether there are important components of NS that are predictive of reading ability outside the realm of phonology stimulus manipulations were made to the NS task to examine the impact of orthographic and phonological processing. Our findings support the orthographic theory for the relationship between NS and reading, suggesting that there are other important components of NS that are predictive of reading ability that are outside the realm of phonology. If the phonological theory were true then increasing phonological similarity should have negatively affected performance. However, we found that on all measures, except for articulation time, the OR and PS tasks were not significantly different from one another. This implies that there was no appreciable influence of phonological similarity on performance. Contrarily, increasing visual similarity negatively affected performance on all measures, supporting the orthographic hypothesis, and implying an influential role of visual processing on NS.

2.4.4 Limitations and future directions

Some limitations of the current study are worth mentioning. First, the behavioral nature of this study may contribute as a limitation, because we cannot claim causation of which specific cognitive process or processes are involved in NS or are responsible for the NS-reading relationship. Future studies can address this by conducting a longitudinal study before reading instruction began comparing at-risk readers with average readers. This will allow researchers to further understand the cognitive processes that are involved and how these processes may break down in subjects with NS deficits. Second, although the number of participants per group was adequate for the analyses conducted in this study, greater numbers would have provided more stability and power. Also, the three groups were not equated on all reading variables, and we did not have a phonological

awareness control measure. Future studies should try to replicate these findings with a larger sample size and by equating groups on all reading measures. Third, the results of this study are restricted to the developmental span and population examined (Grades 1 to 4), thus these findings may or may not be applicable to older children and adults with and without dyslexia. Future studies should replicate this study and incorporate groups of subjects in older age groups. This is crucial because studies have reported that the observed relationships with NS may decrease for older children (e.g. Meyer, Wood, Hart, & Felton, 1998; McBride-Chang & Manis, 1996).

2.4.5 Conclusion

This study presents results of what determines NS, what differentiates dyslexics from controls, and what predicts reading ability. We found that pause time and fixation duration are the two variables that contributed the most to the NS-reading relationship, and that increasing visual similarity of the letter matrix had the greatest effect on NS and eye movement performance for both dyslexics and controls. These findings add to a growing number of studies that have examined the underlying cognitive processes involved in the NS-reading relationship (e.g., Georgiou, Parrila, Cui, & Papadopoulos, 2013; de Jong, 2011; Jones et al., 2013; Protopapas, Altani, & Georgiou, in press; Yan et al., 2013; Zoccolotti et al., in press). We conclude that NS is related to reading via pause times and fixation durations; longer pause times in children with dyslexia reflect the greater amount of time needed to prepare to respond to stimuli, and longer fixation durations reflect the greater amount of time needed to acquire visual/orthographic information from stimuli.

Chapter 3

General Discussion

NS has been known to be an independent source of variance in predicting concurrent and future reading ability in both developing readers and in poor readers (Bowers & Swanson, 1991; Kirby, Parrila, & Pfeiffer, 2003; Young & Bowers, 1995; Bowers, 1993). The nature of this relationship has been proposed to stem from the similar processes between these two tasks (Wolf & Bowers, 1999). For example, both require rapid attentional, visual, and phonological processing in order to fluently produce phonological codes and name stimuli. However, despite NS comprising a ‘microcosm’ of the low-level processes that are involved in reading fluency beyond that associated with other skills, such as phonological awareness (Cutting & Denckla, 2001), it is still not clear what cognitive process or processes are involved.

The goals of this study were to use stimulus manipulations, NS components, and eye movement methodology to: (1) analyze the relationship between NS and reading, (2) determine whether eye movements, NS performance, and NS components are affected by increasing phonological and/or visual similarity, and (3) investigate whether there are differences in performance between dyslexics and average readers and with increased reading ability. We investigated three groups of participants, dyslexics, CA controls, and RL controls, and used a letter NS task and three variants that either increased phonological and/or visual similarity (Compton, 2003) while subjects’ eye movements and articulations were recorded. The results indicated that fixation duration and pause time play a crucial role in the NS-reading relationship, and increasing visual similarity of

the NS task had the greatest effect on performance for both dyslexics and controls. This latter result was indicated by the decrease in efficiency and eye-voice span, increase in naming errors, saccades, and regressions, and longer pause times and fixation durations for all participants. This suggests that the ability to discriminate between visually similar features of letters influences the speed of retrieval of orthographic representations from the lexical store, demonstrating an important role of visual and orthographic processing in NS performance and reading fluency.

3.1 Overall implications and clinical relevance

In this study pause time and fixation duration accounted for variance in predicting both NS efficiency and overall reading ability (see Table 2.9), indicating that in addition to orthographic processing NS may be related to reading because of serial ocular-motor programming. The oculomotor components of NS tasks and reading are similar; in both tasks participants are required to quickly and accurately serially inspect and name letters arranged in a visual array while repeatedly engaging and disengaging attention from the stimuli as their eyes move through the array. Pause time and fixation duration may then be capturing important variance associated with processing rapidly occurring serial information. Currently, NS tasks are the only assessment tool that directly measures the serial ocular-motor programming of reading behaviour (Kuperman & Van Dyke, 2011). Therefore, analyzing eye movements and NS components during NS tasks early in reading acquisition may be able to highlight key differences in ocular-motor behaviour between dyslexics and average readers that can help identify early warning signs in children who may be at-risk for developing a reading disability (Rayner, 1985).

