Contributions of Phonology and Orthography to Spelling in Children with Dyslexia

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Abstract

Learning to spell is dependent on a child's ability to simultaneously process phonological (i.e., related to sounds) and orthographic (i.e., related to letters) information. The contributions of phonological and orthographic processes in children with dyslexia have been explored more in reading than in spelling. Evidence from reading research indicates that children with dyslexia tend to rely on relatively preserved orthographic knowledge to compensate for their phonological weaknesses. More studies are needed in spelling, as existing evidence is not clear as to whether phonological and orthographic processes make joint or separate contributions. The present study used phonological and orthographic neighbors (i.e., words differing by a single sound or letter) to examine processing abilities in children with dyslexia and children with typical reading skills.

A total of 57 children with dyslexia (grade 4), age-matched typically developing children (grade 4), and reading-level-matched typically developing children (grades 1 and 2) were recruited from elementary schools in Kansas. Participants were asked to spell and read nonwords that varied in the number of phonological and orthographic neighbors (i.e., dense/large neighborhoods vs. sparse/small neighborhoods).

Our results revealed that nonwords with many phonological neighbors facilitated spelling and reading performances, whereas nonwords with many orthographic neighbors did not. Performances were similar between children with dyslexia and typical readers. Our findings do not support the idea of orthographic compensation in children with dyslexia and instead, they suggest that children rely more on their phonological knowledge than their orthographic knowledge. We discuss how our findings inform theoretical models of spelling and reading, and how methodological characteristics may explain discrepancies between our study and previous studies.

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Table of Contents

Chapter 1: Introduction

Developmental dyslexia is considered as the most common type of learning disability, with an estimated prevalence up to 17% among school-age children (Shaywitz, 1998). It is characterized by difficulties with accurate and/or fluent word recognition and spelling, and it occurs regardless of intelligence level, learning opportunities, or motivation (Lyon, Shaywitz, & Shaywitz, 2003). Due to their difficulties in the acquisition of reading and spelling, children with dyslexia are at higher risk of school dropout, low academic achievement, and unemployment (Maughan, 1995; Snowling, 2000; Cortiella & Horowitz, 2014).

Successful spelling depends on children's phonological (i.e., sounds and sound patterns) and orthographic (i.e., letters and letter patterns) knowledge and their efficient interactions. Therefore, a disruption in the connections between phonological and orthographic processes will most likely impede children's progress in spelling (Ehri & Wilce, 1980; Tunmer & Nesdale, 1982; Bruck, 1992; Landerl, Frith, & Wimmer, 1996). It is well documented that children with dyslexia experience difficulties with spelling due to underlying deficits in phonological processes (see Cassar & Treiman, 2004). What is less clear is how the presence of dyslexia affects the developmental trajectory of phonological and orthographic processes, and more importantly, the nature of their interactions. Evidence from reading research suggests that children with dyslexia have adequate orthographic processing skills and, to some degree, they compensate for their poor phonological processing skills (Goswami & Bryant, 1990; Olson, 1985; Siegel, Share, & Geva, 1995; Stanovich, Siegel, & Gottardo, 1997; van der Leij & van Daal, 1999). Such evidence raises the possibility of a dissociation between phonological and orthographic processes and of a different developmental course between typical and poor readers in learning to read.

The few studies, however, that have examined the nature of interactions between phonological and orthographic processes in spelling give a mixed picture (Lennox & Siegel, 1996; Bourassa & Treiman, 2003; Cassar, Treiman, Moats, Pollo, & Kessler, 2005). The purpose of the current study was to examine the degree of integration between phonological and orthographic processes to support spelling abilities of children with dyslexia compared to typically readers.

Theories of Spelling Development

Learning to spell is founded on children's understanding that speech sounds are represented by letters of the alphabet. In the early elementary years, children gradually become aware of letter-sound correspondences and of the rules that govern the way words are spelled. For example, children must learn that /k/ is spelled 'c' before a, o, u, or any consonant (e.g., cat, cost, cup, crust) and 'k' before e, i, or y (e.g., key, kite, kyanite).

Traditional theories of spelling development suggest that beginning spellers rely primarily on phonological skills when attempting to spell new words. This is reflected in phonetic errors, like *dragon* spelled as *jragn, try* as *chrie*, or *home* as *hom* (Treiman, 1993). These theories also postulate that children begin to develop orthographic (i.e., related to letters) knowledge only after they gain more experience with printed words (Cassar & Treiman, 1997; Cassar & Treiman, 2004). Therefore, children are seen to progress through distinct stages of spelling development and each stage is defined by the mastery of a specific set of skills.

However, the notion of stages has been challenged by evidence pointing to an early emergence of orthographic knowledge and interactions between phonology and orthography (Ehri & Wilce, 1980; Tunmer & Nesdale, 1982; Treiman, 1993; Treiman, Berch, & Weatherston, 1993; Snowling, 1994; Thomson, Fletcher-Flinn, & Cottrell, 1999). A popular example is that of overshoot errors, defined as children's tendency to overestimate the number of sounds in words that contain silent letters (e.g., i***s***land) or digraphs (e.g., ***ph***one) (see Ehri & Wilce, 1980; Tunmer & Nesdale, 1982). Children's use of analogy when spelling is another example of the interactions between phonological and orthographic knowledge. Goswami (1988) found that young children can use sounds or spelling patterns of known words to spell new words (e.g., beak – peak). In support of an interactive model, a recent brain imaging study found that children's spelling performance decreased when there was a mismatch between words that have similar spelling of the rime but different pronunciation (e.g., pint – mint), suggesting a simultaneous involvement of phonological and orthographic processes (Bitan et al., 2006). These different findings illustrate that beginning spellers engage both phonological and orthographic processes and that the interplay between the two systems is important in supporting children's developing word knowledge.

Interactions between Phonology and Orthography in Dyslexia

Due to their difficulties with the phonological structure of the English language, children with dyslexia struggle with both reading and spelling. Spelling is formally recognized as one of the areas of concern in dyslexia; yet, we have limited understanding of how spelling develops in the presence of dyslexia, individual differences in spelling ability, and which types of instruction are effective to remediate spelling difficulties (Treiman, 2017). These gaps in knowledge may result from educational policies that focus almost exclusively on reading achievement and from misconceptions about the degree of irregularity in the English writing system that discourage teachers to teach spelling in an explicit manner (see Reed, 2012).

Thus, it is not surprising that the question of the nature of interactions between phonological and orthographic processes has been researched more in reading than it has in spelling. Overall, existing evidence is inconsistent regarding the reciprocity between the two processes in reading and spelling. Reading studies have shown that despite poor phonological abilities, children with dyslexia relied on preserved orthographic abilities to make some progress in reading. On the other hand, spelling studies have produced mixed results, making it unclear whether phonological and orthographic processes are dissociable in spelling, as they appear to be in reading.

In a study by Olson (1985), children with dyslexia and younger reading-level-matched peers participated in a phonological task, in which they were asked to choose nonwords that sounded like familiar words (e.g., kake vs. dake), and in an orthographic task, in which they were asked to choose the real words from a list of phonetically identical pairs (e.g., rain vs. rane). Although children with dyslexia demonstrated significantly lower phonological skills than typical readers, their orthographic skills were similar. These findings imply a dissociation between processes and a preserved sensitivity to orthographic conventions in children with dyslexia.

Siegel and colleagues (1995) asked children with dyslexia and younger typical readers to read an increasingly difficult list of nonwords (e.g., laip, cigbet, bafmotbem) and to select nonwords that contained conventional letter sequences (e.g., lund vs. dlun). They found that children with dyslexia performed significantly worse than typical readers in the phonological task, but significantly better in the orthographic task. The authors argued that because of their poor phonological skills, children with dyslexia learn to pay more attention to the orthographic form of a word and develop knowledge about which letter sequences are permissible (e.g., -nd as a final cluster) and which are not (e.g., dl- as an initial cluster).

In a study by Stanovich and colleagues (1997), children with dyslexia showed poor phonological sensitivity in a phoneme (i.e., smallest unit of sound) and syllable deletion task, but similar orthographic abilities as younger typical readers when they were asked to select nonwords with permissible letter sequences (e.g., filv vs. filk). These findings suggest that orthographic processing may be less affected by dyslexia.

van der Leij and van Daal (1999) found that children with dyslexia read better high-frequency real words and nonwords with high-frequency clusters, due to their tendency to appreciate orthographic structure better than phonological structure.

In a more recent study, Cassar and colleagues (2005) found that children with dyslexia tended to perform better in choosing words with permissible orthographic sequences (e.g., vowel doublets, doublet position, initial consonant clusters, final consonant clusters) than younger level-matched typical readers.

Only few studies have compared phonological and orthographic characteristics in spelling between children with dyslexia and typical readers and they have produced mixed results. Lennox and Siegel (1996) compared spelling performance between average and poor spellers in phonological and visual similarity tasks. The phonological similarity task determined whether misspellings preserved the phonological form of a target word (e.g., reach – reche) and the visual similarity task determined the amount of overlap between the letters in misspellings and the target word (e.g., heaven – heven). They found that while average spellers accurately used both phonological rules and orthographic patterns, poor spellers relied primarily on orthographic strategies. The authors argued that the mismatch between phonological and orthographic skills of poor spellers suggests a different developmental course in learning to spell.

Two later studies compared spelling performance between children with dyslexia and spelling-level-matched peers on real words and nonwords (Bourassa & Treiman, 2003; Cassar et al., 2005). Both studies did not find any significant differences in terms of strategies that children with dyslexia and typical readers used when spelling new words. These results did not support the idea that children with dyslexia tend to compensate for their poor phonological abilities by relying on good or better orthographic abilities. It is possible that the presence of dyslexia disrupts the interactions between phonological and orthographic processes more in reading than in spelling. However, results from the two studies by Bourassa and Treiman (2003) and Cassar et al., (2005) require a more cautious interpretation because they appear to have been based on the same participant pool.

To summarize, evidence from reading research raises the possibility that phonological and orthographic processes are less integrated in children with dyslexia compared to typical readers. The fact that reading and spelling rely on the same cognitive underpinnings leads us to expect a similar pattern during spelling development. So far, spelling research has not yet provided a clear picture of the nature of interactions between phonological and orthographic processes. Further investigation is warranted to determine how dyslexia affects word processing during spelling.

Explicit and Implicit Representations

To determine whether children with dyslexia primarily use orthographic strategies over phonological strategies during spelling, it is helpful to consider how previous studies approached this question. Methodological differences between studies are subtle; all studies used tasks that aimed to examine children’s explicit knowledge of written conventions, such as sound-letter correspondences, permissible letter sequences, and positional constraints. Similar tasks were also used in reading studies, but unlike in spelling, they consistently captured some dissociation between phonological and orthographic processes in children with dyslexia. It could be that a dissociation between phonological and orthographic processes enables compensatory strategies in reading but not in spelling (Bourassa & Treiman, 2003). We must also consider that because learning to spell is more difficult than learning to read, traditional spelling tasks that examine children's explicit knowledge of written conventions may not fully capture the intricate interplay in underlying processes. Alternative measures may be necessary for more in-depth examination of how phonological and orthographic processes develop and interact in poor readers.

The current study considered this possibility and examined the interactions between phonological and orthographic processes through children's implicit knowledge. Implicit knowledge is knowledge acquired in previous episodes but it cannot be readily accessed or verbalized (Reber, 1993; Dienes & Berry, 1997; Steffler, 2001). Spelling involves both explicit knowledge, like knowledge about letter-sound correspondences and permissible letter sequences, and implicit knowledge, like knowledge about the frequency of occurrence of sound and letter patterns in the English language. Implicit knowledge, although expressed unintentionally, can affect performance during a spelling task and can be an indicator of the nature of underlying representations (Steffler, 2001). To examine implicit knowledge, we varied the number of phonological and orthographic neighbors for each stimulus and we determined their effects on children's spelling performance.

Phonological and orthographic neighbors. Phonological neighbors are words differing from a given stimulus item by a single *sound* substitution, deletion, or addition (Luce & Pisoni, 1998). For example, *bat*, *cab*, and *cut* are phonological neighbors of *cat*. Orthographic neighbors are words differing from a given stimulus item by a single *letter* substitution, deletion, or addition (Coltheart, Davelaar, Jonasson, & Besner, 1977). For example, *ten*, *pea*, and *pet* are orthographic neighbors of *pen*. Phonological and orthographic neighborhood density may vary considerably across words, such as some words have few neighbors (e.g., 'frog' has 2 orthographic neighbors and 3 phonological neighbors) and some words have many neighbors (e.g., 'book' has 13 orthographic neighbors and 20 phonological neighbors). Phonological and orthographic neighborhood densities can be correlated for some words (e.g., frog, book) but not for other words (e.g., 'girl' has 4 orthographic neighbors and 16 phonological neighbors).

