Graduate School ETD Form 9
(Revised 01/14)

PURDUE UNIVERSITY
GRADUATE SCHOOL
Thesis/Dissertation Acceptance

This is to certify that the thesis/dissertation prepared

By Meredith Sue Saleta

Entitled
Orthography and Modality Influence Speech Production in Skilled and Poor Readers

For the degree of Doctor of Philosophy

Is approved by the final examining committee:

Lisa Goffman	Jessica Huber
Diane Brentari	
Jeffrey Haddad	
Tiffany Hogan	

To the best of my knowledge and as understood by the student in the *Thesis/Dissertation Agreement. Publication Delay, and Certification/Disclaimer (Graduate School Form 32)*, this thesis/dissertation adheres to the provisions of Purdue University's "Policy on Integrity in Research" and the use of copyrighted material.

Approved by Major Professor(s): Lisa Goffman

Approved by: Jessica Huber 06/18/2014

Head of the Department Graduate Program Date

ORTHOGRAPHY AND MODALITY INFLUENCE SPEECH PRODUCTION IN SKILLED AND POOR READERS

A Dissertation

Submitted to the Faculty

of

Purdue University

by

Meredith Sue Saletta

In Partial Fulfillment of the

Requirements for the Degree

of

Doctor of Philosophy

August 2014

Purdue University

West Lafayette, Indiana

For Mom, Dad, and Chuck. Thank you for everything.

ACKNOWLEDGMENTS

I wish to express my heartfelt gratitude to my mentor, Dr. Lisa Goffman, for her profound impact on my professional development. Her guidance and patience have enabled me to develop as a scientist, scholar, and teacher. Because she has always challenged me to achieve the next level in my work, she has enabled me to expand my horizons more than I could ever have imagined.

I am indebted to the members of my doctoral committee for their input, encouragement, and many constructive criticisms. Drs. Diane Brentari, Jeffrey Haddad, Tiffany Hogan, and Jessica Huber each contributed to my growth as a doctoral student in a unique and very important way. Thanks to their varied backgrounds and perspectives, I was fortunate to experience well-rounded training in methods of data acquisition and analysis, knowledge of theoretical constructs, and introduction to scientific writing.

This dissertation would not have been possible without the support of the students and research associates who work in Dr. Goffman's laboratory. From helping to conceptualize the structure of this project at its very beginning, to assisting with the labor-intensive processes of running the equipment and trimming data for each and every session, to performing reliability coding in the final stages, I relied upon their help on a daily basis. Mitch Barna, Sara Benham, Janna Berlin, Barb Brown, Fuwen Cai, Allison

Gladfelter, Daniel Miller, Peter Richtsmeier, and Janet Vuolo: you are more than colleagues, you are lifelong friends.

Finally, special thanks go to all of the participants and their families for their enthusiastic contributions of time and effort, and especially for their interest in the process of research.

TABLE OF CONTENTS

Page

LIST OF TABLES viii
LIST OF FIGURES ix
ABSTRACT x
INTRODUCTION 1
Conceptual Overview 2
Literacy Skills Influence the Perception and Production of Spoken Language 3
The Processing of Orthography by Typically-Developing Readers 3
The Processing of Orthography by Low-Proficiency Readers 8
Orthographic and Phonological Characteristics Related to Language Processing 13
Neighborhood Density 13
Phonotactic Probability 20
Explicit versus Implicit Linguistic Processing 24
Previous Investigations: Explicit Processing 24
The Current Investigation: Implicit Processing 25
Indexing Implicit Learning and Language Production via Speech Production Analyses 28
The Relationship between Language, Reading, Speech, and Motor Skills 33
Overview of Methods 38
Questions and Objectives 40
Question #1 40
Question #2 41
Measures Used to Quantify Modality and Transparency Effects 43
METHODS 45
Participants 45

Page

Age and Socio-Economic Status 45
General Summary of Assessment Battery 46
Characteristics of Each Group 48
Group Comparisons Based on Behavioral Testing 50
Equipment 55
Procedures and Session Structure 56
Counterbalancing 58
Stimuli 59
Details of the Task 62
Data Processing 65
Outcome Variables 65
Segmental Accuracy 65
Segmental Variability 66
Speech Movement Stability 67
Statistical Analyses 69
RESULTS 71
Analytic Issues 71
Transcription Reliability 71
Missing Data 71
Dependent Measures 72
Segmental Accuracy 72
Segmental Variability 75
Speech Movement Stability 78
Relationship between Reading Skills and Performance on the Experimental Task...81
DISCUSSION 83
Differences in Phonetic and Articulatory Factors Across Groups 84
Modality and Transparency Influence Phonological and Motor Learning 85
Effects of Modality on Phonological Learning 85
Effects of Transparency on Motor Learning 87

Page

Speech Production Measures Index Implicit Processing 93
Expanding Upon Previous Models of Language-Motor Interactivity 95
Individual Differences..99
Future Directions...100
Conclusions 104
LIST OF REFERENCES 106
VITA 131

LIST OF TABLES

Table Page

Table 1. Four subgroups of poor readers, according to Catts, Kamhi, and Adlof (2012). 9

Table 2. Summary of reading standard scores used for inclusionary criteria. 48

Table 3. Summary of oral language and nonverbal reasoning scores. 48

Table 4. Adult-Typ characteristics and behavioral scores for each participant. 52

Table 5. Child participant characteristics and behavioral scores for each participant. 53

Table 6. Adult-LP characteristics and behavioral scores for each participant. 54

Table 7. Session structure: three phases in each of three conditions. 58

Table 8. Counterbalancing scheme. 59

Table 9. Number of participants in each counterbalancing scheme. 59

Table 10. Orthographic characteristics of target nonwords. 61

Table 11. Phonological characteristics of target nonwords. 61

Table 12. Examples of errors which warranted online cueing. 64

Table 13. Examples of participants who improved or worsened with exposure to orthography in the transparent spelling condition. 77

Table 14. Descriptive statistic for TTR; percent of participants who improved from the pretest to the learning phase. 77

LIST OF FIGURES

Figure Page

Figure 1. An example of an illustration of one alien. 57

Figure 2. A PowerPoint slide used to introduce the task. 63

Figure 3. Examples of extracted movement sequences from the utterance, "Bob saw a /mΛnfik/ before." 69

Figure 4. PCC data. 73

Figure 5. PCC condition by phase interaction. 74

Figure 6. PCC pretest/posttest difference scores. 75

Figure 7. TTR data. 76

Figure 8. LA index data. 79

Figure 9. LA index pretest/posttest difference scores. 80

Figure 10. Relationship between articulatory stability and decoding. 81

Figure 11. Relationship between articulatory stability and comprehension. 82

ABSTRACT

Saletta, Meredith Sue, Ph.D., Purdue University, August 2014. Orthography and Modality Influence Speech Production in Skilled and Poor Readers. Major Professor: Lisa Goffman.

The acquisition of literacy skills influences both the perception and production of spoken language. The connection between spoken and written language processing develops differently in individuals with varying degrees of reading skill. Some specific phonological and orthographic factors which play a role in this developmental course include neighborhood density, orthographic transparency, and phonotactic probability. In the current study, nonword stimuli which contain manipulations of the above factors were created. Participants repeated or read aloud the nonwords. Three groups of readers participated: adults with typical reading skills, children developing reading skills typically, and adults demonstrating low levels of reading proficiency. Analyses of implicit linguistic processing, including measures of segmental accuracy, segmental variability, and articulatory stability, were conducted. Results indicated that these three groups followed a consistent pattern on all three measures, in that the typical adults demonstrated the strongest performance, the children demonstrated the weakest performance, and the adults with low levels of reading skill demonstrated intermediate performance. All three groups improved in both phonological and motor learning with practice, but only the adults with low reading skills demonstrated learning as a direct consequence of orthographic transparency. Finally, reading skill was correlated with articulatory stability in both groups of adults. These data make an important contribution to the understanding of the typology of reading disorders, as well as the influence of orthographic factors on typical language and reading development.

INTRODUCTION

The ways in which readers process the orthographic characteristics of words and nonwords have been well documented. Many studies have looked at meta-linguistic measures, which target an explicit level of processing, to assess this type of learning. However, less is known about readers' implicit processing of words' or nonwords' orthographic characteristics, especially how this type of learning varies as a function of reading proficiency. Studying speech kinematics may be an informative way to explore implicit learning. This is an especially valuable method because it quantifies speech motor skill, which may vary along with other motor skills in individuals with differing degrees of reading proficiency. The objective of the current study is to index readers' implicit processing of the orthographic characteristics of nonwords by examining speech kinematics and other aspects of speech production, and to compare this processing in typical, low-proficiency, and developing readers. These participants produced nonwords which varied in modality of presentation (either auditory or written) and orthographic transparency, and the impact of these variables on participants' speech production was assessed. This paradigm has important theoretical implications, as it can provide evidence for the ways in which the acquisition of literacy skills (in both typical and atypical development) impacts individuals' processing and production of spoken and written language. Exploring this issue via speech production methods can shed light on the implicit processing of orthographic characteristics by individuals with varying degrees of reading skill.

This study may have important clinical applications regarding both assessment and intervention. If speech motor skills vary as a function of reading proficiency, it might be possible to include tests of these skills in screening batteries to assist in the early identification of at-risk individuals. Additionally, if adults with low levels of reading proficiency show the same patterns of learning as do children who are developing reading skills typically, it might indicate whether to incorporate elements of the developmental sequence into interventions for struggling readers.

Conceptual Overview

This study addresses two main issues. First, it will explore the ways in which the acquisition of literacy skills influences the perception and production of spoken language. This section will include a discussion of the reorganization of spoken and written language processing in concert with the development of reading skill, and how this progression proceeds in individuals with both typical and atypical development. Second, the literature review will address the ways in which specific orthographic and phonological characteristics are processed by individuals with various levels of reading skill. Specifically, this section will examine neighborhood density, orthographic transparency, and phonotactic probability, and will discuss how these factors are manipulated in the current experiment. Finally, the methods used to address the above questions will be described. The distinction between explicit and implicit linguistic processing will be emphasized, with a focus on the ways in which production measures can go beyond the limitations of previous studies.

Literacy Skills Influence the Perception and Production of Spoken Language

The Processing of Orthography by Typically-Developing Readers

The first goal of the current study is to investigate the ways in which the acquisition of literacy skills influences the perception and production of spoken, as well as written, language. Many previous works have demonstrated that as an individual acquires literacy skills, his or her perception and production of spoken language become transformed as well. As described by Frith (1998), "one might liken the possession of an alphabetic code to a virus. This virus infects all speech processing, as now whole word sounds are automatically broken up into sound constituents. Language is never the same again" (p. 1011).

It is important to consider the developmental progression here in order to differentiate typical changes from what may occur when development proceeds atypically. It is unclear whether low-proficiency adult readers use similar strategies as young children when confronted with a reading task; determining how adults who are low- proficiency readers compare with children who are typical readers is a central goal of this project. Ultimately, understanding this distinction may enable researchers and clinicians to determine whether or not to draw from the typical developmental sequence when designing interventions for struggling readers.

Throughout typical development, children's language processing becomes reorganized. This is true for both the oral and written systems; however, the directions of this reorganization are different for each system. In general, children's spoken language processing is thought by many researchers to progress from a holistic-based system to a more segmental method of processing. In contrast, children's written language processing progresses from a holistic-based system to more segmental processing and then back to a more holistic or automatic type of analysis.