Assessing NS is important for both clinical and educational purposes for multiple reasons. From a clinical or diagnostic standpoint multiple longitudinal studies have shown that along with phonological skills, letter name, and sound knowledge, NS is one of the most robust early predictors of reading difficulties (Norton & Wolf, 2012). Therefore, using published normed measures examiners can determine how children's NS ability compares with what is typically expected for their age or grade. Administration of NS tasks in kindergarten or first grade can help identify the subset of children who have a NS deficit and which may lead to future problems in fluent reading and comprehension, but have average phonological awareness skills and decoding ability (Wolf et al., 2002). From an educational standpoint, speed and automaticity are two essential components needed to become a good reader. Typically English language researchers have only assessed accuracy as a measure for reading. However, myriad studies have shown that some accurate readers are not necessarily fluent readers, and have a hidden speed deficit which is not typically identified until later in school (Breznitz, 2006). Therefore, it is important to have reading assessments that take into account both speed and automaticity (Norton & Wolf, 2012).

3.2 Future directions

This study has highlighted key areas that require further research. In this study we found that pause times were one of the most significant components that highlighted the differences between dyslexics and CA controls (see Figure 2.3). Pause times are involved in the management of attentional processes regarding eye movements, and are a function of the recognition and preparation to respond to stimuli. However, it is necessary to separate pause times into two components: (1) processing of surrounding letters, and (2)

processing of the current letter itself (or the next letter to be named) (Wolf & Bowers, 1999). The importance of analyzing these components is because NS tasks require the effective inhibition of already named stimuli and processing of the next stimulus, which is provided by information from the parafovea. Both inhibition and parafoveal processing impairments have been found in dyslexic readers (Lorusso et al., 2004; Hari & Renvall, 2001). Therefore, separating pause times into these two components could contribute to elucidating why dyslexics have significantly longer pause times than CA controls (see Figure 2.3), and could enhance early identification and diagnosis for children with reading disabilities (Georgiou, Parrila, & Kirby, 2006).

We also found a developmental trend in eye movements for normal readers; as reading skill increased, fixation duration and the frequency of saccades and regressions decreased indicating faster information processing (Buswell, 1922; Olitsky & Nelson, 2003). Compared to CA controls, dyslexics made longer fixations, and more saccades and regressions (see Figure 2.4). It is important to determine the extent to which these different eye movement patterns found for dyslexics contribute to their reading disability. Three hypotheses can be made to explain the differences in eye movements between these two groups. First, dyslexics' eye movements are a reflection of the problems that they have with reading. Second, these abnormal eye movements may be the cause of dyslexia. Third, erratic eye movements and dyslexia are the symptoms of one or more commonly shared or independent but parallel central deficits (Olitsky & Nelson, 2003; Rayner, 1998). More research needs to be conducted in the field in order to be able to determine which, if any, of these three theories explains the atypical eye movements that are observed in readers with dyslexia.

To further understand the NS-reading relationship, longitudinal studies that incorporate eye tracking and brain imaging could be conducted before reading instruction began. Following children from the pre-literacy stage to the early stages of literacy would allow researchers to investigate the relationship of NS with both concurrent and subsequent reading ability after developing early reading skills (Cobbold, Passenger, & Terrell, 2003). This will investigate whether slow NS contributes to the development of reading difficulties (Cobbold et al., 2003). Furthermore, analyzing eye movements and neural correlates that are involved with NS will lead to a more complete understanding of the cognitive processes that are involved in the NS-reading relationship, and how these processes may break down in children with NS deficits.

This will also establish a stronger background in neurophysiological research specializing in saccadic eye movements and reading by advancing the knowledge of the neuroanatomy and neural circuitry that are involved, and how this may change with reading acquisition or with compensation for readers with dyslexia. For instance, in the literature researchers have found that for normal readers the left occipitotemporal region is correlated with activation in the left inferior frontal gyrus during reading (Shaywitz, Mody, & Shaywitz, 2006). However, for readers with dyslexia the left occipitotemporal region is correlated with right prefrontal areas, which is associated with memory (Shaywitz et al., 2006). This leads to a hypothesis that readers with dyslexia may rely on their memory networks to read more than average readers. It will be interesting to analyze whether this same pattern of activation exists when naming letters, or if there are additional regions that are introduced in this circuit.

Furthermore, fMRI studies have found that the neural systems involved in reading are malleable and do respond to effective reading interventions (Shaywitz et al., 2006; Shaywitz et al., 2004; Shaywitz & Shaywitz, 2005), which further emphasizes the importance of early diagnosis and intervention (Shaywitz & Shaywitz, 2008). Conducting a longitudinal study before reading instruction began and after interventions have been provided to children with reading disabilities will contribute to understanding the long-term impact of interventions, especially on the development of reading fluency and the neural systems that are involved (Shaywitz & Shaywitz, 2008).

This ties into the last key area that requires further research, which is determining appropriate intervention programs for children with NS deficits who may not benefit from phonologically based interventions. As previously mentioned, both phonological processing deficits (Wolf, Bowers, & Biddle, 2000) and NS deficits (Kirby, Georgiou, Martinussen, & Parrila, 2010; Norton & Wolf, 2012) have been found to be at the core of reading failure. Existing phonological remediation programs have been successful in remediating children with phonological processing deficits by improving their phonological awareness skills and decoding ability (Wolf et al., 2009; Torgesen, 2004; Hulme, Bowyer-Crane, Carroll, Duff, & Snowling, 2012). However, it is harder to design remediation programs to improve NS ability compared to phonological processing abilities because there are multiple causes of why NS breaks down, and the cognitive processes that are involved in NS are still not well understood. This has led to a current controversy in the reading field about how to improve NS ability and thus reading fluency.

A majority of researchers have argued that training children on NS tasks is not an optimal way to improve reading fluency because NS is related to developmental processes (Norton & Wolf, 2012). Even though NS times and raw scores improve with age and reading acquisition, subjects' standard scores based on age remain relatively consistent in overall naming ability. NS may portray a basic index of processing because, despite interventions improving language and reading variables, there are few changes in overall naming ability from pre- to post-treatment (Norton & Wolf, 2012).