Evidence from typical development suggests that words with many orthographic neighbors are easier to spell than words with few orthographic neighbors (Laxon, Coltheart, & Keating, 1988). This pattern also extends to children with poor reading skills (Laxon et al., 1988). Words with many orthographic neighbors tend to have consistent (i.e., one to one) letter-sound correspondences and therefore, they are thought to facilitate spelling performance (Ziegler, Muneaux, & Grainger, 2003; Grainger, Muneaux, Farioli, & Ziegler, 2005). To our knowledge, the effects of phonological neighborhood density on spelling have not yet been determined. However, given the interactions between phonology and orthography and children's tendency to spell by analogy (Goswami, 1988), we expect that words that share phonological similarities with many other words would be easier to spell than words that share phonological similarities with few other words.

Current Study

The evidence reviewed from previous reading studies suggests an imbalance between phonological and orthographic processes in children with dyslexia (Olson, 1985; Siegel et al., 1995; Stanovich et al., 1997; van der Leij & van Daal, 1999; Cassar et al., 2005). However, it remains unclear if phonological and orthographic processes interact to support their spelling development. Additional research is needed to determine whether children with dyslexia display weaknesses in phonological processing but strengths in orthographic processing when learning to spell.

As a primary objective, we examined whether children with dyslexia produced spellings that showed low sensitivity to phonological structure and high sensitivity to orthographic structure, indicating a dissociation between phonological and orthographic processes. To this end, children with dyslexia and typical readers were asked to spell a set of nonwords that varied in terms of phonological and orthographic neighborhood densities.

For typical readers we hypothesized that they would show higher spelling accuracy with nonwords from high-density phonological and orthographic neighborhoods. This finding would indicate that efficient interactions between phonological and orthographic processes are necessary to support typical spelling development. Given the mixed results in the spelling literature, we offer two predictions for children with dyslexia. If phonological and orthographic processes interact, then children with dyslexia would also show higher spelling accuracy with nonwords from high-density phonological and orthographic neighborhoods. Their overall accuracy would be, however, lower than that of age-matched peers. Alternatively, if these processes are dissociable, then children with dyslexia would show higher spelling accuracy with nonwords from low-density phonological neighborhoods and high-density orthographic neighborhoods. This would suggest that orthographic knowledge acts as a compensatory factor.

As a secondary objective, we examined the nature of interactions between phonological and orthographic processes in reading. We included a reading task because we wanted to confirm previous findings and determine whether progress in reading and spelling depends on the same underlying mechanisms.

For typical readers, we hypothesized that they would show higher reading accuracy with nonwords from high-density phonological and orthographic neighborhoods. In line with previous findings, we hypothesized that children with dyslexia would show higher reading accuracy with nonwords from low-density phonological and high-density orthographic neighborhoods.

Chapter 2: Method

Participants

The participants for this study were 57 children, 34 boys and 23 girls, divided in three groups based on their performance in reading efficiency: 1) 20 children with dyslexia from grade 4 (115 – 130 months old; *M* = 118; *SD* = 6), 2) 20 age-matched typically developing (age-TD) children from grade 4 (114 – 131 months old; *M* = 120; *SD* = 6), and 3) 17 younger reading-level-matched typically developing (level-TD) children from grades 1 and 2 (77 – 98 months old; *M* = 84; *SD* = 8).

Participants were recruited from Kansas through referrals, networking with the community of families who have a child with dyslexia, and word of mouth (i.e., flyers, social media) (see Table 1). The average maternal education level was at 16 years (i.e., standard college or university graduation) with a range from 10 to 20 years. Eighteen out of 20 participants with dyslexia were receiving intervention services provided by a school-based professional (e.g., Reading Specialist, Speech-Language Pathologist) or by a private practitioner. Additional demographic (e.g., race, ethnicity) and health (e.g., comorbid disorders) information are reported in Table 1.

Dyslexia was defined by below-average word reading (Test of Word Reading Efficiency – 2; TOWRE-2; Wagner, Torgesen, & Rashotte, 2011) and typical nonverbal intelligence (Reynolds Intellectual Assessment Scales-2; RIAS-2; Reynolds & Kamphaus, 2015). This definition is in line with previous research (Pennington, Gilger, Olson, & DeFries, 1992; Shaywitz, Shaywitz, Fletcher, & Escobar, 1990; Snowling, Bishop, & Stothard, 2000; Lyon et al., 2003).

Using the grade-level norms, children with dyslexia received composite scores below 88 on the TOWRE-2, age-TD children received composites scores above 88, and level-TD children received similar raw scores as children with dyslexia corresponding to composite scores above 88 (see Table 2). All participants had normal nonverbal intelligence (i.e., RIAS standard score above 85) and hearing.

Clinical Assessments

Clinical evaluations were completed in three 20- to 45-minute sessions and were audio and/or video recorded. We administered assessments to determine children's reading efficiency (TOWRE-2), nonverbal intelligence (RIAS), hearing, oral language (Clinical Evaluation of Language Fundamentals-4; CELF-4; Semel, Wiig, & Secord, 2002), phonological awareness (Comprehensive Test of Phonological Processing-2; CTOPP-2; Wagner, Torgesen, Rashotte, & Pearson, 2013), and spelling ability (Wide Range Achievement Test-4; WRAT-4; Wilkinson & Roberston, 2006). A summary (i.e., *M*, *SD*, range) of children's reading efficiency, nonverbal intelligence, oral language, phonological awareness, and spelling abilities is presented in Table 2. Table 3 shows the number of children in each group scoring in the clinical range (i.e., $< 16^{th}$ percentile) in the TOWRE-2, CELF-4, CTOPP-2, and WRAT-4.

Reading efficiency. The TOWRE-2 is a timed test and includes two subtests: a) the 'Sight Word Efficiency' subtest required participants to read a list of real words as fast as they could in 45 seconds, and b) the 'Phonemic Decoding Efficiency' subtest required participants to read a list of nonwords as fast as they could in 45 seconds.

Nonverbal intelligence. Two subtests from the RIAS were used to assess nonverbal intelligence: a) the ‘Odd-Item Out’ subtest required participants to identify the odd picture among a choice of six, and b) the ‘What’s Missing’ subtest required participants to identify what is missing from a target picture.

Hearing. According to guidelines from the American Speech-Language-Hearing Association (ASHA, 1997), children were required to pass a hearing screening at 20dB for 1000, 2000, and 4000 Hz in both ears.

Oral language. Oral language was evaluated using four subtests of the CELF-4. Subtests varied depending a participant’s age, in accordance with the instructions for obtaining a core language score. Children between the ages of 6 and 8 received the ‘Concepts and Following Directions’, ‘Word Structure’, ‘Recalling Sentences’, and ‘Formulated Sentences’ subtests. Children between the ages of 9 and 10 received the ‘Concepts and Following Directions’, ‘Recalling Sentences’, ‘Formulated Sentences’, and ‘Word Classes’ subtests. The ‘Concepts and Following Directions’ subtest required participants to point to pictures that matched a series of directions that included time, location, and descriptive elements. The ‘Word Structure’ subtest required participants to complete sentences with the correct grammatical form of a word. The ‘Recalling Sentences’ subtest required participants to repeat sentences verbatim. The ‘Formulated Sentences’ subtest required participants to make up sentences about various pictures by using target words given by the examiner. The ‘Word Classes’ subtest required participants to choose two words from sets of three or four that were similar in some way and then to state how those items when together.

Phonological awareness. Phonological awareness was evaluated using three subtests from the CTOPP-2. In accordance with the instructions provided in the manual, the combination of subtests depended on a participant's age. Children between the ages of 6 and 7 received the 'Elision', 'Blending Words', and 'Sound Matching' subtests.

Table 1: Participant demographic, health, and recruitment information.

		Dyslexia	Age-TD	Level-TD
Gender	Male	12	12	10
	Female	8	8	7
Race	American Indian or Alaska Native	-	-	-
	Asian	-	1	-
	Black or African American	2	-	1
	Native Hawaiian or Other Pacific Islander	-	-	-
	White	18	18	14
	Mixed	-	1	2
Ethnicity	Hispanic or Latino	2	-	4
	Not Hispanic or Latino	17	18	13
	Unknown	1	1	-
Type of School	Public/Private school	19	18	16
	Homeschool	1	2	1
Dyslexia Diagnosis	Yes	9	-	-
	No	11	-	-
Comorbid Disorders	Attention Deficit Hyperactivity Disorder (ADHD)	2	3	-
	Tourette Syndrome	1	-	-
	Asperger Syndrome	-	1	-
	Obsessive-Compulsive Disorder (OCD)	-	1	-
	Post-Traumatic Stress Disorder (PTSD)	-	1	-
	Anxiety	-	1	-
	Other (e.g., Juvenile Idiopathic Arthritis, Disruptive Mood Dysregulation Disorder)	1	-	1
	None	16	17	16
Special Services	School-based professional (Speech-Language Pathologist, Reading Specialist)	13	2	3
	Private tutor	5	-	-
	No services	2	18	14
Recruitment Sources	Elementary schools (letters sent to parents)	4	8	11
	Referrals	8	-	-
	Social media / Word of mouth	8	12	6

Table 2: Means and standard deviations of group standard scores on clinical assessments.

	Dyslexia			Age-TD			Level-TD		
Clinical Assessments	**Mean**	**SD**	**Range**	**Mean**	**SD**	**Range**	**Mean**	**SD**	**Range**
Reading Efficiency	75	9	55-88	102	10	88-126	103	10	89-122
Nonverbal Intelligence	106	15	87-135	113	11	91-136	115	16	97-149
Oral Language	102	19	73-142	112	17	88-144	98	10	75-112
Phonological Awareness	90	13	71-114	100	10	80-118	105	10	92-122
Spelling Ability	84	8	68-100	110	14	90-145	105	10	84-127

Table 3: Number of children with below-average performances (i.e., <16th percentile).

	Dyslexia	Age-TD	Level-TD
Clinical Assessments			
Reading Efficiency	16	-	-
Oral Language	4	-	2
Phonological Awareness	8	1	-
Spelling Ability	12	-	1

Children between the ages of 8 and 10 received the ‘Elision’, ‘Blending Words’, and ‘Phoneme Isolation’ subtests. The ‘Elision’ subtest required participants to manipulate words by dropping syllables. The ‘Blending Words’ subtest required participants to blend words or sounds together. The ‘Sound Matching’ subtest required participants to match words with the same first or last sound. The ‘Phoneme Isolation’ subtest required participants to identify initial, medial, or final sounds in words.

Spelling ability. Spelling ability was evaluated using the spelling subtest of the WRAT-4 which required participants to spell a set of letters and a set of increasingly complex words. Words were presented individually and in context sentences.

Stimuli

Study stimuli consist of 32 consonant-vowel-consonant (CVC) nonwords, equally divided in four conditions (see Appendix A): 1) dense phonological neighborhood and dense orthographic neighborhood (P+ O+), 2) dense phonological neighborhood and sparse orthographic neighborhood (P+ O-), 3) sparse phonological neighborhood and dense orthographic neighborhood (P- O+), and 4) sparse phonological neighborhood and sparse orthographic neighborhood (P- O-). Nonwords in sparse neighborhoods have 4 to 7 neighbors and nonwords in dense neighborhoods have 10 to 15 neighbors.

Stimuli Variables

Phonological neighbors. Phonological neighbors are words differing from a given stimulus by a single phoneme substitution, deletion, or addition (Luce & Pisoni, 1998). The current nonwords and phonological neighborhood estimates were taken from a database created by Storkel, Hogan, and Vitevitch at the Word and Sound Learning Lab (see Storkel, 2013).

Orthographic neighbors. Orthographic neighbors are words differing from a given stimulus item by a single letter substitution, deletion, or addition (Coltheart et al., 1977). Orthographic neighborhood size for the selected stimuli were calculated using the ‘MCWord: An Orthographic Wordform Database’ (Medler & Binder, 2005).