Children's Reorganization of Spoken Language

Many researchers have argued that children's processing of the phonological elements in spoken language proceeds along a protracted developmental course, following a continuum from holistic processing to a more segmental level of processing. According to Nittrouer, Studdert-Kennedy, and McGowan (1989), children's earliest language is mediated by meaning. The earliest contrastive unit used by children is often one or a few syllables composing the word or formulaic phrase, rather than the phoneme or feature. By most children's second birthdays, they have begun to reorganize their phonological processing from the whole-word level to a more segmental level (Dodd & McIntosh, 2009). This change is due in part to the development of the child's vocabulary. Specifically, when a child has only a few words, only a few articulatory routines are required to produce known words. Then, as children's vocabulary knowledge develops, it is essential that new routines emerge (Nittrouer et al., 1989). That is, initially, when only a few words are necessary for communication, the child can communicate effectively with a few basic patterns. Later, when it becomes necessary to distinguish among a critical number of vocabulary words (50 according to Ingram, 1976; 200 according to Vogel Sosa & Stoel-Gammon, 2006), the child's coordination across various articulators becomes more precise and consistent (Nittrouer, 1993). Then, as toddlers mature into preschoolers, differentiation below the level of the syllable gradually emerges.

According to Nittrouer et al. (1989), there are several pieces of evidence which support the idea of holistic processing in young children's earliest speech production. First, children may master phonetic forms in one word but not in another, suggesting that they contrast the word as a whole instead of the individual phonemes as adults do (Ferguson & Farwell, 1975). Second, they may produce the same word in widely differing ways on different occasions. That is, they may omit or incorrectly sequence gestures in each attempt, implying that they do not process the word as a collection of individual segments (Browman & Goldstein, 1986; Ferguson & Farwell, 1975). Third, children may omit or harmonize segments in syllables containing an alternation in manner or place of articulation (e.g., /gʌk/ or /dʌt/ for /dʌk/), indicating that they have assembled the word as a single prosodic unit before attempting to produce it (Menn, 1983). Finally, the findings of Nittrouer et al. (1989) indicate that young children (ages three to five) demonstrate greater coarticulation and less distinction in their contrast of minimal pairs than older children (age seven) or adults. This further suggests that young children have not yet mastered the production of speech as segmental units. However, the above may be an oversimplification. As Goffman, Smith, Heisler, and Ho (2008) point out, mappings across these levels are complex, and coarticulation may cross word and phrase boundaries for both children and adults. Therefore, in both child and adult talkers, larger units such as the phrase may co-occur with smaller units such as segments or features.

Children's Reorganization of Written Language

Typical reading development also encompasses several diverse skills. Proponents of the *Simple View of Reading* state that there are two components of reading: decoding (i.e., word recognition processes) and linguistic comprehension (i.e., interpreting words, sentences, and discourse; Gough & Turner, 1986; Kamhi & Catts, 2012). More specifically, according to the classic psycholinguistic framework of Coltheart (1978), readers may use either of two routes to identify words. The *indirect route* allows readers to use the rules of grapheme-phoneme correspondence to identify infrequent and regularly-spelled words. The *direct route* bypasses the use of phonological cues, enabling the reader to access semantics for frequent and irregularly-spelled words.

The changes occurring to a child's perception of the spoken word are mirrored in the changes occurring to his or her system of reading. En route to achieving reading expertise, children progress through several stages – the direction of which is different than that of the stages involved in spoken language reorganization. Proficient reading requires access to a route of visual recognition which does not rely on phonological mediation. In the process of achieving proficient reading, there is first a *visual* or *logographic stage* during the preschool years, when children do not use letters as cues but rather utilize salient graphic features to associate the printed word with the spoken word.

These young pre-readers rely on holistic visual symbols. For instance, when researchers printed the Coca-Cola logo on a Rice Krispies box, the majority of preschoolers believed that the word said "Rice Krispies" (Kamhi & Catts, 2012; Masonheimer, Drum, & Ehri, 1984).

As the emergent literacy period gives way to the *alphabetic stage*, children begin to analyze words at a more segmental level by using the rules of grapheme-phoneme correspondence to decode new words (Kamhi & Catts, 2012). This ability goes beyond the rote memorization of letter "sounds" and "names," but involves the insight that these sounds make up spoken language (Adams, 1990). Finally, as they become proficient readers, a more automatic identification of written words emerges (Ventura et al., 2007). This next phase involves automatic visual sight word recognition (also called the *orthographic* or *consolidated stage*), and occurs after children accumulate knowledge of spelling patterns (Ehri, 1991, 2005; Firth, 1985). Readers at this level use regularly-occurring patterns, including morphemes and words that share letter sequences, to bypass phonological conversion (Kamhi & Catts, 2012). These distinctions between the changes occurring to young talkers and young readers suggest that there is fluidity between lexical and sublexical processing in children.

The spoken and written language systems are related in that changes in sublexical processing occur in concert with reading development. Nittrouer (1996) hypothesizes that listeners integrate multiple temporal and spectral properties of the acoustic signal in order to determine phonetic structure (as opposed to alternate theories which state that these acoustic properties correspond to phonetic features in a one-to-one fashion; e.g., Blumstein & Stevens, 1980). These weightings of acoustic speech parameters are modeled in the Developmental Weighting Shift (Nittrouer, Manning, & Meyer, 1993). For example, toddlers initially attend to formant transitions; then, the attention of young children (ages 3.5-7.5) gradually shifts to the silent gaps indicating vocal tract closure, duration of vowels, and the spectral distribution of fricatives. According to Johnson and colleagues (2011), the weighting of these sublexical acoustic cues changes as speech perception, phonemic awareness, and reading skills develop.

The above represents a summary of the research regarding the ways in which typically-developing readers process orthography and how this processing may relate to developmental changes in speech production. Next, the discussion will turn to the important differences which occur when this development proceeds atypically.

The Processing of Orthography by Low-Proficiency Readers

When an individual's development of literacy skills proceeds atypically, the influence of orthography on language processing is altered. This transformation is apparent in the behavioral differences between typical and atypical readers (e.g., Castro-Caldas & Reis, 2003; Zeigler, Muneaux, & Grainger, 2003). In addition, difficulty in acquiring literacy skills may have cascading effects on neural organization. Numerous neuroimaging studies have revealed differences in language processing in individuals with poor reading skills. Shankweiler, Mencl, Braze, Tabor, Pugh, and Fulbright (2008) state that, "as a person's literacy advances, the foundation of reading skill becomes increasingly integrated with the biologically endowed speech system, such that the neurobiology of speech and print become richly interconnected at each level of linguistic processing from the grapho-phonologic subword level (Atteveldt, Formisano, Goebel, & Blomert, 2004) to the syntactic-pragmatic sentence and discourse levels" (p. 771).

Returning to the *Simple View of Reading* described above, Catts, Kamhi, and Adlof (2012) describe four subgroups of poor readers based upon their skills in decoding and comprehension (Table 1). Readers with problems decoding but typical comprehension skills (and who are therefore able to understand text when it is read aloud to them) are categorized as having dyslexia, whereas individuals demonstrating the opposite profile are characterized as having a specific comprehension deficit. Readers with problems in both areas are classified as having "mixed" deficits, and individuals with difficulty reading for other reasons are classified as "non-specified."

Table 1. Four subgroups of poor readers, according to Catts, Kamhi, and Adlof (2012).

		Decoding	
		Poor	*Good*
Listening Comprehension	*Good*	Dyslexia	Non-specified
	Poor	Mixed	Specific Comprehension Deficit

The current definition of dyslexia is consistent with the above typology. According to the International Dyslexia Association, dyslexia is neurobiological in origin; has its source in the phonological component of language; is unexpected in relation to other cognitive skills; persists despite adequate classroom instruction; and may include secondary problems associated with reduced reading experience (Catts, Kamhi, & Adlof, 2012; Lyon, Shaywitz, & Shaywitz, 2003).

Exploring the differences between skilled and poor readers is central to the current study. According to Bruck (1990) and Vellutino, Fletcher, Snowling, and Scanlon (2004), adults with low levels of reading proficiency should show immature, not deviant, processes. Therefore, adults with dyslexia should pattern more closely to children with typical development than to adults with typical reading skills. This invites the question of how, specifically, differences between these groups of readers are manifest. Previous literature is equivocal on this point. Some researchers indicate that individuals with reading disabilities may use a relatively global or coarse coding rather than the fine-grained grapheme-phoneme mappings used by typical readers. This means that they may rely to a greater extent on words' visual characteristics rather than their phonological characteristics (Lavidor, Johnston, & Snowling, 2006). In contrast, according to Bolger, Hornickel, Cone, Burman, and Booth (2008), individuals who are more proficient readers are influenced to a greater degree by any phonological/orthographic inconsistency. Thus, individuals with higher reading skills should be more sensitive to changes to words or nonwords' orthographic transparency, whereas children in early elementary school experience weak and variable effects of these orthographic factors.

Recall the segmentation hypothesis explored above, which states that children's processing of spoken language undergoes an important shift from holistic to segmental. This model is also relevant to children (and perhaps adults) who are developing reading skills atypically. These children may fail to reorganize their phonological representations adequately. When their lexical representations become more and more segmented, their phonological representations may fail to keep up with the developmental shift, reflecting the importance of segmental information. According to the phonological model of reading disabilities, the failure to reorganize causes these children to experience phonological difficulties. This deficit is first manifest by difficulties in the development of phonological awareness, which then affects the acquisition of letter knowledge (Fowler, 1991; Snowling, 2013).

Johnson and colleagues (2011) explored the deficits in phonological representation in three groups of children: those who had previously presented with speech sound disorders (although these difficulties did not persist at the time of the study), those currently presenting with reading disabilities, and those demonstrating a combination of the two. These investigators examined the question of why reading disabilities may begin without previous speech sound disorders, and why speech sound disorders may resolve without later reading disabilities. These inconsistencies are not in agreement with the phonological model of reading disabilities, which states that a core phonological deficit is sufficient to cause reading disabilities (Fowler, 1991; Snowling, 2000; Stanovich & Seigel, 1994). They found that the specific deficit in phonological representation differs between these three groups, as measured by three specific tasks (categorical perception of voice onset time, attention to formant transition, and attention to fricative noise). Specifically, all children responded equally well to the voice onset manipulation, but the groups with speech and/or reading difficulties exhibited problems integrating the other two acoustic cues. The children with speech sound disorders alone as well as the children with speech sound disorders plus reading disabilities differed from controls in their weighting of the spectra of fricative noise. The children with reading difficulties alone did not differ from controls in this measure; the groups also did not differ in their sensitivity to formant transitions. The authors concluded that speech perception deficits for children with speech sound disorders (with or without concomitant reading disorders) persist beyond the age at which the overt speech deficit has resolved, indicating that these children's perceptual deficit is broader than previously suggested and includes more difficulties than just producing speech errors. Specifically, children with poor phonemic awareness skills demonstrated difficulty in integrating acoustic cues in order to perceive linguistic information.

Disorders of written and spoken language may also be related. Specific language impairment (SLI), like dyslexia, is a disorder of exclusion. The diagnostic criteria for SLI specify that the child must have significant deficits in language that are not explained by factors such as hearing loss, intellectual impairment, or motor deficits (Leonard, 1998). The problems experienced by these two populations tend to overlap. For instance, children with dyslexia may have deficits in semantics and syntax like those seen in SLI (e.g., Snowling, Gallagher, & Frith, 2003), and children with SLI may have deficits in phonological processing and word recognition as have been described in children with dyslexia (e.g., Snowling, Bishop, & Stothard, 2000). However, this does not mean that dyslexia and SLI are variants of one language disorder. Several investigators, including Tomblin, Records, Buckwalter, Zhang, Smith, and O'Brien (1997), Bishop and Snowling (2004), and Catts, Adlof, Hogan, and Weismer (2005) suggest that SLI and dyslexia are distinct but potentially comorbid disorders, based upon children's performance in tasks including phonological awareness and nonword repetition.

Thus far, the discussion has explored the influence of orthography on the general linguistic processing of individuals with typical and atypical reading, speech, and language proficiency. Next, the focus will turn to two word-level factors which impact the processing of language differently for highly-skilled and less-skilled readers.

Orthographic and Phonological Characteristics Related to Language Processing

Two word-level factors are particularly relevant to children's and adults' language processing, and they provide evidence for the interface between phonological and lexical processing. These include neighborhood density, which in the orthographic domain generally aligns with orthographic transparency, and phonotactic probability. These two factors may differentially impact individuals with various levels of reading proficiency. Also, these two factors affect both perception and production – an important application to the current study, which focuses on speech production.