To date, two studies have directly analyzed whether participants can be explicitly trained on NS. Fugate (1997) randomly assigned first grade children into either a letter-training group or a comparison group to examine the effects of letter naming training over 12 school days. Children in the letter-training group practiced letter naming by doing drill tasks in naming individual letters on flashcards, while children in the comparison group worked on journal assignments. At the end of the 12 day training period children in the letter-training group had higher letter naming speed and oral reading fluency than the comparison group, but there was no significant difference between these two groups seven weeks after training. Conrad and Levy (2009) also examined the effects of letter naming training for children in Grade 1 and 2 who had slow digit NS and poor word reading skills. Participants were assigned to one of three groups: letter naming training followed by orthographic training, orthographic pattern training followed by letter naming training, or math instruction (control group). Prior to training participants did not differ in word reading, orthographic processing, letter naming, or phonological awareness. Letter NS improved only when letter naming training followed the orthographic training, indicating that improving children's orthographic awareness

helps improve NS. However, it is not clear whether these improvements are long lasting or how well these improvements translate to reading fluency.

Furthermore, currently only two studies have been conducted that target the rapid naming of letter sounds. De Jong and Vrielink (2004) trained Dutch children in Grade 1 by administering 10 sessions, each lasting 15 minutes, over two weeks that focused on eight letter sounds (four consonants and four vowels). Participants were first trained on isolated letters and then on sets of letters. Compared to controls, children who received the training did not have faster letter-sound naming or improved word reading skills. These findings were also reported by Hintikka, Aro, and Lyytinen (2005) who trained at-risk Grade 1 Finnish children on the relations between phonemes and their orthographic representations through a computerized program, which took place three times per week for 10 to 20 minutes for six weeks. During training participants were required to listen to a letter sound and find its matching orthographic representation among distracters. Children who received the training did not significantly improve naming speed or reading relative to controls. The results from both studies indicate that it may be difficult to improve the rate at which children retrieve letter-sounds. However, it also indicates that the duration of the training may have been too short for children to improve their rapid naming of letter sounds, and longer training periods may be needed to see improvements relative to controls.

Due to the complex system of NS, breakdowns may occur in any of the subsystems. Individuals may have a breakdown in single or multiple components, or they may have a failure in being able to integrate information across subprocesses. Therefore, it may be beneficial to have programs that target the multiple levels of language and the

multiple cognitive processes that are involved in reading (Norton & Wolf, 2012). Furthermore, having intervention programs focused on enhancing one skill, such as phonological processing ability, may lead to the overrepresentation of children with phonological processing deficits and the underrepresentation of children with deficits in other areas (Wolf et al., 2002).

Despite fluent reading comprehension depending on accuracy and automaticity at every level of language, such as orthography, morphology, syntax, and semantics, only a few intervention programs have incorporated these different levels. To examine the effect of different reading intervention programs Morris et al. (2011) randomly assigned 279 Grade 1 and 2 children with reading difficulties to one of four different intervention programs: two multicomponential intervention programs which trained children on either strategies for word identification or trained children on the different levels of reading (such as orthography, semantics, syntax, and morphology), a phonological control program, and a control program in which no reading instruction was administered but targeted study skills and math instruction. On reading accuracy and fluent comprehension children who received the multicomponential intervention programs performed significantly better than children who were in the other two programs. This improvement was maintained one year after the intervention. These findings highlight the importance of having multicomponential intervention programs that target the different aspects of reading, and help children build connections among the different processes that are involved in reading. These types of intervention programs are especially crucial for children with NS or double deficits in NS and phonological awareness whose deficits are not adequately addressed by phonological decoding programs.

3.3 Summary and conclusions

The primary contribution of this study was to reveal what distinguishes dyslexics from controls and how NS is related to reading through the use of stimulus manipulations, NS components, and eye movement methodology. Our results demonstrated that NS is related to orthographic processing more so than phonological processing, and unique variance was consistently explained by pause time and fixation duration with predicting both NS efficiency and overall reading ability (see Table 2.9). These results add to the growing body of research aimed to understand NS deficits and to determine how NS is related to reading.

Due to the multicomponential nature of reading, dyslexia may have multiple causes. Understanding that dyslexia is a heterogeneous reading disorder is important for identifying and remediating children with reading difficulties. Typically schools have either thought that children's reading difficulties will disappear with time and they will grow out of it, or interventions have been provided that do not meet a child's specific strengths and/or weaknesses. These two approaches can be detrimental to a child's future because unremediated reading difficulties lead to unemployment, underemployment, and incarceration (Snow, Burns, & Griffen, 1998; Norton & Wolf, 2012; Grigorenko, 2006; Humphrey & Mullins, 2002; Svensson, Lundberg, & Jacobson, 2001). Therefore early identification, which can be provided by administering NS tasks, can lead to early diagnosis and interventions which is imperative for changing the overall outcome of a child's future (Snow et al., 1998; Norton & Wolf, 2012).

References

- Anderson, S. W., Podwall, F. N., & Jaffe, J. (1984). Timing analysis of coding and articulation processes in dyslexia. *Annals of the New York Academy of Science*, *433(1)*, 71-86.
- Arguin, M., & Bub, D. (1995). Priming and response selection processes in letter classification and identification tasks. *Journal of Experimental Psychology: Human Perception and Performance*, *21*, 1199-1219.
- Balota, D. A., & Abrams, R. A. (1995). Mental chronometry: Beyond onset latencies in the lexical decision task. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *21*, 1289-1302.
- Best, W., & Howard, D. (2005). "The W and M are mixing me up": Use of a visual code in verbal short- term memory tasks. *Brain and Cognition*, *58*, 274-285.
- Blachman, B. A. (1984). Relationship of rapid naming ability and language analysis skills to kindergarten and first-grade reading achievement. *Journal of Educational Psychology*, *76*, 610-622.
- Bowers, P. G. (1993). Text reading and rereading: Determinants of fluency beyond word recognition. *Journal of Reading Behavior*, *25*, 133-153.
- Bowers, P. O., Golden, J., Kennedy, A. & Young, A. (1994) Limits upon orthographic knowledge due to processes indexed by naming speed. In: V.W. Berninger (Ed.), *The varieties of orthographic knowledge*, Vol. I: *Theoretical and developmental issues* (pp. 173-218). Dordrecht/Boston/London: Kluwer Academic Publishers.