Phonotactic probability. Phonotactic probability refers to the likelihood of occurrence of a sound sequence in the English language, with sound sequences being categorized into common (e.g., /bʌs/ - bus) and rare (e.g., / lɛg/ - leg) (Storkel, 2004a). Phonotactic probability is positively correlated with phonological neighborhood density, with common and rare sound sequences tending to reside in dense and sparse neighborhoods, respectively (Storkel, 2004a; Vitevitch, Luce, Pisoni, & Auer, 1999). Phonotactic probability estimates were taken from the database created by Storkel and colleagues and were based on an approximately 5,000-word child database developed by the first author. Two measures were used to estimate phonotactic probability: positional segment sum and biphone sum. Positional segment sum was computed by summing the log frequencies of all the words in the database containing the target phoneme in the target word position and dividing by the sum of the log frequencies of all words in the database that had any phoneme in the target word position (Storkel, 2004a). Positional segment sum was computed for each phoneme in a nonword and individual values were summed to provide a single measure for each nonword. Biphone sum was computed by summing the log frequencies of all the words in the database containing the target phoneme pair in the target word position and dividing by the sum of the log frequencies of all words in the database that had any phoneme in the target word position (Storkel, 2004a). Biphone sum was computed for each phoneme pair in a nonword and individual values were summed to provide a single measure for each nonword. Phonotactic probability for the current nonwords ranged within one standard deviation of the mean.

Orthotactic probability. Orthotactic probability refers to the likelihood of occurrence of a letter sequence in the English language, with letter sequences being categorized into common (e.g., car - /kɑr/) and rare (e.g., shoe - /ʃu/) (Apel, Wolter, & Masterson, 2006). Correlations between orthotactic probability and orthographic neighborhood have not yet been documented. However, given the interactions between phonology and orthography, we would expect positive correlations similar to the ones reported for phonotactic probability and phonological neighborhood density. That is, common letter sequences will tend to reside in dense orthographic neighborhoods and rare letters sequences will tend to reside in sparse orthographic neighborhoods. Orthotactic probability estimates were taken from the MCWord database.

Orthotactic probability was calculated by summing the log frequencies of all words in the dictionary that contained the target bigram (two-letter) sequence in the target word position and dividing by the sum of the log frequencies of all words in the dictionary that contained any bigram in the target word position. Orthotactic probability for the current nonwords ranged within one standard deviation of the mean.

Number of friends. Friends are words whose phonological rimes are spelled in the same way (e.g., gear, fear, hear) (Ziegler, Ferrand, Montant, 2004). To determine number of friends for each nonword: 1) we listed all phonological neighbors for the target nonword using the Child Calculator (Storkel & Hoover, 2010; http://129.237.148.107/cml/post_ccc.vi), 2) we listed all orthographic neighbors for the target nonword using the Hoosier Mental Lexicon (HML; Nusbaum, Pisoni, & Davis, 1984) and the Merriam-Webster's Collegiate Dictionary (11th Edition), and 3) we selected the words whose phonological rimes are spelled in the same way. For example, /hɔIn/ - 'hoin' has six phonological neighbors (/hɛn/- hen, /kɔIn/-coin, /ʤɔIn/-join, /lɔIn/-loin, /hon/-hone, and /h^n/-Hun) and four orthographic neighbors (coin -/kɔIn/, loin-/lɔIn/, join-/ ʤɔIn/, and horn-/horn/). Thus, 'hoin' has three friends whose phonological rimes are spelled in the same way - coin, loin, and join. Number of friends for the current stimuli is provided in Appendix A and a complete list of their phonological and orthographic neighbors is provided in Appendix B. As shown in Appendix A, nonwords with many phonological neighbors tend to have more friends (P+O+ M = 6; P+O- M = 3.125) than nonwords with few phonological neighbors (P-O+ M = 1.125; P-O- M = 1.875), probably because there are more opportunities for phonological rimes to be spelled in the same way. Evidence suggests that words with many friends facilitate reading and spelling by allowing the use of analogy strategies (Gibson & Levin, 1976; Marsh et al., 1980; Goswami, 1986; 1988; Treiman, Goswami, & Bruck, 1990; Nation &

Hulme, 1998). It remains unclear, however, whether and how number of friends and phonological and orthographic neighborhood densities interact to influence spelling, and how previous findings apply to nonwords. Therefore, number of friends was included as a covariate to control for any confounding effects.

Consistency. Nonwords were divided into three categories: 1) consistent – their phonological rimes can be spelled in only one way (e.g., /-ʌn/ is spelled only as -un), 2) inconsistent – their phonological rimes can be spelled in multiple ways (e.g., /-it/ can be spelled as -eat or -eet), and 3) other – there are no phonological rimes. For example, /hɔIn/ - 'hoin' is a consistent nonword (/-ɔIn/ is only spelled as -oin), /vʊt/ - 'voot' is an inconsistent nonword (/-ʊt/ can be spelled as -oot or -ut), and /paʊm/ - 'poum' belongs into the 'other' category (does not share rime similarities with any real words). As shown in Appendix A, the P+O+, P+O-, and P-O- conditions have items in all three categories, but the P-O+ condition has only inconsistent and 'other' items.

Evidence points to a facilitatory effect of consistency on reading and spelling, that is, children tend to do better with consistent words than inconsistent words, and better with consistent/inconsistent words than 'other' words (Davis & Weekies, 2005; Treiman et al., 1990). Consistency was also included as a covariate in the current analysis because it is unclear how consistency effects interact with phonological and orthographic neighborhood densities during spelling.

Procedures

Spelling dictation task. Each participant was seated in front of a computer that presented auditory stimuli through tabletop speakers. The order of stimuli presentation was controlled and randomized using the DirectRT software (Jarvis, 2002). The spelling dictation task used in the current study was adapted from Bourassa and Treiman (2003). The child was told that he/she would spell some 'made-up' words. The experimenter first asked the child to spell his/her first name. Once a nonword was presented, the child was asked to repeat it and was given one chance to do so. A second presentation for an item was allowed in case of equipment malfunction, child inattention, or background noise (e.g., people in public library, TV in the living room). The child then wrote the target nonword on a piece of paper. The experimenter provided general encouragement but did not indicate whether spellings were correct or incorrect. The session was audio- and/or video-recorded. In some settings, (e.g., participants' houses, public libraries, elementary schools) video recording was not possible due to limited space. Children's spellings were scored as correct or incorrect (0/1).

A scoring rubric was created to account for all phonetically correct spellings per item. For example, /jet/ can be spelled as 'yate', 'yait', or 'yeat'. All spelling alternatives and estimates of orthographic neighborhood density, number of friends, and consistency levels are provided in Appendix C. It is important to note that spelling alternatives follow the conventional spelling rules of the English language. Spelling alternatives for some items did not generate any estimates of orthographic neighborhood density and they were not included in Appendix C. If a spelling exactly matched with one of possible alternatives from the rubric, then the item was scored as correct. The statistical analysis considered responses from spelling alternatives and their estimates of orthographic neighborhood density, number of friends, and consistency levels. For example, if a child spelled /zaIp/ as 'zype' instead of 'zipe', then the estimates for 'zype' (i.e., PhonoN = 5; OrthoN = 1; Number of Friends = 1; Consistency = Inconsistent) were the ones included in the statistical analysis. After considering alternative spellings, condition membership changed for some items. For example, 'voot' for / vʊt / is in the P-O+ condition, but 'vout' for

/vʊt / is in the P-O- condition. Two examiners conducted scoring reliability on 30% of the sample and reached 100% interscorer agreement (i.e., Agreement/(Agreement + Disagreement) x 100).

Reading task. Each participant was seated in front of a computer that presented visual stimuli. The order of stimuli presentation was controlled and randomized using the DirecRT software. The child was told that he/she would read some 'made-up' words. Once a nonword was presented on the screen, the child was asked to read the nonword and was given one chance to do so. A second attempt to read a nonword was allowed if there was an equipment malfunction. Sometimes, the experimenter would request a child to repeat their response in case of background noise or unintelligibility. The experimenter provided general encouragement but did not indicate whether productions were correct or incorrect. The session was audio- and/or video-recorded. Responses were phonetically transcribed and were scored as either correct or incorrect. A response was scored as correct if it contained all three correct phonemes in the correct word position. A scoring rubric was also created to account for all potential pronunciations according to conventional rules, and their estimates of phonological neighborhood density, number of friends, and consistency levels (see Appendix D). Just like spelling alternatives, alternative pronunciations were the ones that were included in the statistical analysis. Two examiners conducted scoring reliability on 30% of the sample and reached 100% interscorer agreement.

Study Design

The current study used a planned missing data design, in which each participant responded to only a subset of stimuli. Benefits of using this type of design include maximizing statistical power and avoiding issues in data quality due to long assessments (Graham, Taylor, Olchowski, Cumsille, 2006; Rhemtulla & Little, 2012). A SAS program randomly generated blocks of 24 stimuli (6 stimuli per condition), and each participant received one block during the spelling dictation task and a different block during the reading task. Although nonword stimuli were assigned into “sparse” and “dense” conditions, they were treated as continuous in the current model to eliminate measurement error (i.e., not all “sparse” items are equally “sparse and not all “dense” items are equally “dense”).

The binary response accuracy outcome was predicted using a logit link function (log = log [p / (1 − p)]) and Bernoulli conditional outcome distribution (with a single parameter of p, which is the probability of 1). All model parameters were estimated using maximum likelihood (ML) estimation based on Laplace approximation in SAS GLIMMIX. In these models, item predictors are considered as level-1 predictors because they can vary as combination of subjects and items (i.e., alternative responses have different item estimates than standard responses) and subject predictors are considered as level-2 predictors. The significance of fixed effects was evaluated with Wald test p-values and the significance of random effects was evaluated with likelihood ratio test (i.e., −2ΔLL with degrees of freedom equal to the number of additional parameters). Effect size was evaluated via Cohen’s d-values. Effect sizes of 0.2, 0.5, and 0.8 are considered small, medium, and large, respectively. Model summaries can be found in Supplemental Material SM1 and Supplemental Material SM2.

Model Building Steps for Spelling and Reading Outcomes

Empty means model. We estimated an empty means model with no subject or item random effects as a baseline model, as indicated in Equation (1.1/2.1):

$$RA_{tis} = \beta_{000} \qquad (1.1/2.1)$$

RA_{tis} is the logit response accuracy for trial *t* to item *i* from subject s. β_{000} is the fixed intercept which is the grand mean logit RA across all trials.

Random subject intercept. A random intercept for subjects was added to examine whether subjects significantly differ from one another in their mean logit RA, as indicated in Equation (1.2/2.2):e s

$$RA_{tis}= \beta_{000} + U_{00s} \quad (1.2/2.2)$$

U_{00s} is the random intercept for subject *s*, which is the deviation of subject's mean logit RA from the grand mean of β_{000}.

Random item intercept. A random intercept for items was added to examine whether mean logit RA significantly differs across items, as indicated in Equation (1.3/2.3):

$$RA_{tis}= \beta_{000} + U_{00s} + U_{0i0} \quad (1.3/2.3)$$

U_{0i0} is the random intercept for item *i*, which is the deviation of the item's mean logit RA from the predicted mean logit RA of β_{000} + U_{00s}. The U_{00s} random intercept for subject *s*, is the deviation of the subject's mean logit RA from the predicted logit RA of $\beta_{000} + U_{0i0}$.

Effects of main item predictors. We examined the main effects and interaction of the item predictors of phonological neighborhood size (PhonoN) and orthographic neighborhood size (OrthoN), as indicated in Equation (1.4/2.4):

$$RA_{tis}= \beta_{000} + \boldsymbol{\beta_{010}}(PhonoN_i - 10) + \boldsymbol{\beta_{020}}(OrthoN_i - 10) + \boldsymbol{\beta_{030}}(PhonoN_i - 10)(OrthoN_i - 10) + U_{00s} + U_{0i0} \quad (1.4/2.4)$$

Item predictors were centered to 10 to include a meaningful 0 point. β_{000} is the expected logit RA for an item with $PhonoN_i$ = 10 and $OrthoN_i$= 10. The main effects of $PhonoN_i$ and $OrthoN_i$ become simple main effects since they are part of an interaction. The simple main effect of $PhonoN_i$ indicates that for an item with $OrthoN_i$= 10, logit RA will change by the value of β_{010}, for every unit higher in $PhonoN_i$. The simple main effect of $OrthoN_i$ indicates that for an item with $PhonoN_i$= 10, logit RA will change by the value of β_{020}, for every unit higher in $OrthoN_i$. The interaction between $PhonoN_i$ and $OrthoN_i$ indicates the change in $PhonoN_i$ slope by the value of β_{030} and the change in $OrthoN_i$ slope by the value of β_{030}.

Predictions. For a nonword with OrthoN=10, response accuracy is expected to be significantly higher by the value of β_{010} for every one unit higher in PhonoN. For a nonword with PhonoN=10, response accuracy is expected to be significantly higher by the value of β_{020} for every one unit higher in OrthoN. The effect of PhonoN is expected to be significantly more positive by the value of β_{030} for every one unit higher in OrthoN, and the effect of OrthoN is expected to be significantly more positive by the value of β_{030} for every one unit higher in PhonoN.