Neighborhood Density

Neighborhood density reflects the influence of the number of words which can be constructed by changing, adding, or deleting one phoneme or grapheme of a target word (Coltheart, Davelaar, Jonasson, & Besner, 1977; Davis, Perea, & Acha, 2009). Thus, we can consider two types of neighborhood density: phonological and orthographic.

The results of studies concerning phonological and orthographic neighborhood density vary depending upon whether speech perception or production is analyzed. These data have been inconsistent, ranging from inhibitory to null to facilitative effects of the density of the neighborhood depending upon the task (Alario, Perre, Castel, & Ziegler, 2007). A summary of experiments involving speech perception is presented below; a summary of experiments involving speech production immediately follows.

Neighborhood Density in Speech Perception Studies

Overall, previous research indicates that phonological neighborhood effects are consistently present, even preschool children presenting with phonological delays (Storkel, Maekawa, & Hoover, 2010). However, orthographic neighborhood effects differ in concert with an individual's reading skill. Ziegler and Muneaux (2007) manipulated orthographic and phonological neighborhood density to index the influence of orthography on spoken word recognition. They tested three groups of children: beginning readers (mean reading age of 7 years), advanced readers (mean reading age of 11.7 years), and readers with dyslexia (who were age-matched with the advanced readers at a mean chronological age of 11.4 and reading level-matched with the beginning readers at a mean reading age of 7.1 years). Their results indicated that, while all three groups demonstrated phonological neighborhood density effects (in this case, demonstrated by response latencies in a lexical decision task), orthographic neighborhood effects were present only for advanced readers and were absent in children with dyslexia.

Findings of neighborhood density studies are equivocal as to whether individuals are helped or hindered by dense neighborhoods. When considering phonological neighborhood density, results indicate that dense neighborhoods create inhibitory effects on speech perception. Ziegler, Muneaux, and Grainger (2003) demonstrated that words are harder to recognize in phonologically dense neighborhoods than in sparse neighborhoods because lexical competition occurs between words which are phonologically similar (Luce & Pisoni, 1998).

With regards to orthographic neighborhood density, speech perception/listening studies indicate that dense orthographic neighborhoods, possibly coupled with the degree of orthographic inconsistency, create facilitative effects for speech perception. Ziegler and Muneaux (2007) found that dense orthographic neighborhoods cause spoken word recognition to occur more efficiently. Miller and Swick (2003) found comparable results, indicating facilitative effects of orthographic characteristics in a lexical decision task. They first replicated the phonological rhyme priming effect of Shulman, Hornak, and Sanders (1978), demonstrating that participants made lexical decisions more quickly when the prime rhymed with the target. Then significantly, Miller and Swick matched some stimuli on orthographic as well as phonological characteristics (e.g., the words "*drawn*"-"*gone*" rhyme, but the words "*tell*"-"*bell*" both rhyme and contain consistent orthography). Their findings indicated that participants experienced facilitative effects of words matched on both orthography and phonology as compared to phonology alone, suggesting an additive effect of these two characteristics.

Viewing the same question from another perspective, Pattamadilok, Perre, Dufau, and Ziegler (2009) found an inhibitory effect of orthographic inconsistency in spoken word recognition. These authors assessed whether orthography is utilized in a semantic categorization task (which clearly does not require orthographic access), and quantified the time course of these effects. Their findings indicate that orthographic inconsistency based on multiple spellings of homophones increased the difficulty of lexical access. In addition, the orthographic effect preceded lexical access and semantic effects, and was time-locked to the onset of the orthographic inconsistency in the auditorily-presented stimulus. The above studies demonstrate that orthographic neighborhood effects influence speech perception even when performing a task which does not require the retrieval of orthographic information.

Neighborhood Density in Speech Production Studies

Speech production studies involving neighborhood density also point to two possible effects. Some findings indicate that dense neighborhoods create facilitative effects for speech production. These include the study of Vitevitch (2002), who used speech error elicitation and picture naming tasks to show facilitative effects of neighborhood density. He found that both accuracy rates (participants' responses to speech-error elicitation techniques) and response times (in picture-naming tasks) improved for words from phonologically dense neighborhoods. Vitevitch theorized that the activation of word forms causes the activation of other word forms which share constituent phonological segments.

Similarly, regarding orthographic neighborhood density, Damian and Bowers (2003) discovered a facilitative effect of transparent orthography on single word speech production. The authors created stimuli with form overlap; that is, the stimuli were consistent in their initial phonological segments but differed in their initial letters (e.g., "*coffee*"-"*kernel*"). They reasoned that, if language is divided into separate modules, orthography would not impact speech production in an auditory priming task. This was not the case; even when experiments were conducted entirely in the auditory domain, there was a disruptive effect of orthographic inconsistency. In contrast, Alario and colleagues (2007) did not replicate Damian and Bowers' (2003) findings of facilitative effects of orthographic similarity. Alario and colleagues argue that the previous results may be due to the possibility that participants used orthography intentionally, as a mnemonic device to remember word pairs.

In contrast, some findings indicate that orthographic neighborhoods may be separate from and irrelevant to speech production. Roelofs (2006) measured production tasks including response latencies in word reading (a task for which spelling was relevant) and picture naming and recalling responses to a prompt (two tasks for which spelling was irrelevant). The findings of this experiment indicated that the orthographic effects only occurred in the word reading task. Roelofs concluded that the disruption caused by spelling inconsistency only occurs when spelling is relevant and is utilized in the task. Similarly, Alario and colleagues (2007) investigated the influence of orthography on spoken language by quantifying response latencies of participants' naming of pictures which were controlled for orthographic and phonological characteristics. They determined that, while phonological similarity facilitated picture naming, orthographic similarity did not, and concluded that the process of speaking is insensitive to orthographic properties. Finally, Rastle, McCormick, Bayliss, and Davis

(2011) investigated whether differences in modality and orthographic transparency would influence participants' auditory lexical decision, picture naming, and shadowing (i.e., repeating words as rapidly as possible). They found orthographic effects in the former two tasks, but not in shadowing. To explain these different findings, they describe the relative time course of orthographic and phonological information. Phonological activation occurs first when repeating a spoken nonword, but when additional processing stages are required (such as is the case for lexical decision), the extra time provides more opportunities for orthographic inconsistencies to interfere.

Neighborhood Density Relates to Orthographic Transparency

Neighborhood density is closely correlated with the construct of orthographic transparency, in that words with more opaque spellings generally reside in low-density neighborhoods. This is of significance to this project because it is predicted that density and transparency should differentially impact speech production in the three participant groups. Consequently, these factors have important implications for the design of the current project's experimental stimuli, in which manipulations of orthographic neighborhood density were used to index orthographic transparency.

Transparency effects in a given language are related to the consistency of grapheme-phoneme correspondence in the language's orthographic representations. Languages such as Italian (Zoccolotti, De Luca, Di Pace, Judica, Orlandi, & Spinelli, 1999), Greek, and Spanish (Ziegler & Goswami, 2005), which contain a preponderance of words with one-to-one grapheme-phoneme correspondence, fall on the *transparent* end of the continuum. Languages such as English and Danish (Borgwaldt, Hellwig, & de Groot, 2004; Ziegler & Goswami, 2005), which represent the same phonetic sequence in multiple ways (e.g., in English, the sequence /ɚ/ can be spelled in several ways, including "*birch, lurch, perch,*" and "*search*;" Ventura et al., 2007), fall on the *opaque* end of the continuum.

Like other word-level characteristics, individuals who experience atypical reading development are also differentially influenced by orthographic transparency. According to Serrano and Defior (2008), languages with greater transparency may be associated with less severe reading difficulties (Jiménez-González & Hernández-Valle, 2000; Ziegler & Goswami, 2005). Children with language impairment may experience greater difficulty in reading languages which are more opaque (Catts & Kamhi, 2005; Kamhi & Catts, 2012). Bilingual children who experience reading instruction in one language may experience facilitative effects which promote literacy in their second language. This effect is partially based on the orthographic transparencies of the two languages; bilingual children perform better on decoding tasks in the language with greater transparency (Schwartz, Leikin, & Share, 2005; Schwartz, Share, Leikin, & Kozminsky, 2008).

Transparency effects may also occur at levels smaller than that of the word, including the rime, syllable, phoneme, grapheme, or even units which are smaller than the grapheme. Different languages are associated with different weightings for these various units. Speakers and readers of languages with opaque orthographies more easily use larger units (such as word bodies) when processing spoken language, whereas speakers and readers of languages with more transparent orthographies prefer smaller units (such as graphemes; Ziegler & Goswami, 2006). This has also been explored in investigations of spelling. Jones, Folk, and Rapp (2009) investigated the effects of sound-spelling frequency of the subgraphemic characteristics of letters within digraphs, such as the *i* and *e* in "*brief*." The authors assessed words containing phonemes which varied in the frequency of their correspondence with individual letters. Participants included a neurologically-compromised individual as well as typical adults spelling under the disruptive effects of a distractor task (in this case, performing a shadowing task while writing to dictation). Both tended to omit or produce incorrectly the more vulnerable letters within digraphs (such as the *i* in "*brief*," which is used less often than the *e* to represent the sound /i/). The authors concluded that letters may be strongly or weakly be activated in orthographic working memory depending upon levels of sound-letter convergence.

In summary, sensitivity to orthographic factors varies as a function of reader skill and the degree of transparency in a speaker's native language (and, in some cases, an individual's fluency as a bilingual speaker). These effects differ depending upon whether perception or production is measured, and may be influenced by the relevance of orthography to the task. Phonotactic probability, discussed in the following section, is another word-level factor which influences both reading and speaking.

Phonotactic Probability

The other important word-level factor in the current study, which is related more purely to phonology, is *phonotactic probability.* This variable is defined as the likelihood of the occurrence of a particular sound sequence in a given language. Quantifying phonotactic probability differentiates common from rare sound sequences (Storkel, 2004). In this section, the discussion will shift away from orthographic characteristics to this other important sublexical factor which may create changes in the processing of spoken or written language. It is important to understand phonotactic probability because, like neighborhood density, its influence may differ as a function of reading proficiency. Also like neighborhood density, this factor has important implications for the design of the current project's experimental stimuli.

Neighborhood density is positively correlated with phonotactic probability, as common sequences of segments often co-occur in words with many related neighbors (Vitevitch, Luce, Pisoni, & Auer, 1999). An important difference between neighborhood density and phonotactic probability is that the former characteristic has a lexical locus, whereas the latter characteristic has a sub-lexical locus (Vitevitch & Luce, 2005). This conclusion was based on assessing reaction time in word naming (i.e., language analyzed at the lexical level) and nonword naming (i.e., language analyzed at the sublexical level; Vitevitch & Luce, 1998). At the lexical level, representations correspond to words and experience competitive processes; at the sublexical level, representations correspond to components of words and are activated during perception (Luce & Pisoni, 1998; Vitevitch, 1997). Because individuals with low levels of reading proficiency may experience greater difficulty accessing sublexical than lexical components of language processing, they may respond differently from skilled readers to manipulations of phonotactic probability.

It is important to inquire whether children or adults with weak phonological representations show different effects of phonotactic probability and neighborhood density than typically developing individuals. Characteristically, the pattern is that children learn common sound sequences from dense neighborhoods more easily than rare sounds from sparse neighborhoods. In contrast, Storkel (2004) demonstrated that children with phonological delays showed the opposite pattern. As a follow-up study, Storkel and colleagues (2010) attempted to disassociate these two factors (phonotactic probability and neighborhood density) in a word learning task. Their results indicated that the word learning of children with typical development was supported by the convergence of phonotactic probability and neighborhood density; however, this was not the case for children with phonological delays. Because of their weaker phonological representations, children in this group did not benefit from common sound sequences and dense neighborhoods (Storkel et al., 2010). To my knowledge, the effects of phonotactic probability have not been investigated in dyslexia.