- Bowers, P. G., & Newby-Clark, E. (2002). The role of naming speed within a model of reading acquisition. *Reading and Writing: An Interdisciplinary Journal*, 15, 109-126.
- Bowers, P. G., & Swanson, L. B. (1991). Naming speed deficits in reading disability: Multiple measures of a singular process. *Journal of Experimental Child Psychology*, 51, 195-219.
- Bradley, L., & Bryant, P. E. (1983). Categorizing sounds and learning to read: A causal connection. *Nature*, 419-421.
- Brady, S., & Shankweiler, D. (Eds.). (1991). *Phonological processes in literacy: A tribute to Isabelle Y. Liberman*. Hillsdale, NJ: Erlbaum.
- Breznitz, Z. (2006). *Reading Fluency: Synchronization of Processes*. Mahwah, NJ: Erlbaum.
- Bruck, M. (1992). Persistence of dyslexics' phonological deficits. *Developmental Psychology*, 28, 874-886.
- Bus, A. G., & van Ijzendoorn, M. H. (1999). Phonological awareness and early reading: A meta- analysis of experimental training studies. *Journal of Educational Psychology*, 91, 403-414.
- Buswell, G. T. (1922). *Fundamental Reading Habits: A Study of Their Development*. University of Chicago Press: Chicago.
- Byrne, B., Wadsworth, S., Corley, R., Samuelsson, S., Quain, P., et al. (2005). Longitudinal twin study of early literacy development: preschool and kindergarten phases. *Scientific Studies of Reading*, 9, 219-235.

- Cain, K. (2010). *Reading development and difficulties: an introduction*. Oxford: Wiley-Blackwell.
- Catts, H. W. (1996). Defining dyslexia as a developmental language disorder: An expanded view. *Topics in Language Disorders, 16*, 14–29.
- Clarke, P., Hulme, C., & Snowling, M. J. (2005). Individual differences in RAN and reading: A response timing analysis. *Journal of Learning Disabilities, 28*, 73-86.
- Cobbold, S., Passenger, T., & Terrell, C. (2003). Serial naming speed and the component elements of speech time and pause time: Relationships with the development of word-level reading in children aged four to five years. *Journal of Research in Reading, 26*, 165-176.
- Compton, D. L. (2003). The influence of item composition on RAN letter performance in first- grade children. *The Journal of Special Education, 37*, 81-94.
- Compton, D. L., Davis, C. J., DeFries, J. C., Gayan, J., Olson, R. K. (2001). Genetic and environmental influences on reading and RAN: an overview of results from the Colorado twin study. In M. Wolf (Ed.), *Time, Fluency, and Developmental Dyslexia* (pp. 277–303). Baltimore, MD: York Press.
- Conrad, N. J., & Levy, B. A. (2009). Training letter and orthographic pattern recognition in children with slow naming speed. *Reading and Writing: An Interdisciplinary Journal, 24*, 91-115.
- Cornwall, A. (1992). The relationship of phonological awareness, rapid naming, and verbal memory to severe reading and spelling disability. *Journal of Learning Disabilities, 25*, 532-538.

- Cutting, L. E., & Denckla, M. B. (2001). The relationship of rapid serial naming and word reading in normally developing readers: an exploratory model. *Reading and Writing, 14*, 673–705.
- Dehaene, S., Cohen, L., Sigman, M., & Vinckier, F. (2005). The neural code for written words: a proposal. *Trends in Cognitive Sciences, 9*, 335–341.
- de Jong, P. F., & van der Leij, A. (1999). Specific contributions of phonological abilities to early reading acquisition: Results from a Dutch latent variable longitudinal study. *Journal of Educational Psychology, 91*, 450–476.
- de Jong, P. F., & Vrielink, L. O. (2004). Rapid automatic naming: Easy to measure, hard to improve (quickly). *Annals of Dyslexia, 54*, 65–88.
- Denckla, M. B. (1972). Color naming deficits in dyslexic boys. *Cortex, 8*, 164–176.
- Denckla, M. B., & Cutting, L. E. (1999). History and significance of rapid automatized naming. *Annals of Dyslexia, 49*, 29–42.
- Denckla, M. B., Rudel, R. G. (1976). Rapid ‘automatized’ naming (R.A.N.): Dyslexia differentiated from other learning disabilities. *Neuropsychologia, 14*, 471–479.
- Ehri, L. C. (1997). Sight word learning in normal readers and dyslexia’s. In B. Blachman (Ed.), *Foundations of reading acquisition and dyslexia: Implications for early intervention* (pp. 163–189). Mahwah, NJ: Erlbaum.
- Ehri, L. C. (2005). Learning to read words: Theory, findings, and issues. *Scientific Studies of Reading, 9*, 167–188.
- Ehri, L. C., Nunes, S. R., Stahl, S. A., & Willows, D. M. (2001). Systematic phonics instruction helps students learn to read: Evidence from the National Reading Panel’s meta-analysis. *Review of Educational Research, 71*, 393–447.