Effects of other item predictors. The main effects of item predictors of number of friends (FriendN) and consistency (ConsCI and ConsCO) were added next to examine whether there are significant fixed effects after controlling for PhonoN and OrthoN, as indicated in Equation (1.5/2.5):

$$RA_{tis} = \beta_{000} + \beta_{010}(PhonoN_i - 10) + \beta_{020}(OrthoN_i - 10) + \beta_{030}(PhonoN_i - 10)(OrthoN_i - 10) + \boldsymbol{\beta_{040}}(FriendN_i - 3) + \boldsymbol{\beta_{050}}(ConsCI_i) + \boldsymbol{\beta_{060}}(ConsCO_i) + U_{00s} + U_{0i0} \qquad (1.5/2.5)$$

The predictor of number of friends was centered to 3 to include a meaningful 0 point. β_{000} is the expected RA for a consistent item with $FriendN_i$ = 3. The slope for of $ConsCI_i$ indicates that relative to consistent items, logit RA for inconsistent items is expected to change by the value of β_{050}. Likewise, the slope for of $ConsCO_i$ indicates that relative to consistent items, logit RA for other items is expected to change by the value of β_{060}.

Predictions. For a nonword with PhonoN=10 and OrthoN=10, response accuracy is expected to be significantly higher by the value of β_{040} for every one unit higher in FriendN. Response accuracy is expected to be significantly lower by the value of β_{050} in inconsistent items relative to consistent items. Response accuracy is expected to be significantly lower by the value of β_{060} in other items relative to consistent items.

Effect of subject group. We examined the main effect of subject group (dyslexia, age-TD, and level-TD) on spelling and reading accuracy, as indicated in Equation (1.6/2.6):

$$RA_{tis} = \beta_{000} + \beta_{010}(PhonoN_i - 10) + \beta_{020}(OrthoN_i - 10) + \beta_{030}(PhonoN_i - 10)(OrthoN_i - 10) + \beta_{040}(FriendN_i - 3) + \beta_{050}(ConsCI_i) + \beta_{060}(ConsCO_i) + \boldsymbol{\beta_{001}}(ReadDA_s) + \boldsymbol{\beta_{002}}(ReadDL_s) + U_{00s} + U_{0i0} \quad (1.6/2.6)$$

Two variables were created to represent the differences between the dyslexia group (reference) and the other groups: 1) ReadDA (dyslexia group = 0, age-matched = 1, level-matched = 0) and 2) ReadDL (dyslexia group = 0, age-matched = 0, level-matched = 1). The slope for $ReadDA_s$ indicates that relative to children with dyslexia (reference), logit RA for age-matched controls is expected to change by the value of β_{001}. Likewise, the slope for $ReadDL_s$ indicates that relative to children with dyslexia, logit RA for level-matched controls is expected to change by the value of β_{002}.

Predictions. Response accuracy is expected to significantly higher by the value β_{001} in age-matched controls relative to children with dyslexia, for a nonword with PhonoN=10 and OrthoN=10. Response accuracy is expected to be similar by the value β_{002} in reading-level-matched controls and children with dyslexia, for a nonword with PhonoN=10 and OrthoN=10.

Effects of subject predictors. We examined the main effects of subject predictors of oral language (CELF), phonological awareness (CTOPP), and spelling ability (WRAT) on spelling and reading accuracy, as indicated in Equation (1.7/2.7):

$$RA_{tis} = \beta_{000} + + \beta_{010}(PhonoN_i - 10) + \beta_{020}(OrthoN_i - 10) + \beta_{030}(PhonoN_i - 10)(OrthoN_i - 10) + \beta_{040}(FriendN_i - 3) + \beta_{050}(ConsCI_i) + \beta_{060}(ConsCO_i) + \beta_{001}(ReadDA_s) + \beta_{002}(ReadDL_s) + \boldsymbol{\beta_{003}}(CELF_s - 104) + \boldsymbol{\beta_{004}}(CTOPP_s - 98) + \boldsymbol{\beta_{005}}(WRAT_s - 100) + U_{00s} + U_{0i0} \quad (1.7/2.7)$$

Each of these variables were centered to their means to include a meaningful 0. The intercept β_{000} is the expected logit RA for a child with dyslexia with $CELF_s = 104, CTOPP_s = 98$, and $WRAT_s = 100$.

Predictions. Response accuracy is expected to be significantly higher by the value of β_{003} for every one unit higher in CELF. Response accuracy is expected to be significantly higher by the value of β_{004} for every one unit higher in CTOPP. Response accuracy is expected to be significantly higher by the value of β_{005} for every one unit higher in WRAT.

Subject differences in the effects of item predictors. We examined whether the effects of item predictors of PhonoN and OrthoN differed between subjects by adding subject random slopes one at a time, as indicated in Equation (1.8/2.8):

$$RA_{tis} = \beta_{000} + + \beta_{010}(PhonoN_i - 10) + \beta_{020}(OrthoN_i - 10) + \beta_{030}(PhonoN_i - 10)(OrthoN_i - 10) + \beta_{040}(FriendN_i - 3) + \beta_{050}(ConsCI_i) + \beta_{060}(ConsCO_i) + \beta_{001}(ReadDA_s) + \beta_{002}(ReadDL_s) + \beta_{003}(CELF_s - 104) + \beta_{004}(CTOPP_s - 98) + \beta_{005}(WRAT_s - 100) +$$

$$U_{00s} + \boldsymbol{U_{02s}}\,(PhonoN_i - 10) + \boldsymbol{U_{03s}}\,(OrthoN_i - 10) + \boldsymbol{U_{04s}}\,(PhonoN_i - 10)(OrthoN_i - 10) + U_{0i0} \quad (1.8/2.8)$$

Interactions between item predictors and subject predictors. First, we examined all possible interactions between item and subject predictors (see Equation 1.9 in SM1 and Equation 2.9 in SM2). Second, we considered all significant and/or relevant interactions. Thus, the final model examined the simple main effects of item predictors (PhonoN and OrthoN) and subject predictors (ReadDA and ReadDL) and their interactions, as indicated in Equation (1.10/2.12):

$$RA_{tis} = \beta_{000} + \beta_{010}(PhonoN_i - 10) + \beta_{020}(OrthoN_i - 10) + \beta_{030}(PhonoN_i - 10)(OrthoN_i - 10) + \beta_{040}(FriendN_i - 3) + \beta_{050}(ConsCI_i) + \beta_{060}(ConsCO_i) + \beta_{001}(ReadDA_s) + \beta_{002}(ReadDL_s) + \beta_{003}(CELF_s - 104) + \beta_{004}(CTOPP_s - 98) + \beta_{005}(WRAT_s - 100) + \boldsymbol{\beta_{011}}(ReadDA_s)(PhonoN_i - 10) + \boldsymbol{\beta_{021}}(ReadDA_s)(OrthoN_i - 10) + \boldsymbol{\beta_{031}}(ReadDA_s)(PhonoN_i - 10)(OrthoN_i - 10) + \boldsymbol{\beta_{012}}(ReadDL_s)(PhonoN_i - 10) + \boldsymbol{\beta_{022}}(ReadDL_s)(OrthoN_i - 10) + \boldsymbol{\beta_{032}}(ReadDL_s)(PhonoN_i - 10)(OrthoN_i - 10) + U_{00s} + U_{0i0} \quad (1.10/2.12)$$

Predictions. For a nonword with OrthoN=10, the effect of PhonoN on response accuracy is expected to be significantly less positive by the value of β_{011} for children with dyslexia than for age-matched controls. For a nonword with PhonoN=10, the effect of OrthoN on response accuracy is expected to be significantly less positive by the value of β_{021} for children with dyslexia than for age-matched controls. The interaction of PhonoN*OrthoN is expected to be significantly different by the value of β_{031} for children with dyslexia and for age-matched controls. These findings would indicate that children with dyslexia have underspecified phonological and orthographic representations compared to age-matched peers.

For a nonword with OrthoN=10, the effect of PhonoN on response accuracy is expected to be significantly less positive by the value of β_{012} for children with dyslexia than for reading-level-matched controls. For a nonword with PhonoN=10, the effect of OrthoN on response accuracy is expected to be significantly more positive by the value of β_{022} for children with dyslexia than for reading-level-matched controls. These findings would indicate a dissociation between phonological and orthographic processes and orthographic compensation in children with dyslexia.

Alternatively, for a nonword with OrthoN=10, the effect of PhonoN on response accuracy is expected to be similar by the value of β_{012} between children with dyslexia and reading-level-matched controls. For a nonword with PhonoN=10, the effect of OrthoN on response accuracy is expected to be similar by the value of β_{022} between children with dyslexia and reading-level-matched controls. These findings would indicate that children with dyslexia and level-matched peers have similar spelling and reading profiles. The interaction of PhonoN*OrthoN is expected to be significantly different by the value of β_{032} for children with dyslexia and for reading-level-matched controls.

Chapter 3: Results

Descriptive Statistics

Overall, participants spelled fewer words correctly than they could read. In the spelling dictation task, children with dyslexia spelled 44.17% of nonwords correctly, age-matched peers spelled 73.13% of nonwords correctly, and level-matched peers spelled 47.79% of nonwords correctly. In the reading task, children with dyslexia read 61.46% of nonwords correctly, age-matched peers read 86.25% of nonwords correctly, and level-matched peers read 64.22% of nonwords correctly. The relationship between overall spelling accuracy and overall reading accuracy was weak but significant ($r = .212$, $p < .001$).

Spelling Outcomes

The analysis from the first three empty models (see SM1) showed a significant variability in mean logit RA across subjects, $-2\Delta LL$ (~1) = 152.00, $p < .001$ (smaller AIC and BIC), and across items, $-2\Delta LL$ (~1) = 190.94, $p < .001$ (smaller AIC and BIC). That is, some subjects did significantly better than others (i.e., 25% of the RA variation was due to mean differences across subjects) and some items were significantly easier to spell than others (i.e., 21% of the RA variation was due to mean differences across items). To describe the size of the random variation across subjects and items, we computed 95% random effects confidence intervals as fixed intercept ± 1.96*SQRT(random intercept variance). 95% of the individual subject RA means are expected to fall between −2.10 and 2.78 (in logits) and 95% of the individual item RA means are expected to fall between −1.87 and 2.55 (in logits). This means that if repeated samples were taken and interval estimates were computed for each sample, then we can expect that 95% of those intervals would contain the population mean.

The addition of item effects significantly improved model fit, $-2\Delta LL$ (~3) = 46.1, $p <$ .001 (smaller AIC and BIC) (see Equation 1.5 in SM1). The addition of subject effects also significantly improved model fit, $-2\Delta LL$ (~3) = 12.3, $p = .006$ (smaller AIC and BIC) (see Equation 1.6 in SM1).

Item effects. The simple main effect of phonological neighborhood (PN) density was not significant ($p = .410$; $d = 0.046$) (see Equation 1.5 in SM1). The simple main effect of orthographic neighborhood (ON) density was significant ($p = .043$; $d = -0.114$), such that higher orthographic neighborhood size was related to lower spelling accuracy. This significance, however, disappeared when additional effects were added in the model. The interaction between phonological neighborhood and orthographic neighborhood densities was not significant (p = .591; d = 0.030). The main effect of number of friends was not significant (p = .296; d = 0.058). The main effect of consistency was significant (p = .005; d = 0.156), such that spelling accuracy for inconsistent items was higher than spelling accuracy for consistent items. Spelling accuracy was nonsignificantly lower in other items relative to consistent items (p = .380; d = −0.049).

Child effects. The main effect of subject group was significant (p < .001; d = 0.259), such that spelling accuracy was higher in age-matched controls relative to children with dyslexia (see Equation 1.6 in SM1). This significance, however, disappeared when the subject predictors of oral language (CELF104), phonological awareness (CTOPP98), and spelling ability (WRAT100) were added in the analysis (see Equation 1.7 in SM1). As Table 4 shows, these predictors are related, thus, it is likely that they competed with one another, leading to weaker effects and higher p-values. We did not find any significant differences in spelling accuracy between children with dyslexia and level-matched controls (p = .453; d = 0.042).

Table 4: Pearson correlation coefficients (*r*) for subject predictors.

	ReadDA	**ReadDL**	**CELF104**	**CTOPP98**	**WRAT100**
ReadDA	1				
ReadDL	-0.479**	1			
CELF104	0.320**	-0.248**	1		
CTOPP98	0.130**	0.363**	0.218**	1	
WRAT100	0.501**	0.231**	0.376**	0.326**	1

** Indicates p < .001

The main effect of oral language was not significant (p = .776; d = 0.016). The main effect of phonological awareness was not significant (p = .079; d = 0.099). There was a significant main effect of spelling ability (p = .009; d = 0.146), such that higher spelling test scores were related to higher spelling accuracy in the experimental task.