Word-Level Factors Manipulated in the Current Study

In summary, the effects of neighborhood density, orthographic transparency, and phonotactic probability vary as a function of reader skill. The current study expands upon the works described above by focusing on speech production. In the current study, participants with varying levels of reading skill repeated and read aloud nonwords which were controlled for phonotactic probability, and contained manipulations of orthographic neighborhood density. Differences in orthographic neighborhood density were used to index the orthographic transparency of the stimuli. Specifically, the nonword stimuli were spelled in two possible ways: one was a relatively transparent spelling which had more orthographic neighbors, while the other was a relatively opaque spelling which had fewer orthographic neighbors. The goal of this manipulation in the current study was to determine whether manipulating orthographic transparency would differentially impact the nonword production of typical readers and individuals with reading impairments.

This study's hypotheses follow from the above-mentioned results regarding the influence of orthography on speech production. It is anticipated that there will be a facilitative effect of transparent orthography (i.e., when participants are exposed to the nonword stimuli which are associated with more orthographic neighbors) and a disruptive effect of opaque orthography (i.e., when participants are exposed to the nonword stimuli which are associated with fewer orthographic neighbors). It is possible that these effects will be more prominent in skilled readers, because this group experiences the influence of orthographic neighborhood density more intensely. On the other hand, it is possible these effects will be more prominent in poor readers, because this group demonstrates weaker phonological representations and experiences greater difficulty accessing the sublexical components of processing.

Next, it is important to consider methodologies that may be used to address hypotheses regarding influences of proficiency on speech production, as well as orthographic neighborhood density effects. Both issues – the ways in which the acquisition of literacy skills influences spoken language production, and the ways in which readers with varying levels of skill process specific orthographic and phonological characteristics – can be explored via a speech production task. Specifically, it will be argued that, in contrast to many previous works which measure explicit linguistic awareness, a speech production task can directly quantify implicit language processing.

This is an important factor in the understanding of readers' processing of the orthographic characteristics of text.

Explicit versus Implicit Linguistic Processing

Previous Investigations: Explicit Processing

Many of the studies concerning the influence of orthography on processing or learning share an important approach, as researchers designed meta-phonological or meta-linguistic tasks to explore this question. For example, participants counted phonemes (Ehri & Wilce, 1980) or monitored lists for rhyming words or certain phonemes (Seidenberg & Tannenhaus, 1979; Zecker, 1999). For these types of activities, participants were required to analyze the sound structure of the stimuli and to make conscious judgments (Snow, Burns, & Griffin, 1998). These studies have focused on meta-linguistic or explicit awareness, which is not required for speaking and may not be present in all competent speakers.

Drawing conclusions regarding linguistic processing based exclusively on meta-linguistic awareness may be misleading. In a classic study, Morais, Cary, Algria, and Bertelson (1979) determined that adults who were illiterate (yet, were perfectly competent speakers) were unable to segment phonemes. In a follow-up study, Read, Zhang, Nie, and Ding (1986) took this idea one step further, and determined that adults who were literate in only a logographic system were also unable to segment phonemes. Taken together, the results of these two studies indicate that cognitive-linguistic maturation alone does not enable a speaker to perform meta-linguistic tasks. Rather, instruction in literacy – and in particular, alphabetic literacy – is required for facility in the performance of some meta-linguistic tasks.

Ziegler and Muneaux (2007) cite Morais and colleagues' study and argue that illiterate adults are unable to segment phonemes regardless of the phonological neighborhood density of the stimuli. This difficulty may arise because one's knowledge of orthography causes all words, regardless of neighborhood density, to have phoneme-based representations.

The Current Investigation: Implicit Processing

Another, perhaps deeper, level of processing is implicit linguistic competence. That is, an individual may speak and listen through his or her natural grasp of the phonological principles of his or her language, without making conscious judgments (Hoff, 2011; Snow et al., 1998). Consequently, measuring speech and language production can circumvent the limitations inherent in studies of exclusively meta-linguistic judgments.

A few paradigms have looked at the ways in which meta-linguistic knowledge can, in fact, reflect a more implicit degree of processing. For example, according to Munson and colleagues (2005), speakers' meta-phonological judgments regarding the wordlikeness of nonword stimuli draw upon their knowledge of phonotactic probability, even though this knowledge is clearly not explicit (Bailey & Hahn, 2001; Frisch, Large, & Pisoni, 2000; Hay, Pierrehumbert, & Beckman, 2004; Munson, 2001).

One specific element which is included under the umbrella of implicit knowledge is procedural learning, in contrast to declarative learning which is more associated with explicit knowledge. A clear example of the difference between using these two types of knowledge while performing the same activity comes from music cognition. While declarative learning is exemplified by the rote memorization of the notes of a D-major scale, procedural learning is illustrated by the practiced execution of this sequence of notes on a given instrument (Dowling, 1993). The procedural system is an implicit system, because the learning and memories are not available for conscious access (Ullman & Pierpont, 2005).

Researchers investigating specific language impairment (SLI) have formulated the Procedural Deficit Hypothesis (Ullman & Pierpont, 2005). These authors cite a dual-systems view of language, in which procedural memory is used to generate the rule-governed components of language (i.e., syntax, morphology, and phonology or the sequencing of sounds), and declarative memory is used for idiosyncratic mappings (i.e., the lexicon). Children with SLI may experience greater difficulty utilizing procedural learning and consequently, may rely to a greater extent on other systems. For example, they may store morphological information with words as "chunks" in declarative memory (Ullman & Pierpont, 2005). As noted above, SLI and dyslexia overlap in many ways, and it is probable that both populations experience procedural deficits (e.g., Nicolson & Fawcett, 2007).

A common task used to explore implicit or procedural learning in development and in clinical populations is the serial reaction time task (SRTT). In this task, researchers present stimuli in a certain complex sequence which is unknown to the participant and then measure reaction time as they track the stimuli. Implicit learning is demonstrated by reduced reaction time to the stimuli suggesting that the individual is predicting the upcoming stimulus, without overt knowledge of the pattern. According to Stoodley, Harrison, and Stein (2006), implicit learning tasks such as the SRTT are advantageous because they reflect experience gained during the task, yet do not require participants' memories or conscious awareness; in addition, the SRTTs are visual tasks which do not require overt language processing (Tomblin, Mainela-Arnold, & Zhang, 2007). For example, Yang and Hong-Yan (2011) asked children to define the order in which stimuli appeared, and found that in no case did this knowledge reach declarative memory (i.e., no child was able to describe the rule, even though their performance differed in response to that rule). Stoodley and colleagues (2006) used the SRTT and found that adults with dyslexia exhibited less decrease in reaction time than control participants during repeated sequences of stimuli, suggesting difficulties with implicit learning.

Very little research has explored implicit learning in individuals with dyslexia. Therefore, the next step in exploring the influence of orthography on processing is to investigate its impact on participants' implicit linguistic competence. The current work follows up on a previous study (Saletta, Goffman, & Brentari, in revision), using methods which integrate measures of speech and language production to target implicit learning. The next section will elaborate on the ways in which these methods can be used to quantify speech and language production. In the current study, these factors were assessed in skilled child and adult readers and in adults with a history of reading difficulty and generally low levels of reading proficiency.

Indexing Implicit Learning and Language Production via Speech Production Analyses

Examining the phonetic aspects of speech production has provided an important window into higher-level aspects of language processing. For example, exemplar-based models of speech production predict that, in contrast to highly discrete theories, lexical representations will be directly associated with phonetic details (Goldrick, Baker, Murphy, & Baese-Berk, 2011), and that interactions are present between lexical, phonological, and phonetic levels of structure (Pierrehumbert, 2002). Methodologies such as the study of speech errors (e.g., Goldrick et al., 2011) and slips of the tongue (i.e., the finding that these types of errors are more likely to be real words than chance substitutions; McMillen, Corley, & Lickley, 2009) provide evidence for more interactive mechanisms. Much of this work has focused on the lexicon, with word status influencing lower-level production processes. Methodologies which quantify speech motor changes, including both articulatory and acoustic measures, provide the most direct analysis of the influences of lexical, grammatical, and phonological factors on the substance of speech production: articulation.

Speech production analyses also include measures of segmental accuracy, segmental variability, and articulatory stability. Segmental accuracy quantifies the percentage of consonant errors, including omissions and substitutions but excluding consonant distortions or allophonic errors (Shriberg, Austin, Lewis, McSweeny, & Wilson, 1997). An increase in an individual's segmental accuracy indicates that he or she is becoming more precise in the production of words or nonwords. Therefore, changes for the better would be indicated by increases in segmental accuracy. In the current study, percent consonants correct (PCC) is used to quantify segmental accuracy.

Segmental variability is used to evaluate the degree to which a given form of a word or nonword becomes well-established or stable, and indicates that even if errors are produced, the individual may have settled upon a single production of that given form. Conventionally, measures of segmental variability have been used to quantify lexical diversity in performance measures such as spontaneous language samples. In these studies, greater variability or diversity represents a positive change, as low lexical diversity in a language sample may be associated with language impairment (e.g., Goffman, Gerken, & Lucchesi, 2007; Scott & Windsor, 2000; Watkins, Kelly, Harbers, & Hollis, 1995). However, in the current study, this traditional measure is examined from the opposite perspective. Greater diversity of errors may be interpreted as an indication that participants experienced more difficulty with the task. Therefore, in the current study, changes for the better would be indicated by decreases in segmental variability. Type-token ratio (TTR) is used to quantify segmental variability.

Measuring articulatory stability is another promising methodology which may target implicit linguistic competence. This approach does not require the participant to make conscious judgments; rather, the speaker need only produce the target words or sentences. Additionally, this approach clearly focuses on production rather than perception. This may be a valuable contribution to the literature, because very little work has described the influence of orthography on speech production, yet there are well-formulated hypotheses from the developmental literature about the transition from holistic to segmental processing that should bridge these areas.

In the current study, the lip aperture (LA) index for spatio-temporal variability is used to quantify articulatory stability. This measure assesses the stability of a participant's repeated utterances throughout a given speech production task. The interaction of three effectors (upper lip, lower lip, and jaw) is quantified during speech. The productions are then time- and amplitude-normalized so as to force all productions to a single scale. The degree to which the productions converge represents their stability.

Previously, measures of articulatory kinematics have quantified speech production in many populations. Children showed increased speech movement stability with maturation of speech production processes, or the mastery of a particular linguistic structure (Smith & Goffman, 1998; Smith & Zelaznik, 2004). Articulatory stability also changes in response to changes in linguistic processing demands such as greater linguistic or prosodic complexity (e.g., Goffman, Gerken, & Lucchesi, 2007; Goffman, Heisler, & Chakraborty, 2006; Maner, Smith, & Grayson, 2000), the inclusion of semantic cues (Heisler, Goffman, & Younger, 2010), or as a consequence of aging (Wohlert & Smith, 1998). Saletta, Darling White, Ryu, Haddad, Goffman, Francis, and Huber (in revision) discovered that individuals with Parkinson's disease demonstrated lower articulatory stability when repeating passive sentences as opposed to sentences with less complex syntax (i.e., active sentences and sentences containing relative clauses). Because English grammar favors a canonical sentence order, the inhibition of which is required for the production of passives, this type of sentence is more difficult to process. Finally, Saletta and Goffman (in preparation) and Goffman and Saletta (in preparation) found that children with SLI were more responsive to manipulations of load than children with typical development. Both groups demonstrated increased speech movement stability when linguistic load was decreased (i.e., sentence repetition versus sentence generation, and word repetition versus word imitation); however, changes to the articulatory stability of the children with SLI were larger than those of the typical group.

The above findings suggest that cognitive-linguistic and speech motor processes interact during speech production. It is anticipated that this interaction will appear differently for the three groups in the current study. Like the influences of linguistic load mentioned above, manipulations of modality (i.e., whether the stimuli are heard or read) and orthographic transparency should similarly impact participants' speech motor stability. Measuring participants' articulatory stability is an informative way to reveal high-level differences in their processing of nonwords' orthographic characteristics.