- Facoetti, A., Paganoni, P., & Lorusso, M. L. (2000). The spatial distribution of visual attention in developmental dyslexia. *Experimental Brain Research*, 132, 531-538.
- Felton, R. H., Naylor, C. E., & Wood, F. B. (1990). Neuropsychological profile of adult dyslexics. *Brain and Language*, 39, 485-497.
- Fisher, S., & DeFries, J. (2002). Developmental dyslexia: genetic dissection of a complex cognitive trait. *Nature Reviews Neuroscience*, 3, 767-780.
- Frackowiak, R., Friston, K., Frith, C., Dolan, R., Price, C., Zeki, S., et al (2004). *Human Brain Function (2nd ed.)*. San Diego: Academic Press, Elsevier Science.
- Francis, D. J., Shaywitz, S. E., Stuebing, K. K., Shaywitz, B. A., & Fletcher, J. M. (1996). Developmental lag versus deficit models of reading disability: A longitudinal, individual growth curves analysis. *Journal of Educational Psychology*, 88, 3-17.
- Frith, U. (1985). Beneath the surface of developmental dyslexia. In C. Hulme and M. Snowling(Ed.), *Dyslexia: Biology, Cognition and Intervention* (pp. 1-19). London: Whurr.
- Fugate, M. H. (1997). Letter training and its effect on the development of beginning reading skills. *School Psychology Quarterly*, 12, 170-192.
- Galaburda, A. M., LoTurco, J., Ramus, F., Fitch, R. H., & Rosen, G. D. (2006). From genes to behavior in developmental dyslexia. *Nature Neuroscience*, 9, 1213-1217.
- Geiger, G., & Lettvin, J. Y. (1987). Peripheral vision in persons with dyslexia. *New England Journal of Medicine*, 316, 1238-1243.

- Geiger, G., Lettvin, J. Y., & Fahler, M. (1994). Dyslexic children learn a new visual strategy for reading: a controlled experiment. *Vision Research*, *34*, 1223-1332.
- Georgiou, G. K., Parrila, R., Cui, Y., & Papadopoulos, T. C. (2013). Why is rapid automatized naming related to reading? *Journal of Experimental Child Psychology*, *115*, 218-225.
- Georgiou, G. K., Parrila, R., Kirby, J. (2006). Rapid naming speed components and early reading acquisition. *Scientific Studies of Reading*, *10*, 199–220.
- Georgiou, G. K., Parrila, R., & Kirby, J. R. (2009). RAN components and reading development from grade 3 to grade 5: what underlies their relationship. *Scientific Studies of Reading*, *13*, 508-534.
- Georgiou, G. K., Parrila, R., Kirby, R., & Stephenson, K. (2008). Rapid naming components and their relationship with phonological awareness, orthographic knowledge, speed of processing and different reading outcomes. *Scientific Studies of Reading*, *12*, 325-350.
- Georgiou, G. K., Parrila, R., Manolitsis, G., & Kirby, J. R. (2011). Examining the importance of assessing rapid automatized naming (RAN) for the identification of children with reading difficulties. *Learning Disabilities: A Contemporary Journal*, *9*, 5-26.
- Gilger, J. W., Borecki, I. B., Smith, S. D., DeFries, J. C., Pennington, B. F. (1996). The etiology of extreme scores for complex phenotypes: An illustration using reading performance. In: Chase CH, Rosen GD, Sherman GF, (Eds.). *Developmental dyslexia. Neural, cognitive, and genetic mechanisms* (pp 63– 85). Baltimore, MD: York Press.

- Gottardo, A., Stanovich, K. E., & Siegl, L. S. (1996). The relationships between phonological sensitivity, syntactic processing and verbal working memory in the reading performance of third-grade children. *Journal of Experimental Child Psychology, 63*, 563-582.
- Grigorenko, E. L. (2006). Learning disabilities in juvenile offenders. *Child and Adolescent Psychiatric Clinics of North America, 15*, 353-371.
- Hari, R., & Renvall, H. (2001). Impaired processing of rapid stimulus sequences in dyslexia. *Trends in Cognitive Sciences, 5*, 525-532.
- Hintikka, S., Aro, M., & Lyytinen, H. (2005). Computerized training of the correspondences between phonological and orthographic units. *Written Language and Literacy, 8*, 79-102.
- Hulme, C., Bowyer-Crane, C., Carroll, J. M., Duff, F. J., & Snowling, M. J. (2012). The causal role of phoneme awareness and letter-sound knowledge in learning to read: combining intervention studies with mediation analyses. *Psychological Science, 23*, 572-577.
- Hulme, C., Newton, P., Cowan, N., Stuart, G., & Brown, G. (1999). Think before you speak: Pauses, memory search, and trace reintegration processes in verbal memory span. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 25*, 447-463.
- Humphrey, N., & Mullins, P. M. (2002). Self-concept and self-esteem in developmental dyslexia. *Journal of Research in Special Education Needs, 2*, 1-13.
- Hung, R. (2012). *Orthographic learning in adults with reading difficulties*. Unpublished Master's thesis, University of Alberta, Edmonton, Canada.

- Hyona, J., & Olson, R. K. (1995). Eye fixation patterns among dyslexic and normal readers: effects of word length and word frequency. *Journal of Experimental Psychology, 21*, 1430-1440.
- Jones, M. W., Ashby, J., & Branigan, H. P. (2013). Dyslexia and fluency: Parafoveal and foveal influences on rapid automatized naming. *Journal of Experimental Psychology: Human Perception and Performance, 39*, 554-567.
- Jones, M. W., Branigan, H. P., Hatzidaki, A., & Obregon, M. (2010). Is the 'naming' deficit in dyslexia a misnomer? *Cognition, 116*, 56-70.
- Jones, M. W., Obregon, M., Kelly, M. L., & Branigan, H. P. (2008). Elucidating the component processes involved in dyslexic and non-dyslexic reading fluency: An eye-tracking study. *Cognition, 109*, 389-407.
- Kail, R., & Hall, L. K. (1994). Processing speed, naming speed, and reading. *Developmental Psychology, 30*, 949-954.
- Kail, R., Hall, L. K., & Caskey, B. J. (1999). Processing speed, exposure to print, and naming speed. *Applied Psycholinguistics, 20*, 303-314.
- Katzir, T., Kim, Y., Wolf, M., O'Brien, B., Kennedy, B., Lovett, M., & Morris, R. (2008). The varieties of pathways to dysfluent reading: Comparing subtypes of children with dyslexia at letter, word, and connected text levels of reading. *Journal of Learning Disabilities, 41*, 47-66.
- Kerek, E., & Niemi, P. (2009). Learning to read in Russian: Effects of orthographic complexity. *Journal of Research in Reading, 32*, 157-179.