We also examined subject differences in the simple main effects of phonological neighborhood and orthographic neighborhood densities and their interaction. We compared the −2LL from Equation 1.8 with the −2LL from Equation 1.7. The addition of a variance for the subject random PN slopes did not significantly improved model fit, −2ΔLL (~2) = 3.8, p = .147 (larger AIC and smaller BIC), indicating that the extent to which phonological neighborhood density affects spelling accuracy does not significantly differ between subjects. The models examining subject differences in the effects of orthographic neighborhood density and interaction between phonological neighborhood and orthographic neighborhood densities did not converge.

Interactions between item and child effects. In the final model (see Table 5), we examined the interactions between item predictors of phonological neighborhood and orthographic neighborhood densities and subject predictors of group (i.e., dyslexia, age-matched controls, level-matched controls). The fixed intercept, β_{000}= 0.086 (probability = 0.521), p = .916, is the expected spelling accuracy for a child with dyslexia with oral language SS = 104, phonological awareness SS = 98, and spelling ability SS = 100, for a consistent item with PN = 10, ON = 10, and number of friends = 3.

Phonological neighborhood density effect. In terms of slopes for each group (see Table 6), the simple main effect of phonological neighborhood density was nonsignificantly positive in children with dyslexia (p = .615, d = 0.028) and in age-matched children (p = .079, d = 0.099), and nonsignificantly negative in level-matched children (p = .94, d = −0.004). Even though the effect of phonological neighborhood density was not significant, children with dyslexia and age-matched children tended to spell nonwords with high phonological neighborhood density more accurately than nonwords with low phonological neighborhood density, whereas level-matched children tended to spell nonwords with high phonological neighborhood density less accurately than nonwords with low phonological neighborhood density (see Figure 1).

In addition to slopes for each group, the results from the main analysis (reported in Table 5) indicate how the simple main effect of phonological neighborhood density differs between groups. The simple main effect of phonological neighborhood density was significantly more positive by β_{011}= 0.148 (p = .005; d = 0.159) in age-matched children than in children with dyslexia. Even though the positive effect of phonological neighborhood density was not significant in age-matched children (see Table 6), they still showed a stronger positive effect relative to children with dyslexia. The simple main effect of phonological neighborhood density was nonsignificantly less positive by β_{012} = −0.068 (p = .191; d = −0.074) in level-matched children than in children with dyslexia. That is, the positive effect of phonological neighborhood density tended to be weaker in level-matched children than it was in children with dyslexia.

Orthographic neighborhood density effect. In terms of slopes for each group (see Table 6), the simple main effect of orthographic neighborhood density was nonsignificantly negative in children with dyslexia (p = .055, d = −0.108) and in level-matched children (p = .29, d = −0.060), and significantly negative in age-matched children (p = .032, d = −0.121). That is, all groups spelled nonwords with high orthographic neighborhood density less accurately than nonwords with low orthographic neighborhood density, but the negative effect was significant only in age-matched children (see Figure 2).

Estimates from the main analysis, reported in Table 5, show how the simple main effect of orthographic neighborhood density differs between groups. The simple main effect of orthographic neighborhood density was nonsignificantly more negative by β_{021} = −0.024 (p = .692; d = −0.022) in age-matched children than in children with dyslexia. This means that in addition of the negative effect of orthographic neighborhood density being significant in age-matched children (see Table 6), it tended to be stronger in age-matched children than it was in children with dyslexia. The simple main effect of orthographic neighborhood density was nonsignificantly less negative by β_{022} = 0.081 (p = .167; d = 0.077) in level-matched children than in children with dyslexia. That is, the negative effect of orthographic neighborhood density tended to be weaker in level-matched children than it was in children with dyslexia.

Interactions. The nonsignificant phonological neighborhood density by orthographic neighborhood density interaction (see Table 5) indicates that in children with dyslexia, the positive effect of phonological neighborhood density is expected to become more positive by β_{030} = 0.002 (p = .933; d = 0.004) for every one unit higher in orthographic neighborhood density and the negative effect of orthographic neighborhood density is expected to become less negative by β_{030} = 0.002 for every one unit higher in phonological neighborhood density. This interaction is nonsignificantly more positive by β_{031} = 0.014 (p = .328; d = 0.055) in age-matched children and nonsignificantly more positive by β_{032} = 0.00006 (p = .997; d = 0.000) in level-matched children.

Table 5: Final model estimates for spelling outcomes.

Model Effects	***Estimate***	***SE***	***p <***	***d***
<u>Model for the Means</u>				
Intercept	0.086	0.806	0.916	
PhonoN10	0.059	0.117	0.615	0.028
OrthoN10	-0.189	0.098	0.055	-0.108
PhonoN10*OrthoN10	0.002	0.022	0.933	0.004
FriendN3	0.148	0.148	0.318	0.056
ConsCI	2.647*	1.027	0.010	0.145
ConsCO	-0.998	0.803	0.214	-0.070
ReadDA	0.390	0.520	0.453	0.042
ReadDL	-0.794	0.550	0.149	-0.081
CELF104	0.003	0.010	0.757	0.017
CTOPP98	0.023	0.013	0.076	0.100
WRAT100	0.038*	0.015	0.008	0.149
PhonoN10*ReadDA	0.148*	0.052	0.005	0.159
OrthoN10*ReadDA	-0.024	0.060	0.692	-0.022
PhonoN10*OrthoN10*ReadDA	0.014	0.014	0.328	0.055
PhonoN10*ReadDL	-0.068	0.052	0.191	-0.074
OrthoN10*ReadDL	0.081	0.059	0.167	0.077
PhonoN10*OrthoN10*ReadDL	0.000	0.014	0.997	0.000
<u>Model for the Variance</u>				
Subject Random Intercept	0.806**	0.224	0.000	
Item Random Intercept	3.405*	1.291	0.004	
<u>ML Model Fit</u>				
Number of Parameters	20			
−2LL	1436.25			
AIC	1476.25			
BIC	1436.25			

* Indicates $p < .05$
** Indicates $p < .001$

Table 6: Slope estimates for each group.

	Estimate	***SE***	***p <***	***d***
Phonological N density slope in dyslexia	0.05885	0.1170	0.6152	0.028
Phonological N density slope in age-TD	0.2072	0.1179	0.0790	0.099
Phonological N density slope in level-TD	-0.00899	0.1194	0.9400	-0.004
Orthographic N density slope in dyslexia	-0.1894	0.09849	0.0547	-0.108
Orthographic N density slope in age-TD	-0.2133	0.09941	0.0321*	-0.121
Orthographic N density slope in level-TD	-0.1081	0.1013	0.2864	-0.060

* Indicates p < .05

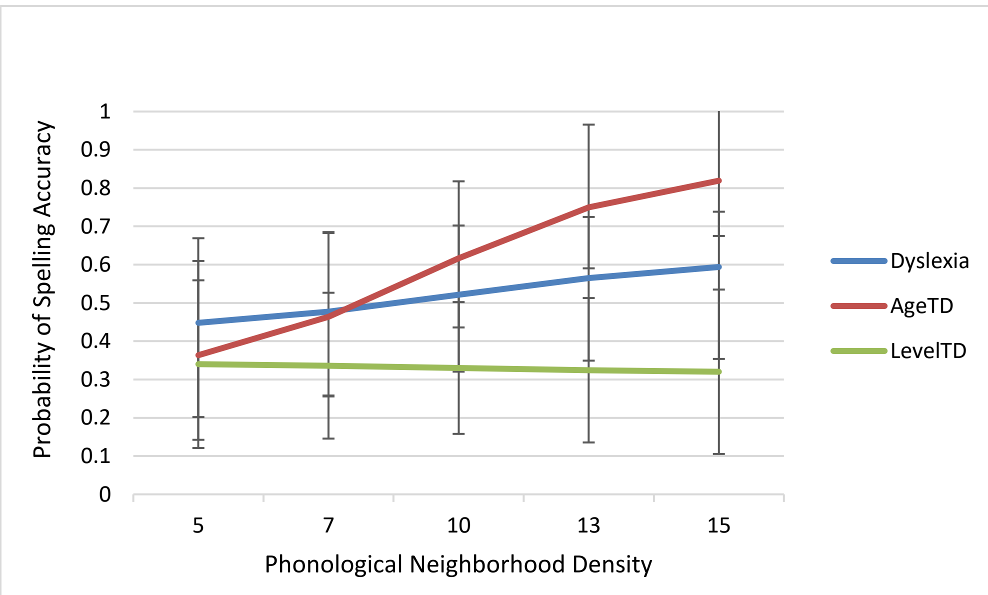

Figure 1: Probability of spelling accuracy as phonological neighborhood density increases.

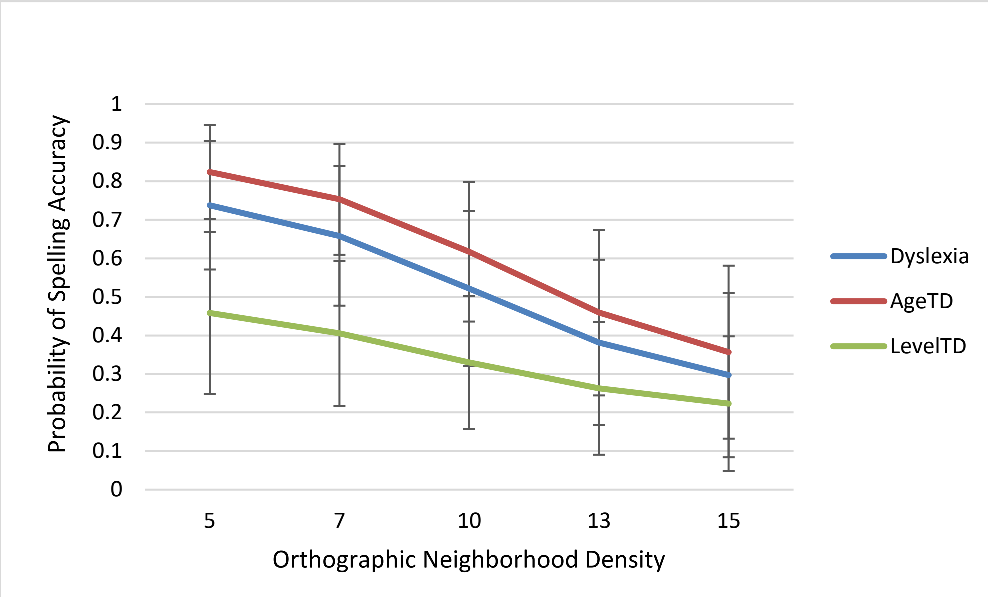

Figure 2: Probability of spelling accuracy as orthographic neighborhood density increases.

Reading Outcomes

The analysis from the first three empty models (see SM2) showed a significant variability in mean logit RA across subjects, −2ΔLL (~1) = 125.35, p < .001 (smaller AIC and BIC), and across items−2ΔLL (~1) = 167.25, p < .001 (smaller AIC and BIC). That is, some subjects did significantly better than others (i.e., 24% of the RA variation was due to mean differences across subjects) and some items were significantly easier to read than others (i.e., 22% of the RA variation was due to mean differences across items). To describe the size of the random variation across subjects and items, we computed 95% random effects confidence intervals as fixed intercept ± 1.96*SQRT(random intercept variance). 95% of the individual subject RA means are expected to fall between −1.14 and 3.62 (in logits) and 95% of the individual item RA means are expected to fall between −1.02 and 3.50 (in logits).

The addition of item effects significantly improved model fit, −2ΔLL (~3) = 9, p = 0.029 (smaller AIC and BIC) (see Equation 2.5 in SM2). The addition of subject effects also significantly improved model fit, −2ΔLL (~3) = 13.8, p = .003 (smaller AIC and BIC) (see Equation 2.6 in SM2).

Item effects. The simple main effect of phonological neighborhood density was significant (p < .001; d = 0.267), such that higher phonological neighborhood size was related to higher reading accuracy (see Equation 2.5 in SM2). The simple main effect of orthographic neighborhood density was not significant (p = .182; d = −0.075). The interaction between phonological neighborhood and orthographic neighborhood densities was not significant (p = .180; d = 0.075). The main effect of number of friends was not significant (p = .268; d = −0.062). Reading accuracy was nonsignificantly lower in inconsistent items relative to consistent items (p = .120; d = −0.087), and nonsignificantly lower in other items relative to consistent items (p = .055; d = −0.108).

Child effects. The main effect of subject group was significant (p < .001; d = 0.268), such that reading accuracy was higher in age-matched controls relative to children with dyslexia (see Equation 2.6 in SM2). Again, this significance disappeared when the subject predictors of oral language (CELF104), phonological awareness (CTOPP98), and spelling ability (WRAT100) were added in the analysis (see Equation 2.7 in SM2). Significant differences in reading accuracy between children with dyslexia and level-matched controls emerged in the final model (p = .020; d = −0.130), such that reading accuracy was lower in level-matched controls relative to children with dyslexia (see Equation 2.12 in SM2).