An additional point to consider is that a nonword production task may be useful in investigations involving individuals with varying degrees of reading skill. Nonword production differentiates high- and low-proficiency readers. Skilled and poor readers are similar in their repetition of words – a task which engages the semantic or lexical pathways. However, they differ in their ability to repeat nonwords – a task which engages the phonological pathway (Castro-Caldas, Petersson, Reis, Stone-Elander, & Ingvar, 1998). Awareness of phonology develops as a child learns to read. If an individual fails to acquire these skills, he or she may experience difficulty in producing nonwords, even into adulthood (Castro-Caldas & Reis, 2003). This is due in part to the development of sublexical representations, which presumably emerge with the development of reading skills and are a requirement for the processing of nonwords (Pattamadilok et al., 2008).

According to Munson et al. (2005), nonword repetition is not a simple task, as it involves several cognitive processes including discriminating the acoustic signal, recalling the phonological representations which correspond to that signal, and planning and finally executing the articulatory movements necessary to repeat the signal. These intricacies are further complicated by the phonological characteristics of the target nonword. For instance, nonwords with low phonotactic probability require the speaker to combine representations of phonemes in order to perform the task. In contrast, a speaker can repeat nonwords with higher phonotactic probability by tapping into subparts of phonological representations of real words, making the task easier. Finally, the results of a longitudinal study by Nation and Hulme (2011) suggest that growth in reading predicts improvement in nonword repetition, and that this relationship was independent of development of oral language skills. These findings indicate that written language is incorporated into children's language processing systems in an interactive way.

Approaches to Investigating Interactions in Speech Motor Production and Reading

Speech production methodologies focused on phonetic accuracy and articulatory variability should be sensitive to the ways in which word-level characteristics, including neighborhood density, orthographic transparency, and phonotactic probability, interact with other levels of processing. Individuals with varying degrees of reading skill should show changes to their speech production in response to the manipulations of modality and transparency.

Since speech production tasks involve the interface between language and speech motor output, it is important to consider the relationship between these skills. Several clinical populations, including individuals with SLI and dyslexia, demonstrate (in some cases, subclinical) motor deficits. Although the purpose of the current study is to examine differences in speech motor output as a function of reading skill and the orthographic characteristics of nonword stimuli, it is also important to consider more global motor skills in these clinical populations. Next, the relationship between language (including reading) skills and speech and limb motor skills will be discussed.

The Relationship between Language, Reading, Speech, and Motor Skills

This study aims to address the relationship between speech, language and reading skills, and the ways in which these domains interact in developing and poor readers. Researchers have traditionally conceptualized language and motor (including speech motor) skills as being discrete processes. In addition, many speech, language, and reading disorders are identified by diagnoses of exclusion – that is, to qualify for a diagnosis such as dyslexia, an individual must display difficulties in reading without any other confounding factors. However, as stated by Zelaznik and Goffman (2010), "Language production, whether spoken, signed, or written, is a motor activity" (p. 383). This statement predicts that there will in fact be a connection between language and motor skills. It is particularly important to analyze this interaction in individuals who experience reading difficulties; indeed, individuals with clinical diagnoses, including dyslexia, SLI, attention deficit hyperactivity disorder, and speech sound disorders, often experience concomitant motor deficits (Diamond, 2000; Johnson et al., 2011; Ramus, Pidgeon, & Frith, 2003; Zelaznik & Goffman, 2010).

Because of the documented motor and speech motor deficits observed in clinical populations, it is anticipated that the current investigation will reveal greater articulatory variability in individuals with reading difficulties. This prediction is based on both behavioral data (described above), as well as neuroanatomical and physiological differences which have been discovered in populations with clinical difficulties in speech, language, reading, and motor skills. Specifically, the literature points to three main areas of the brain which are associated with the language-motor interaction: the cerebellum, Broca's area, and the motor cortex. Each of these thee areas will be detailed in the subsequent section.

The Role of the Cerebellum in the Language-Motor Interface

According to Nicolson and Fawcett (1994, 2011), the subclinical motor problems experienced by individuals with dyslexia may include difficulties in performing such diverse activities as swimming, riding a bicycle (Augur, 1985), throwing and catching, walking backwards (Haslum, 1989), and executing fine motor skills such as writing (Benton, 1978) and tying shoelaces (Miles, 1983). Additionally, by conducting fine-grained gait and balance analyses to quantify body sway and response to perturbation from external forces in a provocation test, researchers are able to differentiate children with and without dyslexia (Moe-Nilssen, Helbostad, Talcott, & Toennessne, 2003). Impairments in sequencing, speed, timing, and balance may also be experienced by children with language or reading impairments, consistent with the Procedural Deficit Hypothesis described above (Ullman & Pierpont, 2005).

One possibility presented in the literature is the automatisation deficit hypothesis (Nicolson & Fawcett, 1990), which proposes that individuals with dyslexia experience difficulties making skills automatic. *Automaticity* is defined as the ability to learn to perform a task without conscious examination (Ramus et al., 2003). Nicolson and Fawcett (2011) break down three critical reading and writing difficulties apparent in dyslexia: the writing problem is due to deficits in motor skill; the initial reading problem is due to deficits in phonological processing; and, the spelling problem and later problems in reading fluency are due to difficulties in skill automatisation.

The cerebellar deficit theory predicts that a dysfunction of the cerebellum is the cause of the motor deficits which underlie writing, pronouncing, and reading problems (Yang & Ho-Yan, 2011). Support for this idea comes from time estimation paradigms, which are assumed to take advantage of the timing functions of the cerebellum (Ivry & Keele, 1989) and on which individuals with dyslexia perform poorly. In these tasks, two tones are presented successively, and participants say whether the second tone is longer or shorter than the first. These studies also included a loudness estimation task, which would not involve the cerebellum, as established by the classic study of Ivry and Keele (1989; Ramus et al., 2003). Indeed, Nicolson, Fawcett, and Dean (1995) demonstrated that children with dyslexia performed poorly on time estimation but performed comparably to controls on loudness estimation (Fawcett, Nicolson, & Dean, 1996). Neurobiological studies indicate that individuals with dyslexia may have lower right-cerebellum activation (Menghini, Hagberg, Caltagirone, Petrosini, & Vicari, 2006;

Nicolson, Fawcett, Berry, Jenkins, Dean, & Brooks, 1999). Structural imaging studies indicate that some adults with dyslexia have anatomical differences in their right anterior cerebellar lobe and inferior frontal gyrus. These areas of the brain are believed to be important for rapid automatic naming and phonological awareness (Eckert, Leonard, Richards, Aylward, Thomson, & Berninger, 2003).

The Role of Broca's Area in the Language-Motor Interface

Broca's area (Broadmann's areas 44 and 45) also plays an important role in the interface between speech, language, and motor execution. Burns and Fahy (2010) state that this area bridges the premotor stages of motor execution with goal-oriented motor control. Broca's area may also be responsible for diverse language tasks, ranging from phonological processing (i.e., organizing discrete actions in time) to semantic and syntactic processing (i.e., a higher organizational hierarchy; Koechlin & Jubault, 2006). This area may also be actively engaged in aspects of language and motor control such as listening, watching, selecting, conducting lexical, grammatical, and phonological decisions, (Burns & Fahy, 2010), and during the observation of hand action (e.g., Bucciono et al., 2001; Buccino, Binkofski, & Riggio, 2004). Other researchers state that that Broca's area is involved in the serial reaction time tasks (SRTT) described above; specifically, in the abstraction process enabling the individual to learn various sequences (Bapi, Miyapuram, Graydon, & Doya, 2006; Bischoff-Grethe, Goedert, Willingham, & Grafton, 2004; Clerget, Poncin, Fadiga, & Olivier, 2012). According to Baumgaertner Buccino, Lange, McNamara, and Binkofski (2007), the response of Broca's area to action stimuli is consistent regardless of the stimuli's modality of presentation (visual processing of video clips or auditory-verbal processing of spoken sentences). Broca's area also plays a crucial role in the observation and execution of manual movements (Heisler, Iacoboni, Maeda, Marcus, & Mazziotta, 2003).

The Role of the Motor Cortex in the Language-Motor Interaction

Jancke, Siegenthalaer, Preis, and Stienmetz (2007) state that many imaging studies have demonstrated the close connection between language perception and production and motor skill in the motor cortex. Both language perception (Floel, Ellger, Breitenstein, & Knecht, 2003) and speech production (Tokimura, Tokimura, Oliviero, Asakura, & Rothwell, 1996) may activate the hand motor cortex. The dorsolateral prefrontal cortex is also involved in motor performance. Some tasks controlled by the frontal cortex include holding information in mind and organizing it; waiting until the appropriate moment to respond; inhibition of incompatible behaviors; and remaining on task – cognitive functions which are also crucial for skilled motor function (Diamond, 2000).

An individual may experience neural activation patterns in response to objects after motor experience with those objects (e.g., James & Atwood, 2009). Similarly, this type of neural activation also occurs when an individual views letters (James & Gauthier, 2006), which may be due to his or her history of writing those letters (James, 2010). *Functional specialization* refers to differentiations in the neural response to particular stimuli – for instance, a region in the left fusiform gyrus may respond more to individual letters than other characters (James, James, Jobard, Wong, & Gauthier, 2005). This type of specialization develops as a function of an individual's experience with reading text. James (2010) explored the developmental course of this functional specialization for letters by comparing preschool children who learned letters by sensory-motor practice (printing the letters) or visual recognition. Her fMRI findings indicated that even preliterate children experience hemispheric differences in responding to letters than to shapes and pseudo-letters. Crucially, sensory-motor experience facilitates processing in these young children, supporting the idea of the connection between improvements in processing and motor experience.

All of the literature cited above establishes the relationship between speech, language, reading, and motor skills in various clinical populations. Most crucial for the current project, individuals with reading disabilities often show deficits in motor, including speech motor, skills. This connection shows that the language and motor domains are not separate, but are in fact connected. Previous investigations have discovered this interaction both at the level of behavior and at the level of the brain. Defining this relationship is important for the current project, as it aims to examine speech production as it relates to language and reading skills.

Overview of Methods

The above literature review establishes key points which are relevant to the current investigation. First, the acquisition of literacy skills influences the perception and production of spoken language. Second, orthographic characteristics such as neighborhood density, orthographic transparency, and phonotactic probability are processed differently by individuals with different levels of reading skill. Measures of language production – including segmental accuracy, segmental variability, and articulatory stability – can be used to quantify implicit language processing. It is the goal of this study to apply these measures to a nonword production task – a type of task which has previously been shown to be effective in analyzing differences between readers with varying levels of skill.

In the current study, three groups of participants were compared: (1) adults with typical levels of reading proficiency (Adult-Typ); (2) children who are developing reading skills typically; and (3) adults with a reported history of reading difficulties and with low levels of reading proficiency (Adult-LP). Participants repeated nonwords which systematically varied in modality of presentation (auditory or written) and, for the written stimuli, in orthographic transparency (relatively transparent or opaque spelling, as defined by orthographic neighborhood density). Individuals participated in three phases (pretest, learning, and posttest) in each of three conditions (auditory presentation only, transparent spelling, opaque spelling). Participants' segmental accuracy, segmental variability, and articulatory stability were measured as they repeated or read the stimuli in each phase within each condition. To quantify segmental accuracy, the percent of consonants produced correctly (percent consonants correct, or PCC) was calculated. To compute segmental variability, type-token ratio (TTR) was calculated. To measure articulatory stability, the lip aperture (LA) variability index was calculated. This measure quantifies the spatial and temporal variability of a participant's repeated productions of a given sentence. All three measures were used to assess how skilled and poor readers processed phonological and orthographic information.