- Kibby, M. Y., & Hynd, G. W. (2001). Neurobiological basis of learning disabilities. In B. Keogh and D. Hallahan (Eds.), *Research and Global Perspectives in Learning Disabilities* (pp. 25-42). Mahwah, NJ: Earlbaum.
- Kirby, J. R., Georgiou, G., Martinussen, R., & Parrila, R. (2010). Naming speed and reading: from prediction to instruction. *Reading Research Quarterly, 45*, 341-362.
- Kirby, J. R., Parrila, R., & Pfeiffer, S. (2003). Naming speed and phonological awareness as predictors of reading development. *Journal of Educational Psychology, 95*, 453-464.
- Kuperman, V., & Van Dyke, J. (2011). Effects of individual differences in verbal skills on eye-movement patterns during sentence reading. *Journal of Memory and Language, 65*, 42-73.
- Lervag, A., & Hulme, C. (2009). Rapid naming (RAN) taps a basic constraint on the development of early reading fluency. *Psychological Science, 20*, 1040-1048.
- Lorusso, M. K., Facoetty, A., Pesenti, S., Cattaneo, C., Molteni, M., & Geiger, G. (2004). Wider recognition in peripheral vision common to different subtypes of dyslexia. *Vision Research, 44*, 2413-2424.
- Lyon, G. R., Shaywitz, S. E., & Shaywitz, B. A. (2003). A definition of dyslexia. *Annals of Dyslexia, 53*, 1-14.
- Manis, F., Doi, L. M., & Badha, B. (2000). Naming speed, phonological awareness, and orthographic knowledge in second graders. *Journal of Learning Disabilities, 33*, 325-333.

- Manis, F., Seidenberg, M. S., & Doi, L. M. (1999). See Dick RAN: Rapid naming and the longitudinal prediction of reading subskills in first and second graders. *Scientific Studies of Reading, 3*, 129-157.
- Mann, V. (1984). Review: Reading skill and language skill. *Developmental Review, 4*, 1-15.
- McBride-Chang, C., & Manis, F. R. (1996). Structural invariance in the association of naming speed, phonological awareness, and verbal reasoning in good and poor readers: A test of the double deficit hypothesis. *Reading and Writing: An Interdisciplinary Journal, 8*, 323-339.
- Meyer, M. S., Wood, F. B., Hart, L. A., & Felton, R. H. (1998). Longitudinal course of rapid naming in disabled and nondisabled readers. *Annals of Dyslexia, 48*, 91-114.
- Misra, M., Katzir, T., Wolf, M., & Poldrack, R. A. (2004). Neural systems for Rapid Automatized Naming in skilled readers: Unraveling the RAN-reading relationship. *Scientific Studies of Reading, 8*, 241-256.
- Morris, R. D., Lovett, M. W., Wolf, M., Sevcik, R.A., Steinbach, K. A., et al. (2011). Multiple-component remediation for developmental reading disabilities: IQ, socioeconomic status, and race as factors in remedial outcome. *Journal of Learning Disabilities, 45*, 99-127.
- Morris, R., Stuebig, K., Fletcher, J., Shaywitz, S., Lyon, R., Shankweiler, D., Katz, L., Francis, D., & Shaywitz, B. (1998). Subtypes of reading disability: A phonological core. *Journal of Educational Psychology, 90*, 347-373.

- Neuhaus, G., Foorman, B. R., Francis, D. J., & Carlson, C. D. (2001). Measures of information processing in rapid automatized naming (RAN) and their relation to reading. *Journal of Experimental Child Psychology, 78*, 359-373.
- Neuhaus, G. F., & Swank, P. R. (2002). Understanding the relations between RAN letter subtest components and word reading in first-grade students. *Journal of Learning Disabilities, 35*, 158-174.
- Nicolson, R. I., & Fawcett, A. J. (1990). Automaticity: A new framework for dyslexia research? *Cognition, 35*, 159-182.
- Norton, E. S., & Wolf, M. (2012). Rapid automatized naming (RAN) and reading fluency: implications for understanding and treatment of reading disabilities. *Annual Review of Psychology, 63*, 427-452.
- Obregon, M. (1994). Exploring naming timing patterns by dyslexic and normal readers on the serial RAN task. Unpublished master's thesis, Tufts University, Medford, MA.
- Olitsky, S. E., & Nelson, L. B. (2003). Reading disorders in children. *The Pediatric Clinics of North America, 50*, 213-224.
- Pammar, K. & Vidyasagar, T. R. (2005). Integration of the visual and auditory networks in dyslexia: A theoretical perspective. *Journal of Research in Reading, 28*, 320-331.
- Papadopoulos, T. C., Georgiou, G. K., & Kendeou, P. (2009). Investigating the double-deficit hypothesis in Greek: Findings from a longitudinal study. *Journal of Learning Disabilities, 42*, 528-547.