The main effect of oral language was not significant (p = .969; d = 0.002). There was a significant main effect of phonological awareness (p = .045; d = 0.113), such that higher phonological awareness skills were related to higher reading accuracy. There was a significant main effect of spelling ability (p = .004; d = 0.163), such that higher spelling test scores were related to higher reading accuracy.

Interactions between item and child effects. In the final model (see Table 7), we examined the interactions between item predictors of phonological neighborhood and orthographic neighborhood densities and subject predictors of group (i.e., dyslexia, age-matched controls, level-matched controls). The fixed intercept, β_{000}= 2.191 (probability = 0.899), p = .002, is the expected reading accuracy for a child with dyslexia with oral language SS = 104, phonological awareness SS = 98, and spelling ability SS = 100, for a consistent item with PN = 10, ON = 10, and number of friends = 3.

Phonological neighborhood density effect. In terms of slopes for each group (see Table 8), the simple main effect of phonological neighborhood density was significantly positive in children with dyslexia (p < .001, d = 0.247), in age-matched children (p < .001, d = 0.31), and in level-matched children (p < .001, d = 0.232). That is, all groups spelled nonwords with high phonological neighborhood density more accurately than nonwords with low phonological neighborhood density (see Figure 3).

Estimates from the main analysis, reported in Table 7, show how the simple main effect of phonological neighborhood density differs between groups. The simple main effect of phonological neighborhood density was significantly more positive by β_{011}= 0.189 (p = .006; d = 0.156) in age-matched children than in children with dyslexia. Even though the positive effect of phonological neighborhood density was significant in age-matched children and children with dyslexia (see Table 8), it was stronger in age-matched children than it was in children with dyslexia. The simple main effect of phonological neighborhood density was nonsignificantly less positive by β_{012} = −0.029 (p = .620; d = −0.028) in level-matched children than in children with dyslexia. Even though the positive effect of phonological neighborhood density was significant in level-matched children and children with dyslexia (see Table 8), it tended to be weaker in level-matched children than it was in children with dyslexia.

Orthographic neighborhood density effect. In terms of slopes for each group (see Table 8), the simple main effect of orthographic neighborhood density was nonsignificantly negative in children with dyslexia (p = .055, d = −0.034) and in level-matched children (p = .118, d = −0.088), and significantly negative in age-matched children (p = .035, d = −0.119). That is, all groups spelled nonwords with high orthographic neighborhood density less accurately than nonwords with low orthographic neighborhood density, but the negative effect was significant only in age-matched children (see Figure 4).

Estimates from the main analysis, reported in Table 7, show how the simple main effect of orthographic neighborhood density differs between groups. The simple main effect of orthographic neighborhood density was significantly more negative by β_{021} = −0.177 (p = .018; d = −0.133) in age-matched children than in children with dyslexia. This means that in addition of the negative effect of orthographic neighborhood density being significant in age-matched children (see Table 8), it was stronger in age-matched children than it was in children with dyslexia. The simple main effect of orthographic neighborhood density was nonsignificantly more negative by β_{022} = −0.103 (p = .094; d = −0.094) in level-matched children than in children with dyslexia. That is, the negative effect of orthographic neighborhood density was weaker in level-matched children than it was in children with dyslexia.

Interactions. The nonsignificant phonological neighborhood density by orthographic neighborhood density interaction (see Table 7) indicates that in children with dyslexia, the positive effect of phonological neighborhood density is expected to become more positive by

β_{030} = 0.024 (p = .304; d = 0.058) for every one unit higher in orthographic neighborhood density and the negative effect of orthographic neighborhood density is expected to become less negative by β_{030} = 0.024 for every one unit higher in phonological neighborhood density. This interaction is nonsignificantly more positive by β_{031} = 0.008 (p = .646; d = 0.026) in age-matched children and nonsignificantly more positive by β_{032} = 0.002 (p = .891; d = 0.008) in level-matched children.

Table 7: Final model estimates for reading outcomes.

Model Effects	***Estimate***	***SE***	***p* <**	***d***
Model for the Means				
Intercept	2.191*	0.642	0.002	
PhonoN10	0.513**	0.117	0.000	0.247
OrthoN10	-0.061	0.102	0.546	-0.034
PhonoN10*OrthoN10	0.024	0.023	0.304	0.058
FriendN3	-0.152	0.152	0.317	-0.056
ConsCI	-0.928	0.703	0.187	-0.074
ConsCO	-1.100	0.616	0.075	-0.100
ReadDA	0.205	0.531	0.699	0.022
ReadDL	-1.272*	0.548	0.020	-0.130
CELF104	0.000	0.010	0.960	0.003
CTOPP98	0.026*	0.013	0.043	0.114
WRAT100	0.044*	0.015	0.004	0.164
PhonoN10*ReadDA	0.189*	0.068	0.006	0.156
OrthoN10*ReadDA	-0.177*	0.074	0.018	-0.133
PhonoN10*OrthoN10*ReadDA	0.008	0.018	0.646	0.026
PhonoN10*ReadDL	-0.029	0.059	0.620	-0.028
OrthoN10*ReadDL	-0.103	0.061	0.094	-0.094
PhonoN10*OrthoN10*ReadDL	0.002	0.015	0.891	0.008
Model for the Variance				
Subject Random Intercept	0.663*	0.209	0.001	
Item Random Intercept	2.179*	0.856	0.006	
ML Model Fit				
Number of Parameters	20			
−2LL	1166.97			
AIC	1206.97			
BIC	1166.97			

* Indicates $p < .05$
** Indicates $p < .001$

Table 8: Slope estimates for each group.

	Estimate	*SE*	*p* <	*d*
Phonological N density slope in dyslexia	0.5131	0.1169	<.0001**	0.247
Phonological N density slope in age-TD	0.7019	0.1272	<.0001**	0.310
Phonological N density slope in level-TD	0.4839	0.1171	<.0001**	0.232
Orthographic N density slope in dyslexia	-0.06149	0.1017	0.5457	-0.034
Orthographic N density slope in age-TD	-0.2383	0.1131	0.0353*	-0.119
Orthographic N density slope in level-TD	-0.1643	0.1051	0.1183	-0.088

* Indicates $p < .05$
** Indicates $p < .001$

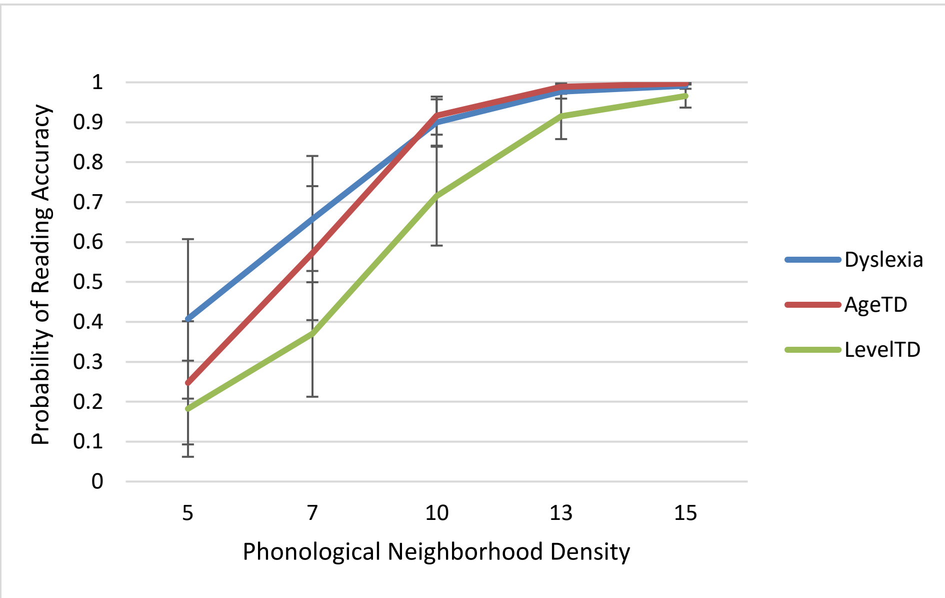

Figure 3: Probability of reading accuracy as phonological neighborhood density increases.

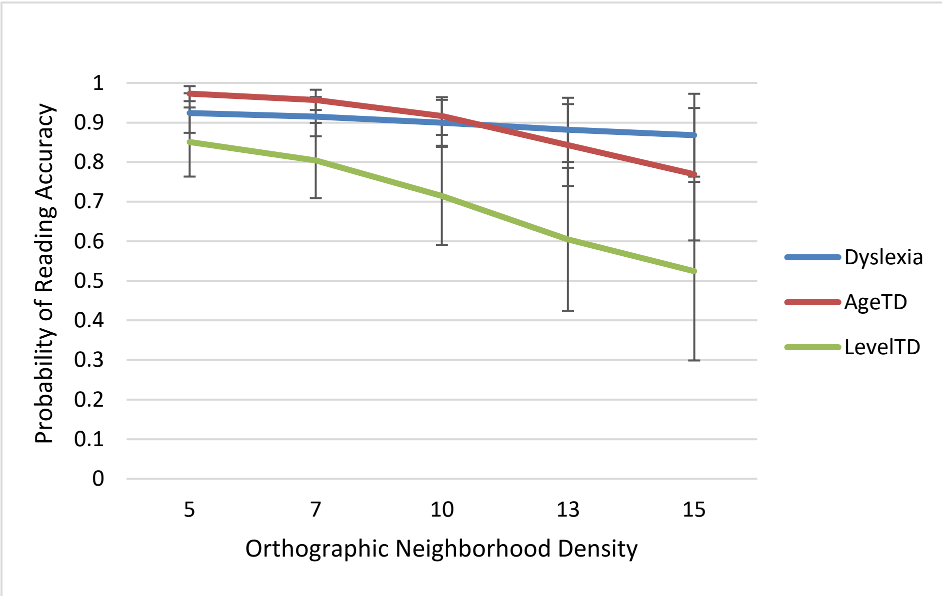

Figure 4: Probability of reading accuracy as orthographic neighborhood density increases.

Chapter 4: Discussion

The current study explored the contributions of phonological and orthographic processes to spelling and reading in children with and without dyslexia. The effects of phonological and orthographic neighborhood densities were used as markers of children's phonological and orthographic processing skills.

Efficient interactions between phonological and orthographic processes are necessary to support children's progress in spelling and reading (Ehri & Wilce, 1980; Tunmer & Nesdale, 1982; Bruck, 1992). Evidence from reading research suggests that such interactions are disrupted in children with dyslexia and any progress in reading may be accomplished through orthographic compensation (for a review see Cassar & Treiman, 2004). The nature of interactions between phonological and orthographic processes in not well understood in spelling. Do children with dyslexia employ both phonological and orthographic strategies to spell new words, or do they rely exclusively on relatively preserved orthographic strategies? We will attempt to answer this question by discussing children's spelling and reading outcomes and compare our findings with those reported in previous studies.

Spelling Outcomes

In terms of spelling outcomes, our results revealed four major findings. First, children with dyslexia achieved similar overall spelling accuracy as their age-matched and level-matched peers. Second, phonological neighborhood density had a strong positive effect in age-matched children, a weak positive effect in children with dyslexia, and weak negative effect in level-matched children. Third, orthographic neighborhood density had a strong negative effect in children with dyslexia and age-matched children, but a weak negative effect in level-matched children. Fourth, we did not find a significant interaction between phonological and orthographic neighborhood densities. Given the absence of a significant interaction effect, our discussion will focus on the main effects of phonological and orthographic neighborhood densities.

First, children with dyslexia spelled words at the same level of accuracy as their age-matched and level-matched peers. On one hand, our findings disagree with those reported in previous studies about poorer spelling abilities in children with dyslexia relative to their age-matched peers (Laxon et al., 1998; Lennox & Siegel, 1996). It is important to note that significant differences between children with dyslexia and age-matched peers did emerge at the beginning of our analysis. This significance, however, disappeared once we considered additional variables, like oral language, phonological awareness, and spelling ability. This suggests that individual differences in language ability can explain spelling performance in addition to reading ability. Previous studies by Laxon and colleagues (1988) and Lennox and Siegel (1996) did not consider how indicators of language ability are related to children's reading level to explain spelling performance. On the other hand, the absence of differences between children with dyslexia and their level-matched peers is in line with previous research reporting similar spelling profiles in groups matched by reading and/or spelling level (Bourassa & Treiman, 2003; Cassar et al., 2005).