Questions and Objectives

Question #1

The above literature review emphasized two main questions which are investigated in the current study. First, it is the goal of this study to explore the ways in which literacy skills influence speech production. Specifically, does exposure to the written word influence production processes? This question will be addressed by examining the ways in which the three groups – adults with typical reading skills (Adult-Typ group), children who are developing reading skills typically, and adults with a history of reading difficulties who also demonstrate low levels of reading proficiency (Adult-LP group) – respond to manipulations of modality (i.e., repeating nonwords that are heard versus reading nonwords).

There are two competing hypotheses based on previous research.

Less skilled readers may be particularly influenced by modality. In this case, the two groups with lower levels of reading proficiency (i.e., children and Adult-LP groups) should show greater changes than more skilled readers in response to these modality and transparency manipulations. This idea is supported by the work of Lavidor, Johnston, and Snowling (2006). These authors stated that individuals with reading disabilities may use a relatively global or coarse coding rather than the fine-grained grapheme-phoneme mappings used by typical readers. This means that they may rely to a greater extent on words' visual characteristics rather than their phonological characteristics, which suggests that the two groups with lower reading skills should demonstrate greater changes in accuracy and stability when they are required to read the nonwords. In contrast, the Adult-Typ group should demonstrate equal amounts of change or practice effects across conditions, with the auditory condition identical to the two written conditions.

On the other hand, *more skilled readers may be particularly influenced by modality, and poorer readers may be relatively immune to these manipulations.* Kamhi and Catts (2012) state that proficient readers rely on visual processing to a greater extent than phonological mediation. That is, individuals with higher reading skills should be more sensitive to the manipulation of the modality in which they learn the nonwords. This suggests that both typical groups (Adult-Typ and children) will demonstrate greater change in accuracy and stability when they are required to read the nonwords. In contrast, the Adult-LP group will demonstrate equal amounts of change or practice effects across conditions, with the auditory condition identical to the two written conditions.

Question #2

The second goal of the current study is to investigate the ways in which specific orthographic characteristics are processed by individuals with various levels of reading skill. This question will be addressed by examining the ways in which the three groups respond to manipulations of orthographic transparency (i.e., transparent versus opaque spellings).

Again, there are two competing hypotheses based on previous literature.

Less skilled readers may be particularly influenced by transparency. It may be the case that poorer readers will be even more disrupted by inconsistencies in orthography and phonology than the groups with better reading skills. Young children with typical development transition from a holistic to a segmental or sublexical processing of spoken language – a transition which is supported by the development of literacy skills. In contrast, individuals who develop reading skills atypically may fail to adequately reorganize their phonological representations (Fowler, 1991), and this difficulty may be exacerbated by the phonological/orthographic inconsistency which is present in the nonword stimuli. Similarly, children who are developing reading skills typically experience a shift towards a more automatic identification of written words (Ventura et al., 2007). Because the nonword stimuli used in the current study are presented with different levels of orthographic transparency, it may be anticipated that typical children should experience a disruption in this automatic identification. Finally, languages containing more transparent orthographic representations may be associated with less severe reading difficulties for both children and adults (Catts & Kamhi, 2005; Jiménez-González & Hernández-Valle, 2000; Kamhi & Catts, 2012; Serrano & Defior, 2008; Ziegler & Goswami, 2005). Thus, individuals with lower levels of reading skill, including children with typical development and adults with reading difficulties, may experience greater facilitative or disruptive effects of orthographic transparency.

On the other hand, *more skilled readers may be particularly influenced by transparency, and poorer readers may be relatively immune to these manipulations.* While all competent speakers demonstrate phonological neighborhood density effects, only competent readers demonstrate orthographic neighborhood density effects (Ziegler et al., 2003; Ziegler & Muneaux, 2007). Similarly, according to Bolger and colleagues (2008), individuals who are more proficient readers are influenced to a greater degree by any phonological/orthographic inconsistency. Thus, it may be expected that the Adult-Typ group will demonstrate greater influences of transparency than the two less-skilled groups.

Measures Used to Quantify Modality and Transparency Effects

To address the above two questions, measures of speech production were applied. These measures index implicit language processing, unlike the meta-linguistic measures which were used in many previous studies. In the current study, there were three dependent variables: segmental accuracy (PCC), segmental variability (TTR), and articulatory stability (LA index). Kinematic measures were used because it is not possible for anyone to consciously apply a strategy to guide his or her motor learning; one cannot make a mindful determination to produce a word with greater articulatory stability. Thus, the kinematic analysis provides an implicit measure of language processing. Furthermore, the fact that a nonword production task was used should contribute to the understanding of this question as it pertains to reading disabilities, as performance on this task relies upon the sublexical representations which are connected to the development of reading skills.

Finally, participants' performance on the dependent measures will provide insight into how the three groups will pattern. It may be that both adult groups will pattern similarly; it may be that both groups of less-skilled readers (i.e., the children and

Adult-LP group) will pattern similarly; or, it may be that all three groups are all different. It might be predicted that typical and clinical groups should demonstrate distinct methods of processing; however, the articulatory stability of the three groups in the current study has not been directly compared.

METHODS

Participants

Approval for this study was granted by the Purdue University Institutional Review Board. Three groups participated: adults with typical levels of reading proficiency (Adult-Typ group), children with developmentally-appropriate levels of reading proficiency, and adults with a history of reading difficulties and low levels of reading proficiency (Adult-LP group). Participants were recruited via advertising throughout the community and contacting disability resource centers at local community colleges and universities. Fifty-two individuals participated in the study, with 17 in the Adult-Typ group, 17 in the child group, and 18 in the Adult-LP group. All participants were native speakers of English; although several studied other languages, everyone indicated that their first and primary language was English, and that their preschool, elementary, and high school educations were conducted in English.

Age and Socio-Economic Status

The Adult-Typ group ranged in age from 19-64 (M = 29.73; SD = 13.16). The Adult-LP group ranged in age from 19-62 (M = 32.82; SD = 13.89). Most of the participants in both adult groups had some college experience, through completed Master's degrees. The Adult-Typ group ranged from completion of some college (socio-economic status [SES] score of 5 on a 7-point scale; Hollingshead, 1975) to the completion of a graduate or professional degree (SES score of 7; *M* = 5.65; *SD* = .79), and the Adult-LP group ranged from completion of the ninth grade (SES score of 2) to the completion of a graduate or professional degree (*M* = 4.94; *SD* = 1.21). Fourteen of the 18 Adult-LP participants had at least some college experience. The results of an ANOVA indicated that the difference in education between these two groups approached significance, $F(1, 33) = 4.09$, $p = .051$, with the Adult-Typ group having more years of education.

Children ranged in age from 6 years old through 8.83 years old (*M* = 7.45; *SD* = .91). Because individuals in the Adult-LP group demonstrated a wide range of reading skills, we chose to recruit children from a relatively wide age span in order to better compare these two groups.

<u>General Summary of Assessment Battery</u>

Reading, oral language, nonverbal reasoning, and hearing were assessed for all participants. Each group was given a slightly different battery of assessments to quantify these skills.

Reading was tested via the *Woodcock Reading Mastery Tests-Revised-Normative Update* (WRMT, Woodcock, 2011), with subtests including word identification, word attack, word comprehension (antonyms, synonyms, and analogies), and passage comprehension. The *Test of Word Reading Efficiency, Second Edition* (TOWRE, Torgesen, Wagner, & Rashotte, 2011), with subtests including sight word reading and decoding, was also used to test reading.

Oral language was evaluated differently for each of the three groups. Oral language assessments included the *Test of Adolescent and Adult Language, Third Edition* (TOAL, Hammill, Brown, Larsen, & Wiederholt, 2011), with subtests including speaking grammar and listening grammar (this test was administered to both adult groups); the *Clinical Evaluation of Language Fundamentals, Fourth Edition* (CELF, Semel, Wiig, & Secord, 2003; this test was administered to the children), with subtests including concepts and following directions, word structure, recalling sentences, and formulating sentences; and the *Peabody Picture Vocabulary Test, Fourth Edition* (PPVT, Dunn & Dunn, 2007; this test was administered to the LP-Adult group). Nonverbal reasoning was assessed via the *Test of Nonverbal Intelligence, Fourth Edition* (TONI, Brown, Sherbenou, & Johnsen, 2010).

Hearing was screened at 25 dB at 500, 1000, 2000, and 4000 Hz. All adults except for six (two Adult-Typ participants and four Adult-LP participants) and all children except for two passed the screening. Of the adults who failed, all responded to the screened frequencies in at least one ear at no higher than 35 dB. Of the children who failed, one responded at 30 dB at 500 Hz in one ear, and the other responded at 35 dB at 4000 Hz in one ear.

Characteristics of Each Group

Reading scores are summarized in Table 2 and oral language and nonverbal reasoning scores in Table 3.

Table 2. Summary of reading standard scores used for inclusionary criteria.

Group	WRMT Word Identification	WRMT Word Attack	WRMT Word Comprehension	WRMT Passage Comprehension
Adult-Typ	104.18 (9.60)	104.29 (11.46)	110.35 (11.47)	111.65 (13.89)
Child	119.35 (6.74)	118.94 (9.00)	118.29 (6.62)	112.41 (7.76)
Adult-LP	88.44 (13.03)	90.89 (9.37)	94.33 (14.15)	96.83 (12.56)

Note. Means (standard deviations) are displayed. Standard scores are reported. WRMT = Woodcock Reading Mastery Tests.

Table 3. Summary of oral language and nonverbal reasoning scores.

Group	TOAL LG	TOAL SG	CELF	PPVT	TONI
Adult-Typ	23.24 (5.93)	19.76 (2.51)	Not tested	Not tested	Not tested
Child	Not tested	Not tested	108.35 (7.96)	Not tested	106.82 (8.86)
Adult-LP	22.61 (7.41)	18.22 (3.56)	Not tested	103.33 (11.54)	94.33 (9.64)

Note. Means (standard deviations) are displayed. Standard scores are reported, except for those tests which are not standardized on readers over age 24; for this reason, raw scores are reported for the two subtests of the TOAL. TOAL = Test of Adolescent and Adult Language. LG = Listening grammar subtest. SG = Speaking grammar subtest. CELF = Clinical Evaluation of Language Fundamentals. PPVT = Peabody Picture Vocabulary Test. TONI = Test of Nonverbal Intelligence.

Participants in the Adult-Typ group received the Woodcock Reading Mastery Tests and the Test of Adolescent and Adult Language. They reported no history of reading or learning difficulties, and their performance on all subtests of the Woodcock Reading Mastery Tests was within normal limits, as defined by a standard score greater than or equal to 85.

Participants in the child group received the Woodcock Reading Mastery Tests, Test of Word Reading Efficiency, Clinical Evaluation of Language Fundamentals, and Test of Nonverbal Intelligence. They had no history of reading or learning difficulties. In addition, their performance on all of the standardized test measures was within normal limits, as defined by a standard score greater than or equal to 85.

Participants in the Adult-LP group received the Woodcock Reading Mastery Tests, Test of Word Reading Efficiency, Test of Adolescent and Adult Language, Peabody Picture Vocabulary Test, and Test of Nonverbal Intelligence. These individuals reported a positive history of dyslexia or other reading difficulties. In addition, these participants either achieved less than a standard score of 85 on one or more subtests of the Woodcock Reading Mastery Tests, and/or demonstrated a significant discrepancy between their reading comprehension skills and their decoding skills. Participants were considered to have this type of discrepancy if their reading comprehension skills (as operationalized by their performance on the Woodcock Reading Mastery Tests word comprehension or passage comprehension subtests) were at least four grade levels above their decoding skills (as operationalized by their performance on the Woodcock Reading Mastery Tests word attack subtest or Test of Word Reading Efficiency decoding subtest). This definition is based on the simple view of reading (Catts, Adlof, & Ellis Weismer, 2006; Gough & Tunmer, 1986; Hoover & Gough, 1990), which states that the act of reading consists of two components: decoding and language comprehension. Individuals with dyslexia typically demonstrate average or above average linguistic comprehension skills, but poor decoding skills (Catts, Kamhi, & Adlof, 2012).