- Pavlidis, G. (1985). Eye movements in dyslexia: their diagnostic significance. *Journal of Learning Disabilities, 18*, 42-50.
- Pennington, B. F., & Gilger, J. W. (1996). How is dyslexia transmitted? In: Chase CH, Rosen GD, Sherman GF (Eds.). *Developmental dyslexia. Neural, cognitive, and genetic mechanisms* (pp 41 - 61). Baltimore, MD: York Press.
- Petrill, S. A., Deater-Deckard, K., Thompson, L. A., DeThorne, L. S., & Schatschneider, C. (2006). Genetic and environmental effects of serial naming and phonological awareness on early reading outcomes. *Journal of Educational Psychology, 98*, 112–121.
- Powell, D., Stainthorp, R., Stuart, M, Garwood, H., & Quinlan, P. (2007). An experimental comparison between rival theories of rapid automatized naming performance and its relationship to reading. *Journal of Experimental Child Psychology, 98*, 46-68.
- Price, C. J, & McCrory, E. (2005). Functional brain imaging studies of skilled reading and developmental dyslexia. In: Snowling MJ and Hulme C (Eds). *The science of reading: A handbook* (pp. 473–496). Blackwell Publishing; Oxford, UK.
- Price, C. J., & Mechelli, A. (2005) Reading and reading disturbance. *Current Opinion in Neurobiology, 15*, 231-238.
- Protopapas, A., Altani, A., & Georgiou, G. K. (in press). RAN backward: A test of the visual scanning hypothesis. *Scientific Studies of Reading*. doi: 10.1080/10888438.2013.769556.
- Rayner, K. (1985). The role of eye movements in learning to read and reading disability. *Remedial and Special Education, 6*, 53-60.

- Rayner, K. (1997). Understanding eye movements in reading. *Scientific Studies of Reading, 1*, 317-339.
- Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin, 124*, 372-422.
- Rayner, K., Juhasz, B. J., & Pollatsek, A. (2005). Eye movements during reading. In M.J. Snowling and C. Hulme (Eds), *The Science of Reading: A Handbook* (pp 79-97). Oxford: Blackwell.
- Scarborough, H. S. (1990). Very early language deficits in dyslexic children. *Child Development, 61*, 1728 –1743.
- Scarborough, H. S. & Parker, J. D. (2003). Matthew effects in children with learning disabilities: Development of reading, IQ, and psychosocial problems from grade 2 to grade 8. *Annals of Dyslexia, 53*, 47-71.
- Scerri, T. S, & Schulte-Korne, G. (2010). Genetics of developmental dyslexia. *European Child and Adolescent Psychiatry, 19*, 179–197.
- Schatschneider, C., & Torgesen, J. (2004). Using our current understanding of dyslexia to support early identification and intervention. *Journal of Child Neurology, 19*, 759-765.
- Shaywitz., S. E. (1996). Dyslexia. *Scientific American, 275*, 98-104.
- Shaywitz, S. (2003). *Overcoming dyslexia: A new and complete science-based program for reading problems at any level*. New York: Alfred A. Knopf.
- Shaywitz, S., Escobar, M., Shaywitz, B., Fletcher, J., & Makuch, R. (1992). Evidence that dyslexia may represent the lower tail of a normal distribution of reading ability. *New England Journal of Medicine, 326*, 145–150.

- Shaywitz, B. A., Holford, T. R., Holahan, J. M., Fletcher, J. M., Stuebing, K. K., Francis, D. J., et al (1995). A Matthew effect for IQ but not for reading: Results from a longitudinal study. *Read Research Quarterly*, 30, 894 –906.
- Shaywitz, S. E., Mody, M., & Shaywitz, B. A. (2006). Neural Mechanisms in Dyslexia. *Current Directions in Psychological Science*, 15, 278-281.
- Shaywitz, S., & Shaywitz, B. (2005). Dyslexia (specific reading disability). *Biological Psychiatry*, 57, 1301–1309.
- Shaywitz, S. E., & Shaywitz, B. A. (2008). Paying attention to reading: the neurobiology of reading and dyslexia. *Development and Psychopathology*, 20, 1329-1349.
- Shaywitz, B., Shaywitz, S., Blachman, B., Pugh, K., Fulbright, R., Skudlarski, P., et al. (2004). Development of left occipito-temporal systems for skilled reading in children after a phonologically-based intervention. *Biological Psychiatry*. 55, 926-933.
- Shaywitz, S. E., Shaywitz, B. A., Fletcher, J. M., & Escobar, M. D. (1990). Prevalence of reading disability in boys and girls. Results of the Connecticut Longitudinal Study. *Journal of the American Medical Association*, 264, 998-1002.
- Shaywitz, S., Shaywitz, B., Fulbright, R., Skudlarski, P., Mencl, W., et al. (2003). Neural systems for compensation and persistence: young adult outcome of childhood reading disability. *Biological Psychiatry*, 54, 25–33.
- Snow, C. E., Burns, M. S., & Griffen, P. (1998). *Preventing reading difficulties in young children*. Washington, DC: The National Academies Press.
- Snowling, M. J. (1981) Phonemic deficits in developmental dyslexia. *Psychological Research*, 43, 219-234.

- Snowling, M. J. (2000). *Dyslexia* (2nd ed.). Oxford: Blackwell.
- Snowling, M. J., & Hulme, C. (1989). A longitudinal case study of developmental phonological dyslexia. *Cognitive Neuropsychology*, *6*, 379-403.
- Sprenger-Charolles, L., Siegel, L. S., Bechenec, D., & Serniclaes, W. (2003). Development of phonological and orthographic processing in reading aloud, in silent reading, and in spelling: A four-year longitudinal study. *Journal of Experimental Child Psychology*, *84*, 194-217.
- Stainthorp, R., Powell, D., Stuart, M., Quinlan, P., & Garwood, H. (2010). Visual processing deficits in children with slow RAN performance. *Scientific Studies of Reading*, *14*, 266-292.
- Stanovich, K. (1988). Explaining the differences between the dyslexic and the garden-variety poor reader: the phonological core variable difference model. *Journal of Learning Disabilities*, *21*, 590-604.
- Starr, M. S., & Rayner, K. (2001). Eye movements during reading: Some current controversies. *TRENDS in Cognitive Sciences*, *5*, 156-163.
- Stein, J. F. (2003). Visual motion sensitivity and reading. *Neuropsychologia*, *41*, 1785-1793.
- Stein, J., & Talcott, J. (1999). Impaired Neuronal Timing in Developmental Dyslexia – The Magnocellular Hypothesis. *Dyslexia*, *5*, 59-77.
- Stein, J., & Walsh, V. (1997). To see but not to read; the magnocellular theory of dyslexia. *Trends in Neurosciences*, *20*, 147-152.