Second, phonological neighborhood density had a positive effect that was stronger in age-matched children than it was in children with dyslexia. Specifically, age-matched children benefitted more from high phonological neighborhood densities than children with dyslexia did. To understand this dense neighborhood advantage and how it is related to reading ability, it is necessary to discuss about what makes some similar-sounding words easier to process than others.

It is generally accepted that words with dense phonological neighborhoods yield better performances than words with sparse phonological neighborhoods (see Thomson, Richardson, & Goswami, 2005). The dense neighborhood advantage has been often discussed in the context of lexical restructuring theory (LRT; Metsala & Walley, 1998). According to LRT, phonological representations become gradually more specified as children's vocabularies grow. The restructuring of children's phonological representations is thought to occur earlier for words in dense phonological neighborhoods than for words in sparse phonological neighborhoods. The dense neighborhood advantage can also be explained in terms of activation. That is, words in dense neighborhoods receive more activation from their neighbors which can make them appear more familiar and allow more efficient processing (Yates, Locker, & Simpson, 2004; Yates, 2005).

Both the LRT and the neighborhood activation model suggest that the quality of phonological representations determines how well children process similarities in sounds between words (for a discussion see Thomson et al., 2005). This implies that phonological neighborhood density might have a facilitative effect for children with well-specified phonological representations, but a different or no effect for children with underspecified phonological representations (Storkel, 2004b; Thomson et al., 2005). Our results agree with this assumption. We found a robust positive effect in age-matched children and a weaker or a negative effect in children with dyslexia and level-matched children, respectively. Overall, our findings suggest that the likelihood of a neighborhood density advantage is closely related to the level of specification in children's phonological representations.

Third, we found a negative orthographic neighborhood density effect that was strong in age-matched children and children with dyslexia, but it was weak in level-matched children. Specifically, children spelled nonwords from dense orthographic neighborhoods less accurately than nonwords from sparse orthographic neighborhoods. These results do not agree with previous work by Laxon and colleagues (1988), showing a positive effect of higher orthographic neighborhood density on spelling accuracy. Before discussing potential reasons behind this discrepancy, we first need to consider an important question. Do similarly spelled words facilitate or hinder spelling accuracy of a target word?

There is some research suggesting that high orthographic neighborhoods may hinder performance due to a phenomenon referred to as the neighborhood frequency effect (Grainger, O'Regan, Jacobs, & Segui, 1989; for reviews see Andrews, 1997; Perea & Rosa, 2000). That is, high-frequency neighbors, because of their higher resting activation levels, tend to compete against each other and to interfere with lexical assess. During spelling, a child hears a word and attempts to access the mental representation of its written form. If a word has many high-frequency neighbors, then these neighbors will be also activated and the competition between them may interfere with the child's ability to retrieve the target word's correct spelling. We are unsure whether this might be the case for our study, but future work should determine the neighborhood frequency for our stimuli.

Considering that the effect of orthographic neighborhood density may change depending on the frequency of neighbors, it is possible that a facilitative effect emerged in the study by Laxon and colleagues (1988) because dense orthographic neighborhoods contained fewer high-frequency neighbors and more low-frequency neighbors. Such types of neighborhoods would typically be characterized by lower activation levels and less competition between neighbors.

Interestingly, the negative effect of orthographic neighborhood density was weaker in children with dyslexia than it was in age-matched children, and it was weaker in level-matched children than it was in children with dyslexia or age-matched children. Again, we believe that this may be due to the quality of children's lexical representations. Specifically, greater competition between neighbors might occur in skilled readers who have higher-quality representations for more words. On the other hand, limited print exposure in less skilled readers could affect the number and the quality of their lexical representations. Fewer high-quality representations could mean less competition between neighbors and a weaker negative effect of orthographic neighborhood density. In addition to neighborhood frequency effect, future research should determine how differences in the quality of lexical representations between skilled and less skilled readers shape the effect of orthographic neighborhood density in spelling.

Reading Outcomes

In terms of reading outcomes, our results revealed four major findings. First, children with dyslexia achieved similar reading accuracy as their age-matched peers, but higher reading accuracy than their level-matched peers. Second, phonological neighborhood density had a strong positive effect for all groups. Third, orthographic neighborhood density had a strong negative effect in age-matched children, but a weak negative effect in children with dyslexia and level-matched children. Fourth, the interaction between phonological and orthographic neighborhood densities was not significant. Our discussion will again focus on the main effects of phonological and orthographic neighborhood densities.

First, we found that children with dyslexia achieved similar reading accuracy levels as their age-matched peers, but higher reading accuracy levels than their level-matched peers. Again, significant differences between children with dyslexia and age-matched peers emerged at the beginning of our analysis, but they disappeared once we considered other child variables that are thought to influence reading outcomes (i.e., oral language, phonological awareness, spelling ability). Previous studies that reported significant differences between children with dyslexia and age-matched peers did not consider additional variables that account for children's overall language ability (Laxon et al., 1998; Stanovich et al., 1997; van der Leij & van Daal, 1999).

Another reason for these results could be that children's performances were affected by two nonword characteristics: length and visual similarity to real words. In terms of word length, studies have shown that longer words and nonwords increase task demands and lead to lower performances among children with dyslexia (van der Leij & van Daal, 1999; Ziegler, Perry, Ma-Wyatt, Ladner, & Schulte-Körne, 2003; Hutzler & Wimmer, 2003). In terms of visual similarity, nonwords that look more like real words (i.e., they differ from real words by one letter) appear to reduce demands on phonological processing and benefit reading accuracy in children with dyslexia (for a review see Rack, Snowling, & Olson, 2012). Unlike previous studies (Laxon et al., 1998; Stanovich et al., 1997; van der Leij & van Daal, 1999), we used only CVC nonwords that differed from real word neighbors by one letter (e.g., yate – late, zake – cake). These nonwords, being less complex, may have reduced differences between children with dyslexia and typical readers.

The finding of higher reading accuracy in children with dyslexia compared to their level-matched peers is surprising given the general expectation that children with dyslexia read at the same level as typical readers that are at least 2 years younger (see Jackson & Butterfield, 1989). One possibility could be that better performances in children with dyslexia reflected effects of reading intervention. This is only a speculation because we have no clear indication of the types of intervention services that children with dyslexia were receiving during their participation in our study. Based on the information provided by parents, we only know that 18 out of 20 participants with dyslexia were receiving some type of remediation services at school and/or through a private practitioner. Future studies should consider how reading intervention shapes reading profiles in children with dyslexia.

Second, we found a strong positive effect of phonological neighborhood density in all groups. That is, children read nonwords with high phonological neighborhood density more accurately than nonwords with low phonological neighborhood density. These results are particularly interesting, because a robust dense neighborhood advantage was not found for all groups in spelling. Perhaps, our findings reflect the differences in spelling acquisition versus reading acquisition. Although learning to spell and read rely on similar underlying knowledge of the relationships between letters and sounds, learning to spell is more difficult than learning to read (see Bosman & Van Orden, 1997). Children usually read more words correctly than they can spell, and spelling difficulties tend to persist longer than reading difficulties (Seymour & Porpodas, 1980; Thomson, 1984; Frith, 1984, 1985; Nicolson & Fawcett, 1994). For example, a longitudinal study that followed children from first through fourth grade found a gradual increase in reading ability over time, but a decline in spelling ability (Mehta, Foorman, Branum-Martin, & Taylor, 2005). Limited or absent formal spelling instruction explains in part this asymmetry between reading and spelling abilities (Simonsen & Gunter, 2001).

Indeed, our analysis of overall spelling and reading accuracy showed that children in each group were better at reading nonwords than spelling them. This may suggest that spelling difficulties limit the effect of dense phonological neighborhood density, regardless of a child's reading level. More research is needed to understand how the divergence between spelling and reading skills manifests in children's lexical development.

Third, the negative effect of orthographic neighborhood density was strong in age-matched children, but weak in children with dyslexia and level-matched children. We have previously discussed about the possibility of high-frequency neighbors competing and interfering with lexical access. In addition, these findings tend to confirm our assumption of the effect of orthographic neighborhood density being dependent on the quality of orthographic representations. That is, limited print exposure and less specified representations most likely prevented children with dyslexia and level-matched children from showing a similar robust negative effect as age-matched children did.

Summary

Taken together, we found that children with dyslexia exhibited weaker but similar density effects as their typically developing peers in spelling and reading. As expected, nonwords with high phonological density facilitated spelling and reading performances, but surprisingly, nonwords with high orthographic neighborhood density did not.

Our findings differ from the existing literature in two main ways. First, children with dyslexia exhibited similar spelling and reading profiles as their typical peers. As previously discussed, differences between children with dyslexia and typical readers appear to be minimal when considering additional variables that are related to spelling and reading development (e.g., oral language), or when using certain stimuli (e.g., shorter nonwords, nonwords with higher visual similarity to real words) that are known to reduce processing demands in children with dyslexia.

Second, we did not find any indication that children with dyslexia tend to rely more on orthographic strategies than on phonological strategies, as suggested in previous studies (Olson, 1985; Siegel et al., 1995; Lennox & Siegel, 1996; Stanovich et al., 1997; van der Leij & van Daal, 1999). On the contrary, they benefitted more from phonological cues, as shown by the facilitative effect of phonological neighborhood density. Most likely, our findings reflect the level of processing that we chose to examine, that is, implicit processing.

Previous studies that looked at children's explicit representations (e.g., explicit knowledge of letter-sound correspondences, acceptable patterns in the English language) found that orthographic knowledge remains relatively intact in the presence of dyslexia and acts as a compensatory factor. On the other hand, our measures of implicit representations (i.e., phonological and orthographic neighborhood densities) revealed that children with dyslexia exhibited profiles closer to those of age-matched peers with an emphasis on phonological processing. Perhaps, children with dyslexia demonstrate difficulties only at an explicit level and it is then that they tend to employ compensatory strategies. To verify this, future work should use item analysis to examine specific strategies that children with dyslexia rely on during spelling and reading.

Limitations

Our work clearly has some limitations. First, the small sample size may have affected the power to detect some effects and cross-level interactions. Second, it is possible that our stimuli were too simple to detect expected differences between children with dyslexia and typical readers. Future work should consider more complex stimuli, such as longer nonwords and nonwords with lower visual similarity to real words.

Third, we scored responses using a correct/incorrect system commonly used in measures of spelling and reading performance, that perhaps, it is not the best indicator of children's underlying knowledge. Our next step should be a more qualitative analysis of children's productions to determine how much they rely on phonological or orthographic strategies.

Finally, we did not collect detailed information about the amount and type of intervention services that children with dyslexia were receiving while participating in our study. This is an important factor that is often overlooked in research. Future research should obtain such information and assess how intervention shapes implicit and explicit lexical representations.

Conclusion

The present study sought to examine whether phonological and orthographic processes make joint or separate contributions to spelling and reading. Children's processing abilities were evaluated at an implicit level using phonological and orthographic neighbors. Our results showed that children with dyslexia and typical readers benefitted from dense phonological neighborhoods but not from dense orthographic neighborhoods, suggesting that phonology and orthography operate independently.

However, we do not dismiss the importance of a reciprocal development of phonological and orthographic processes in spelling and reading. Rather, we believe that our focus on children's implicit representations limits our conclusion about the way that orthographic processing shapes children's ability to spell and read. To understand the role of orthographic knowledge in spelling and reading, it is necessary for future research to examine children's processing skills within a comprehensive framework that considers both implicit and explicit representations.