Group Comparisons Based on Behavioral Testing

Post hoc observation of the data revealed that adults in the LP group showed lower nonverbal performance, as measured by standard score on the Test of Nonverbal Intelligence, compared with the children, $F(1, 35) = 9.93$, $p = .003$. Three participants in the Adult-LP group achieved a standard score of less than 85 on the Test of Nonverbal Intelligence. However, because these three generally matched the education level of the rest of the Adult-Typ group (two having had some college experience), and because they provided important information regarding the discrepancy between reading comprehension skills and decoding skills, data from these individuals were included in all analyses.

The two adult groups were similar in their oral language skills, as quantified by their raw scores on the Test of Adolescent and Adult Language, listening grammar subtest, $F(1, 33) = .08$, $p = .79$, and speaking grammar subtest, $F(1, 33) = 2.17$, $p = .15$. Raw scores were used for the Test of Adolescent and Adult Language because this test does not include adults over the age of 24 in its standardization group.

Comparisons on reading measures revealed that each group was significantly different from the other two groups in their raw scores on all of the Woodcock Reading Mastery Tests subtests (word identification, $F(2, 49) = 68.17$, $p < .001$; word attack, $F(2, 49) = 15.55$, $p < .001$; word comprehension, $F(2, 49) = 68.86$, $p < .001$; and passage comprehension, $F(2, 49) = 83.55$, $p < .001$). In every case, the Adult-Typ raw scores were the highest, the child scores were the lowest, and the Adult-LP scores were in the middle. Raw scores (rather than standard scores) were used for these comparisons in order to directly associate the performance of the three groups. In addition, the child and Adult-LP groups differed from each other in their raw scores on both of the Test of Word Reading Efficiency subtests. The Adult-LP group had higher sight word reading scores, $F(1, 33) = 15.13$, $p < .001$, and higher decoding scores, $F(1, 33) = 7.50$, $p = .01$. Raw scores were used for the Test of Word Reading Efficiency because this test does not include adults over the age of 24 in its standardization group. See Tables 4-6 for individual data.

Table 4. Adult-Typ characteristics and behavioral scores for each participant.

Age	SES	WRMT Word Identification, Raw scores	WRMT Word Attack, Raw scores	WRMT Word Comprehension, w-scores	WRMT Passage Comprehension, Raw scores	TOAL Listening, Raw scores	TOAL Speaking, Raw scores
58.25	6	106	44	561	64	31	23
23.00	6	93	39	537	55	24	17
39.92	7	99	43	560	62	34	21
27.33	5	96	39	542	59	22	22
64.25	7	103	38	552	63	16	20
19.50	5	93	31	518	44	18	16
22.42	5	95	32	532	49	17	20
33.92	7	102	29	550	62	21	21
23.83	5	96	38	541	59	21	21
27.92	5	101	38	551	62	33	20
23.33	6	102	38	560	67	25	22
26.08	6	97	37	548	63	23	20
19.25	5	92	37	545	61	25	14
32.83	6	97	40	541	55	21	16
19.67	5	99	39	542	54	28	20
21.67	5	99	39	540	64	12	22
22.17	5	101	39	546	61	24	21
29.73	5.65	98.29	37.65	545.06	59.06	23.24	19.76
(13.16)	(.79)	(3.92)	(3.84)	(10.79)	(5.93)	(5.93)	(2.51)

Note. Age is reported in years. Mean (SD) are reported in the bottom two rows. SES = socioeconomic status, according to the 7-point scale of Hollingshead (1975). WRMT = Woodcock Reading Mastery Tests. TOAL = Test of Adolescent and Adult Language.

Table 5. Child participant characteristics and behavioral scores for each participant.

Age	WRMT Word Identification, Raw scores	WRMT Word Attack, Raw scores	WRMT Word Comprehension, w-scores	WRMT Passage Comprehension, Raw scores	TOWRE Sight Word, Raw scores	TOWRE Decoding, Raw scores	TONI, Raw scores
7.83	58	21	491	27	59	20	28
6.58	48	17	480	26	59	13	27
8.42	65	31	490	30	70	31	23
8.00	67	30	496	37	71	41	24
7.83	56	22	484	25	50	15	19
6.00	33	14	462	15	32	6	19
6.08	21	18	454	14	17	7	15
7.83	63	23	489	29	57	23	26
8.67	68	34	500	32	58	31	34
6.08	18	15	438	8	16	7	14
7.58	61	38	489	33	57	29	32
8.17	63	26	503	29	63	24	25
7.08	72	38	498	32	82	48	28
6.58	37	11	466	16	30	6	15
8.83	74	32	510	47	76	33	23
7.75	62	36	504	33	52	31	28
7.33	56	20	489	27	59	18	36
7.45	54.24	25.06	484.88	27.06	53.41	22.53	24.47
(.91)	(17.06)	(8.79)	(19.40)	(9.48)	(19.19)	(12.65)	(6.52)

Note. Age is reported in years. Mean (SD) are reported in the bottom two rows. SES = socioeconomic status, according to the 7-point scale of Hollingshead (1975). WRMT = Woodcock Reading Mastery Tests. TOWRE = Test of Word Reading Efficiency. CELF = Clinical Evaluation of Language Fundamentals. TONI = Test of Nonverbal Intelligence.

Table 6. Adult-LP characteristics and behavioral scores for each participant.

Age	SES	WRMT Word Identification, Raw scores	WRMT Word Attack, Raw scores	WRMT Word Comprehension, w-scores	WRMT Passage Comprehension, Raw scores	TOWRE Sight Word, Raw scores	TOWRE Decoding, Raw scores	TONI, Raw scores
34.50	7	101	36	555	60	85	43	37
40.17	4	82	31	529	48	66	26	28
21.67	5	90	31	531	60	81	32	44
30.00	5	85	31	525	46	88	44	28
35.08	6	97	36	539	56	99	51	38
21.58	2	81	32	493	40	80	29	19
62.92	6	95	35	532	60	82	42	34
63.67	4	87	17	520	47	63	13	20
28.33	7	91	33	526	52	74	40	44
24.08	5	55	16	496	40	53	7	22
45.42	3	88	36	525	46	60	35	23
23.50	5	89	29	541	49	102	33	44
42.17	5	88	26	533	59	87	35	29
37.05	5	91	34	541	58	34	19	39
20.17	5	89	36	540	55	90	49	27
20.67	5	83	24	526	53	81	30	24
20.08	5	92	31	529	51	84	42	48
19.33	5	93	37	542	64	77	40	42
32.80 (13.89)	4.94 (1.21)	87.61 (9.61)	30.61 (6.24)	529.44 (7.09)	52.44 (7.09)	77.00 (16.66)	33.89 (11.89)	32.78 (9.44)

Table 6 continued. Adult-LP characteristics and behavioral scores continued.

TOAL Listening, Raw scores	TOAL Speaking, Raw scores
30	26
17	14
25	21
15	14
33	16
12	13
19	19
16	20
30	22
10	14
28	19
20	20
28	21
26	19
25	15
23	17
15	16
35	22
22.61	18.22
(7.41)	(3.56)

Note. Age is reported in years. Mean (SD) are reported in the bottom two rows. SES = socioeconomic status, according to the 7-point scale of Hollingshead (1975). WRMT = Woodcock Reading Mastery Tests. TOWRE = Test of Word Reading Efficiency. PPVT = Peabody Picture Vocabulary Test. TONI = Test of Nonverbal Intelligence. TOAL = Test of Adolescent and Adult Language.

Equipment

Three-dimensional kinematic data were collected at 250 samples/second using a three-camera 3D Investigator motion capture system (Northern Digital Inc., Waterloo, Ontario, Canada). Small (6 mm) infrared light emitting diodes (IREDs) were attached with anti-allergenic medical adhesive to each participant's upper lip, lower lip, and a lightweight splint attached to the chin at midline. Five additional IREDs were used to create a three-dimensional head coordinate system in order to subtract head motion artifact, according to the methods of Smith, Johnson, McGillem, and Goffman (2000). A time-locked acoustic signal was collected at 16,000 samples/second to confirm that movement records aligned with target nonword productions. Video recordings were also collected in order to analyze phonetic accuracy.

Procedures and Session Structure

Each of the individuals in the Adult-Typ group participated in one session of approximately 75 minutes. Because of the extra behavioral testing, children and adults in the Adult-LP group participated in one session of approximately 60 minutes and a second session of approximately 90 minutes.

Participants heard six nonwords described as the names of make-believe aliens. Each nonword was associated with a specific illustration of a novel character (Ohala, 1996; Figure 1). Participants listened to each character's name and then said its name in the sentence, "Bob saw a (insert name) before." This carrier sentence, which contains several labial consonants, was used to facilitate kinematic analysis.

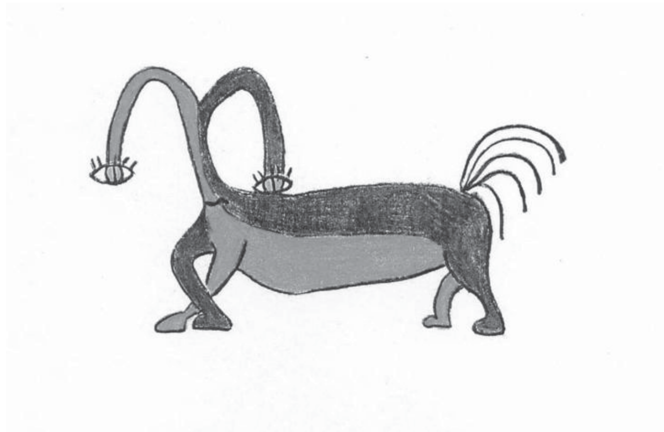

Figure 1. An example of an illustration of one alien.

As shown in Table 7, the task was divided into three conditions: transparent spelling, opaque spelling, and auditory-only presentation. Each condition was further divided into three phases: pretest, learning, and posttest. During the pretest phase, participants heard each nonword multiple times and repeated it in the carrier sentence. Words were each presented ten times in a quasi-random order, with no more than two of the same words occurring consecutively. During the learning phase, participants either read each nonword (in the transparent and opaque spelling conditions) or heard each nonword (in the auditory-only condition, to control for the number of exposures to the stimuli across conditions) and inserted it in the carrier sentence. The posttest phase was identical to the pretest phase. Thus, the learning phases of the written conditions contained the crucial manipulations of the nonword stimuli. Two nonwords were associated with each condition.

Table 7. Session structure: three phases in each of three conditions.

	Auditory only	Transparent spelling	Opaque spelling
Pretest	Hear/repeat	Hear/repeat	Hear/repeat
Learning	Hear/repeat	Read/repeat	Read/repeat
Posttest	Hear/repeat	Hear/repeat	Hear/repeat

Critical comparisons included: (1) how participants responded to manipulations of modality (i.e., as a result of experience with reading or listening to the stimuli); and (2) how participants responded to manipulations of orthographic transparency.

Counterbalancing

The order of conditions, as well as which condition contained which nonwords, were counterbalanced across participants. Within each condition, stimuli were presented in a quasi-random order, with no more than two of the same nonwords occurring consecutively. Three blocked versions of the task were used to counterbalance the order of conditions, as well as which nonwords were associated with each condition. The numbers of participants viewing each version were generally equivalent across groups. Table 8 shows the counterbalancing scheme. Table 9 shows the number of participants in each group who viewed each version of the counterbalancing scheme.

Table 8. Counterbalancing scheme.

Version	First block	Second block	Third block
A	Auditory; pair 1	Transparent; pair 2	Opaque; pair 3
B	Opaque; pair 2	Auditory; pair 3	Transparent; pair 1
C	Transparent; pair 3	Opaque; pair 1	Auditory; pair 2

Table 9. Number of participants in each counterbalancing scheme.