- Svensson, I., Lundberg, I., Jacobson, C. (2001). The prevalence of reading and spelling difficulties among inmates of institutions for compulsory care of juvenile delinquents. *Dyslexia*, 7, 62- 76.
- Swanson, H. L., Trainin, G., Neochea, D. M., & Hammill, D. D. (2003). Rapid naming, phonological awareness, and reading: A meta-analysis of the correlation evidence. *Review of Educational Research*, 73, 407-440.
- Torgesen, J. K. (2004). Avoiding the devastating downward spiral: the evidence that early intervention prevents reading failure. *American Journal of Education*, 28, 6–19.
- Torgesen, J. K., Wagner, R. K., & Rashotte, C. A. (1994). Longitudinal studies of phonological processing and reading. *Journal of Learning Disabilities*, 27, 276-286.
- Torgesen, J. K., Wagner, R. K., Rashotte, C. A., Burgess, S., & Hecht, S. (1997). Contributions of phonological awareness and rapid automatic naming ability to the growth of word-reading skills in second to fifth-grade children. *Scientific Studies of Reading*, 1, 161-185.
- Vellutino, F. R. & Fletcher, J. M. (2005). Developmental dyslexia. In Snowling & C. Hulme (Eds). *The science of reading: A handbook* (pp. 362-378). Malden, MA: Blackwell Publishing.
- Vellutino, F. R., Fletcher, J. M., Snowling, M. J., & Scanlon, D. M. (2004). Specific reading disability (dyslexia): what have we learned in the past four decades? *Journal of Child Psychology and Psychiatry*, 45, 2-40.

- Vellutino, F. R., Scanlon, D. M., & Tanzman, M. S. (1998). The case for early intervention in diagnosing specific reading disability. *Journal of School Psychology, 36*, 367-397.
- Waber, D. P., Wolff, P. H., Forbes, P. W., & Weiler, M. D. (2000). Rapid automatized naming in children referred for evaluation of heterogeneous learning problems: How specific are naming speed deficits to reading disability? *Child Neuropsychology, 6*, 251-261.
- Wagner, R. K., & Torgesen, J. K. (1987). The nature of phonological processing and its causal role in the acquisition of reading skills. *Psychological Bulletin, 101*, 192-212.
- Wagner, R. K., Torgesen, J. K., Laughon, P. L., Simmons, K., & Rashotte, C. A. (1993). Development of young readers' phonological processing abilities. *Journal of Educational Psychology, 85*, 83-103.
- Wagner, R. K., Torgesen, J. K., & Rashotte, C. A. (1994). The development of reading related phonological processing abilities: New evidence of bi-directional causality from a latent variable longitudinal study. *Developmental Psychology, 30*, 73-87.
- Wagner, R. K., Torgesen, J. K., & Rashotte, C. A. (1999). *Comprehensive Test of Phonological Processing*. Austin, TX: PRO-ED.
- Wechsler, D. (1999). *Wechsler abbreviated scale of intelligence*. San Antonio, TX: Harcourt Assessment.
- Whitney, C., & Cornelissen, P. (2005). Letter-position encoding and dyslexia. *Journal of Research in Reading, 28*, 274-301.

- Wolf, M., Bally, H., & Morris, R. (1986). Automaticity, retrieval processes, and reading: a longitudinal study in average and impaired readers. *Child Development, 57*, 988-1000.
- Wolf, M., Barzillai, M., Gottwald, S., Miller, L., Norton, E., et al. (2009). The RAVE-O intervention: connecting neuroscience to the classroom. *Mind Brain Education, 3*, 84-93.
- Wolf, M., & Bowers, P. G. (1999). The double-deficit hypothesis for the developmental dyslexias. *Journal of Educational Psychology, 91*, 415-438.
- Wolf, M., Bowers, P. G., & Biddle, K. (2000). Naming-speed processes, timing, and reading: A conceptual review. *Journal of Learning Disabilities, 33*, 387-407.
- Wolf, M., & Denckla, M. B. (2005). *Rapid automatized naming and rapid alternating stimulus tests (RAN/RAS)*. Austin, TX: PRO-ED.
- Wolf, M., Goldberg, A., Cirino, P., Gidney, C., Morris, R., & Lovett, M. (2002). The unique and combined contribution of naming speed and phonological processes in reading disability: A Test of the Double-Deficit Hypothesis. *Reading and Writing, 15*, 43-72.
- Yan, M., Pan, J., Laubrock, J., Kliegl, R., & Shu, H. (2013). Parafoveal processing efficiency in rapid automatized naming: A comparison between Chinese normal and dyslexic children. *Journal of Experimental Child Psychology, 115*, 579 – 589.
- Young, A., & Bowers, P. G., (1995). Individual differences and text difficulty determinants of reading fluency and expressiveness. *Journal of Experimental Child Psychology, 60*, 428-454.

Zoccolotti, P., de Luca, M., Lami, L., Pizzoli, C., Pontillo, M., & Spinelli, D. (in press).

Multiple stimulus presentation yields larger deficits in children with developmental dyslexia: A study with reading and RAN tasks. *Child Neuropsychology*. doi:10.1080/09297049.2012.718325.