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Appendix A

Stimuli[1]	Spelling	PhonoN	OrthoN	Condition	FriendsN	Consistency
/ʤaId/	jide	12	10	P+O+	6	Inconsistent
/gov/	gove	15	12	P+O+	6	Inconsistent
/baʊr/	bour	12	13	P+O+	5	Inconsistent
/fæb/	fab	14	15	P+O+	7	Consistent
/zek/	zake	12	10	P+O+	10	Inconsistent
/jet/	yate	15	10	P+O+	10	Inconsistent
/wir/	weer	10	11	P+O+	0	Other
/baIf/	bife	13	10	P+O+	4	Consistent
/gɔIl/	goil	15	7	P+O-	6	Inconsistent
/vun/	vune	13	5	P+O-	4	Inconsistent
/zot/	zote	12	6	P+O-	5	Inconsistent
/haIb/	hibe	10	6	P+O-	1	Consistent
/dæf/	daf	12	6	P+O-	0	Other
/lɛʃ/	lesh	13	6	P+O-	2	Consistent
/gip/	geep	14	7	P+O-	5	Inconsistent
/vɝm/	verm	10	5	P+O-	2	Inconsistent
/ʤɔd/	jod	4	12	P-O+	1	Inconsistent
/dɔʃ/	dosh	7	10	P-O+	0	Other
/wos/	wose	7	11	P-O+	1	Inconsistent
/vʊt/	voot	6	10	P-O+	2	Inconsistent
/bʊf/	boof	7	10	P-O+	2	Inconsistent
/tɑv/	tov	4	10	P-O+	0	Other
/jɑg/	yog	5	12	P-O+	3	Inconsistent
/fur/	fure	7	13	P-O+	0	Other
/zaIp/	zipe	5	4	P-O-	3	Inconsistent
/jɛv/	yev	5	6	P-O-	1	Consistent
/v^ʧ/	vutch	7	4	P-O-	2	Inconsistent
/job/	yobe	4	4	P-O-	2	Consistent
/hɔIn/	hoin	6	4	P-O-	3	Consistent
/mʊθ/	mooth	5	6	P-O-	0	Other
/paʊm/	poum	4	4	P-O-	0	Other
/væθ/	vath	7	6	P-O-	4	Inconsistent

[1] International Phonetic Alphabet (IPA) transcription

Appendix B

Stimuli	Spelling	PhonoN	Phonological Neighbors	OrthoN	Orthographic Neighbors
/ʤaId/	jide	12	/baId/, /ʧaId/, /gaId/, /haId/, /paid/, /raid/, /said/, /taId/, /waId/, /ʤed/, /ʤaIb/, /ʤaIv/	10	bide, hide, ride, side, tide, wide, vide, jade, jibe, jive
/gov/	gove	15	/kov/, /dov/, /hov/, /mov/, /rov/, /wov/, /gev/, /gIv/, /goʃ/, /god/, /gol/, /got/, /gor/, /go/, /grov/	12	grove, dove, hove, move, rove, wove, cove, love, gave, give, gore, gone
/baʊr/	bour	12	/daʊr/, /laʊr/, /saʊr/, /bar/, /bɛr/, /bIr/, /bor/, /baʊt/, /baʊl/, /baʊɚ/, /aʊr/, /baʊ/	13	hour, sour, dour, lour, four, tour, your, bout, boar, bur, our, pour, boor
/fæb/	fab	14	/kæb/, /dæb/, /gæb/, /ʤæb/, /læb/, /næb/, /tæb/, /fIb/, /fɑb/, /fæd/, /fæg/, /fæn/, /fæŋ/, /fæt/	15	cab, dab, gab, lab, nab, tab, jab, fob, fib, fad, fag, fan, far, fat, fay
/zek/	zake	12	/bek/, /kek/, /fek/, /hek/, /lek/, /mek/, /rek/, /sek/, /ʃek/, /tek/, /wek/, /ek/	10	bake, cake, fake, hake, lake, make, rake, sake, take, wake
/jet/	yate	15	/bet/, /det/, /fet/, /get/, /het/, /let/, /met/, /pet/, /ret/, /set/, /wet/, /jɛt/, /jɑt/, /et/, /je/	10	date, fate, gate, hate, late, mate, pate, rate, sate, ate
/wir/	weer	10	/wor/, /wɛr/, /waIr/, /wik/, /wil/, /win/, /wiv/, /wid/, /wip/, /wi/	11	beer, deer, peer, jeer, leer, week, weed, weep, wear, veer, wee
/baIf/	bife	13	/faIf/, /naIf/, /laIf/, /raIf/, /waIf/, /bif/, /b^f/, /baIu/, /baId/, /baIt/, /baIk/, /baIl/, /baI/	10	fife, life, rife, wife, bide, bike, bile, bite, bine, biff
/gɔIl/	goil	15	/bɔIl/, /kɔIl/, /mɔIl/, /sɔIl/, /tɔIl/, /vɔIl/, /gel/, /gɔl/, /gul/, /gIl/, /gɝl/, /gol/, /gaIl/, /g^l/, /ɔIl/	7	boil, coil, moil, soil, toil, oil, foil
/vun/	vune	13	/bun/, /kun/, /dun/, /ʤun/, /lun/, /mun/, /nun/, /run/, /sun/, /tun/, /ven/, /væn/, /vain/	5	dune, june, tune, rune, vine
/zot/	zote	12	/bot/, /kot/, /dot/, /got/, /mot/, /not/, /rot/, /ʃot/, /tot/, /vot/, /zon/, /ot/	5	note, rote, tote, vote, dote
/haIb/	hibe	10	/ʤaIb/, /hɝb/, /hɑb/, /h^b/, /haIt/, /haId/, /haIk/, /haIr/, /haIv/, /haI/	6	jibe, hide, hie, hike, hire, hive
/dæf/	daf	12	/kæf/, /ʧæf/, /gæf/, /hæf/, /læf/, /dɛf/, /dɑf/, /dæb/, /dæd/, /dæm/, /dæʃ/, /dæft/	6	daft, deaf, dab, dad, dam, day

/lɛʃ/	lesh	13	/mɛʃ/, /læʃ/, /liʃ/, /l^ʃ/, /lɛr/, /lɛd/, /lɛʤ/, /lɛg/, /lɛk/, /lɛs/, /lɛt/, /lɛf/, /flɛʃ/	6	mesh, flesh, lash, less, leash, lush
/gip/	geep	14	/ʧip/, /dip/, /hip/, /kip/, /lip/, /nip/, /pip/, /rip/, /sip/, /ʃip/, /wip/, /gæp/, /gep/, /gis/	7	keep, deep, weep, peep, seep, jeep, beep
/vɝm/	verm	10	/fɝm/, /ʤɝm/, /tɝm/, /wɝm/, /vIm/, /vɝb/, /vɝʤ/, /vɝs/, /vɝv/, /vɝml/	5	germ, term, verb, very, vert
/ʤɔd/	jod	4	/gɔd/, /lɔd/, /ʤed/, /ʤɔ/	12	cod, hod, god, mod, nod, pod, rod, sod, job, joy, jot, jog
/dɔʃ/	dosh	7	/wɔʃ/, /dæʃ/, /dIʃ/, /duʃ/, /dɔb/, /dɔn/, /dɔg/	10	posh, gosh, bosh, josh, dish, dash, dose, tosh, mosh, nosh
/wos/	wose	7	/dos/, /wæs/, /wor/, /wod/, /wok/, /wov/, /wo/	11	dose, hose, lose, nose, rose, pose, worse, woe, woke, wove, wore
/vʊt/	voot	6	/fʊt/, /pʊt/, /sʊt/, /væt/, /vɛt/, /vot/	10	boot, foot, root, soot, loot, coot, hoot, toot, moot, volt
/bʊf/	boof	7	/hʊf/, /wʊf/, /bif/, /b^f/, /bʊk/, /bʊl/, /bʊʃ/	10	roof, woof, hoof, goof, book, boom, boob, boon, boot, boo
/tɑv/	tov	4	/tɑr/, /tɑg/, /tɑp/, /tɑt/	10	toe, too, top, toy, ton, tot, tow, tog, tor, to
/jɑg/	yog	5	/ʤɑg/, /kɑg/, /tɑg/, /jɑt/, /jɑn/	12	jog, cog, tog, bog, dog, fog, hog, log, nog, yon, you, yob
/fur/	fure	7	/fɛr/, /far/, /fIr/, /faIr/, /for/, /fud/, /ful/	13	sure, cure, pure, lure, fur, fume, furl, fury, fuse, furze, fare, fire, fore
/zaIp/	zipe	5	/paIp/, /raIp/, /taIp/, /waIp/, /zIp/	4	pipe, ripe, wipe, zip
/jɛv/	yev	5	/rɛv/, /jɛl/, /jɛn/, /jɛs/, /jɛt/	6	ye, yea, yen, yes, yet, rev
/v^ʧ/	vutch	7	/vɛʧ/, /vaʊʧ/, /d^ʧ/, /h^ʧ/, /m^ʧ/, /s^ʧ/, /t^ʧ/	4	dutch, hutch, butch, vetch
/job/	yobe	4	/lob/, /rob/, /jok/, /jor/	4	lobe, robe, yoke, yore
/hɔIn/	hoin	6	/hɛn/, /kɔIn/, /ʤɔIn/, /lɔIn/, /hon/, /h^n/	4	coin, join, loin, horn
/mʊθ/	mooth	5	/mæθ/, /mɝθ/, /mɔθ/, /maʊθ/, /mIθ/	6	tooth, booth, math, moth, mouth, moot
/paʊm/	poum	4	/pɑm/, /paʊʧ/, /paʊt/, /paʊɚ/	4	pout, poem, pour, plum
/væθ/	vath	7	/bæθ/, /læθ/, /mæθ/, /pæθ/, /ræθ/, /væn/, /væt/	6	oath, path, lath, math, vat, bath

Appendix C

Stimuli	Spelling	Spelling Alternatives	PhonoN	OrthoN	FriendsN	Consistency
/ʤaId/	jide	jied	12	6	1	Inconsistent
		jyde	12	1	0	Other
/gov/	gove	goav	15	3	0	Other
/baʊr/	bour	bower	12	12	0	Other
/zek/	zake	zeak	12	6	0	Other
/jet/	yate	yeat	15	11	0	Other
		yait	15	3	3	Inconsistent
/wir/	weer	wear	10	13	0	Other
		weir	10	2	0	Other
		wier	10	2	0	Other
		were	10	7	0	Other
		wheer	10	2	0	Other
		where	10	2	0	Other
/baIf/	bife	byfe	13	1	0	Other
/zot/	zote	zoat	12	5	5	Inconsistent
/vun/	vune	voon	13	7	7	Inconsistent
		voun	13	1	0	Other
/haIb/	hibe	hybe	10	1	1	Inconsistent
/dæf/	daf	daff	12	3	1	Inconsistent
/lɛʃ/	lesh	leash	13	4	0	Other
/gip/	geep	geap	14	6	4	Inconsistent
		geip	14	1	0	Other
		gepe	14	2	0	Other
/vɝm/	verm	virm	10	1	1	Inconsistent
/ʤɔd/	jod	jad	4	18	0	Other
		jud	4	7	0	Other
		jaud	4	2	2	Inconsistent
/wos/	wose	woas	7	2	0	Other
		whose	7	5	0	Other
		whoas	7	1	0	Other
		wosse	7	3	0	Other
/vʊt/	voot	vut	6	11	1	Inconsistent
		vutt	6	3	0	Other
		vout	6	8	0	Other
/jɑg/	yog	yag	5	15	0	Other
		yug	5	10	0	Other

/bʊf/	boof	bouf	7	1	0	Other
		buf	7	7	0	Other
		buff	7	5	0	Other
		buph	7	1	0	Other
		bough	7	6	0	Other
/tɑv/	tov	tav	4	9	0	Other
		tuv	4	8	0	Other
/fur/	fure	foor	7	8	0	Other
		four	7	11	0	Other
/dɔʃ/	dosh	dash	7	10	0	Other
		dush	7	12	0	Other
/zaIp/	zipe	zype	5	1	1	Inconsistent
/v^ʧ/	vutch	vuch	7	3	2	Inconsistent
		vouch	7	3	1	Inconsistent
/yob/	yobe	yowb	4	1	0	Other
/paʊm/	poum	powm	4	1	0	Other
/mʊθ/	mooth	mouth	5	3	0	Other
		muth	5	7	0	Other
/jɛv/	yev	yeav	5	3	0	Other

Appendix D

Stimuli	Spelling	Reading Alternatives	PhonoN	OrthoN	FriendsN	Consistency
/gov/	gove	/g^v/	10	12	3	Consistent
/baʊr/	bour	/bur/	11	13	0	Other
/vun/	vune	/vʊn/	3	5	0	Other
/ʤɔd/	jod	/ʤɑd/	17	12	9	Inconsistent
		/ʤ^d/	9	12	0	Consistent
/dɔʃ/	dosh	/dɑʃ/	15	10	6	Consistent
		/d^ʃ/	18	10	0	Consistent
/wos/	wose	/woz/	15	11	7	Consistent
		/wus/	10	11	0	Inconsistent
		/wuz/	12	11	1	Inconsistent
/vʊt/	voot	/vut/	14	10	7	Inconsistent
/bʊf/	boof	/buf/	11	10	2	Consistent
/tɑv/	tov	t^v	9	10	0	Consistent
		/tɔv/	6	10	0	Other
/jɑg/	yog	/jɔg/	8	12	5	Consistent
		/j^g/	12	12	0	Consistent
/v^ʧ/	vutch	/vʊʧ/	3	4	0	Other
/mʊθ/	mooth	/muθ/	15	6	3	Inconsistent
/paʊm/	poum	/pum/	12	4	0	Inconsistent
		/pɔm/	5	4	0	Other
		/p^m	23	4	0	Inconsistent
		/pom/	18	4	0	Inconsistent