Group	Version A	Version B	Version C
Adult-Typ	6	5	6
Child	6	5	6
Adult-LP	7	6	5

Stimuli

Each target nonword began with a labial consonant to facilitate kinematic analysis. Each nonword was disyllabic (pilot work suggested that a task consisting of exclusively monosyllabic nonwords would not be sufficiently challenging for adults). Each nonword was trochaic, and each syllable followed a consonant-vowel-consonant (CVC) pattern. The first syllable was present only in order to increase the complexity of the nonword, and the second syllable in each nonword was subject to the relevant manipulations. The critical component of the nonword stimuli occurred in the second (i.e., unstressed) syllable for two reasons. First, unstressed syllables may be more susceptible to error and thus may make the task more sensitive to relatively small differences in processing. Second, research indicates that orthographic cues may have a greater impact on processing when they occur at the end of the word (Arciuli & Cupples, 2006); thus, these syllables are predicted to be most sensitive to the orthographic manipulation.

All of the nonword stimuli are listed in Table 10. The first syllables of each nonword were drawn from the list of 120 high-probability nonsense syllables presented by Vitevitch, Luce, Charles-Luce, and Kemmerer (1997). Each nonword's second syllable was constructed based on a pair of homophones with the initial consonant changed. For example, the homophone /pik/ ("*peek/pique*") was changed to /fik/ ("*feek/fique*"); this syllable made up the second syllable of the nonword stimulus /mΛnfik/. The degree of orthographic transparency or opacity was quantified based on the number of orthographic neighbors of each spelling. To continue the above example, the spelling of the nonword /fik/ as "*feek*" has six orthographic neighbors, while the spelling "*fique*" has one orthographic neighbor; thus, "*feek*" is more transparent than "*fique*." The syllable's more transparent spelling (e.g., "*munfeek*") was used in the transparent condition, and its more opaque spelling (e.g., "*munfique*") was used in the opaque condition. Finally, the second syllables in the nonwords were balanced for phonological neighborhood density and phonotactic frequency (specifically, positional segment frequency and biphone probability). These characteristics were calculated using the online Speech and Hearing Lab Neighborhood Database of Washington University in St. Louis (Sommers, 2002).

Table 10. Orthographic characteristics of target nonwords.

Homophone pairs	Transcription	Transparent spelling	Opaque spelling	Number of orthographic neighbors for transparent spelling	Number of orthographic neighbors for opaque spelling
"strait/straight"	/fispet/	*"feespait"*	*"feespaight"*	15	1
"peek/pique"	/mʌnfik/	*"munfeek"*	*"munfique"*	6	1
"ate/eight"	/baɪnvet/	*"binevate"*	*"bineveight"*	12	1
"loot/lute"	/pʌlvut/	*"pulvoot"*	*"pulvute"*	18	9
"cash/cache"	/fʌlvæʃ/	*"fulvash"*	*"fulvache"*	12	2
"side/sighed"	/bispaɪd/	*"beespide"*	*"beespighed"*	13	0

Table 11. Phonological characteristics of target nonwords.

Transcription	Number of phonological neighbors	Positional segment frequency	Biphone probability of medial consonants
/fispet/	34	0.1796	.0081
/mʌnfik/	20	0.1318	.0022
/baɪnvet/	19	0.1176	.0113
/pʌlvut/	26	0.1305	.0015
/fʌlvæʃ/	15	0.1096	.0015
/bispaɪd/	5	0.1566	.0081

Along with the two target nonwords (each repeated ten times), each condition was associated with ten fillers (nonwords which were permissible in English, and which had phonetic characteristics similar to the target words). Fillers were not analyzed, but were included to increase the difficulty of the task. The nonword stimuli used for fillers were either one or three syllables in length, and were created from the list of high probability syllables in Vitevitch and colleagues (1997). The one-syllable filler words were /tʃɅn, sɅʃ, Ɵin, lel, wes/ and /rem/. The three-syllable filler words were /hɅspəvet, gestədʒən, kɅkləfis/ and /rigləsep/.

<u>Details of the Task</u>

A research assistant placed the IREDs on the participant's face and goggles. To become familiar with the task, the participant first viewed a series of PowerPoint slides depicting a boy, a spaceship, and colorful aliens. The participant heard the following script introducing the task; the script was also written, allowing the participant to read and follow along. Adults were told that this script was also being used with children.

> "This is a boy named Bob. Bob is going to ride in a spaceship to visit another planet. On his trip, Bob is going to meet some aliens. All of the aliens have funny names from their planet. You are going to hear the aliens' names, and sometimes, you will see them in writing, too. When you hear an alien's name, say its name in this sentence: 'Bob saw a *(blank)* before.'"

See Figure 2 for an example of a slide from this introductory script.

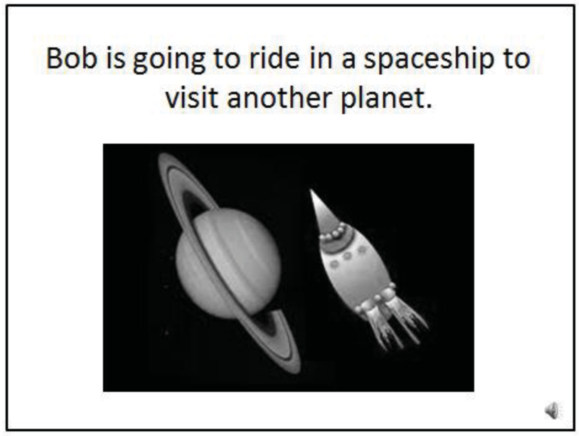

Figure 2. A PowerPoint slide used to introduce the task.

The participant was informed that, for the aliens' names presented in writing, the text would always appear beneath the picture of the alien and would disappear quickly. The auditory and visual stimuli were both presented briefly, so that both would be similarly transient. For the Adult-Typ group, the text disappeared after one second. However, because preliminary data revealed that the other two groups would need more time to read the words, the text disappeared after two seconds for the child and Adult-LP groups. Participants were then given four practice attempts in each modality. Children and adults were given the same instructions. Nonwords which were similar to the ones used in the task were used for the practice items (e.g., /pΛlfod/ and /bispom/). Participants were encouraged to ask questions at any time. Prior to beginning each phase of each condition, the experimenter informed the participant whether he or she would be repeating or reading the nonwords. As new conditions were introduced, the participants were reminded that they would hear two new alien names.

During the task, some online cueing was necessary. Only target words were cued; errors in filler items were ignored. For some errors – notably, those errors which would impede the processing of the kinematic data – the experimenter interrupted the participant to clarify or remind him or her of the correct response, and then encouraged the participant to reattempt the sentence. Three types of cues were used: visual placement cues, semantic cues, and phonological cues (see Table 11 for examples of errors which warranted online cueing). For other errors, the experimenter did not interrupt the participant. Errors which were not cued included the substitution of one labial phoneme for another labial phoneme, vowel errors, and errors for which the participant self-corrected (in which case, only the second, corrected production was analyzed).

Table 12. Examples of errors which warranted online cueing.

Error	Cue	Example
Participant made a placement error on the initial phoneme of the nonword (i.e., substituted a non-labial phoneme, as in "*theespait*" for "*feespait*").	*Placement cue:* Experimenter pointed to her lips to indicate that the phoneme should be a labial.	"That word actually starts with a [f] sound."
Participant used a name other than *Bob* to begin the sentence (frequently, the name *Paul* was substituted for *Bob* for the sentence containing the nonword *"pulvoot"*).	*Semantic cue:* Experimenter reminded the participant of the correct name.	"Remember, the boy's name is *Bob*."
During the reading phase, the participant did not read the nonword correctly.	*Phonological cue:* For the first three attempts of each nonword, the experimenter played the audio to remind him or her of the correct pronunciation. (If the participant continued making errors after hearing the audio three times, cueing was discontinued.)	"Listen to the way the lady on the computer says that word."

Data Processing

The kinematic data were processed in Matlab (The Mathworks, 2009). The sentences were segmented from each trial and then sorted by condition and phase in preparation for measurement. When processing the kinematic data, some productions could not be used. Excluded productions were those which contained extra or missing syllables or phonemes; disfluencies or interruptions in the speech signal (e.g., laughing or pausing); phonemes which differed from the target in place of articulation (i.e., the substitution of non-labial phonemes for labial phonemes); extra, silent opening and closing of the lips; inconsistent use of the article *"a"* (however, if the article was consistently omitted, these productions were analyzed); and/or IREDs which were missing from the cameras' view.

Outcome Variables

Segmental Accuracy

Video and high quality audio recordings were used to transcribe each utterance and determine the percent consonants correct (PCC). The PCC quantifies speech accuracy by measuring the proportion of consonants in each nonword which were produced accurately. PCC was evaluated separately for each phase (pretest and posttest) in each condition (auditory, transparent, and opaque). PCC was calculated for the entire nonword; each nonword contained four consonants. Reliability of phonetic transcription was established by using an independent coder to transcribe 20% of the sessions.

Analyses included both the PCC score as well as the pretest/posttest difference scores. The difference score is a more direct index of within-individual change from the pretest to the posttest. As such, the difference score is particularly relevant to assessing learning as a consequence of orthographic cues.

Segmental Variability

The type-token ratio (TTR) was used to assess the amount of segmental variability produced for each nonword. This analysis can be used to quantify the consistency of participants' productions. That is, some participants made consistent errors (e.g., for the target /mΛnfik/, the error /bΛnfik/ was consistently produced), whereas other participants made many different productions (e.g., for the target /mΛnfik/, the forms /mΛnvet/, /mΛnvik/, /bΛnfik/, and /bΛnvet/ were produced). To calculate the TTR for each participant, every ten attempts of each nonword (i.e., each phase within each condition) were coded as to the number of different productions. Nonwords which were produced with the same segments for all ten attempts were assigned a score of zero. Nonwords which were produced with different segments for all ten attempts were assigned a score of one. Degrees between these extremes were assigned a ratio (e.g., if five different productions were made out of ten attempts, the ratio was .5; see Goffman, Gerken, & Lucchesi, 2007).

Both group and individual effects were calculated for TTR. Group effects were assessed in the same manner as the PCC data above and LA index data below. Individual effects were shown as many participants switched from one extreme to the other when they were able to read the nonwords in the learning phases of the task. For some, the exposure to orthography seemed to help them settle on one pronunciation of a given nonword, even if that pronunciation were incorrect. These individuals experienced a *facilitative effect* of orthography. For others, the exposure to orthography seemed to upset their performance, causing them to grope and to vary the errors which they produced. These individuals experienced a *disruptive effect* of orthography. To explore this difference, in addition to the analysis of the main TTR data, a sign test was conducted. The difference between the pretest phase and the learning phase was analyzed to determine whether participants' productions became more stable or more variable as a consequence of exposure to orthography. Participants were considered to demonstrate a facilitative effect of orthography if their TTR decreased from the pretest to the learning phase; participants were considered to demonstrate a disruptive effect of orthography if their TTR increased from the pretest to the learning phase.

Speech Movement Stability

The lip aperture variability (LA) index is a composite measure of spatial and temporal variability which quantifies the movement of three effectors (upper lip, lower lip, and jaw) as they interact during speech to control oral opening and closing (Smith &

Zelaznik, 2004). The LA index values were evaluated separately for each phase in each condition.

To calculate the LA index, the onsets and offsets of each sentence were extracted based on peak velocity. Movement onsets and offsets were selected by visually inspecting the velocity record for local minima. An algorithm then established the minimum value, determining the point at which velocity crossed zero within a 25-point (100-ms) window of the point selected by the experimenter. The movement trajectories were then linearly time normalized by setting each extracted record to a time base of 1000 points and using a cubic spline to interpolate between points. Amplitude normalization was accomplished by setting the mean to zero and the standard deviation to one. After normalizing the data, the standard deviations were computed at 2% intervals in relative time across the ten records and added together. The sum of the 50 standard deviations is the LA variability index; a higher value reflects greater movement variability (see Goffman 1999; Goffman et al., 2007; Goffman and Smith, 1999; Smith & Goffman, 1998; Smith et al., 1995; Smith & Zelaznik, 2004). Figure 3 illustrates this approach. The top panel represents the raw records. The middle panel represents the time- and amplitude-normalized records. The bottom panel represents the standard deviations used to calculate the LA variability index values.

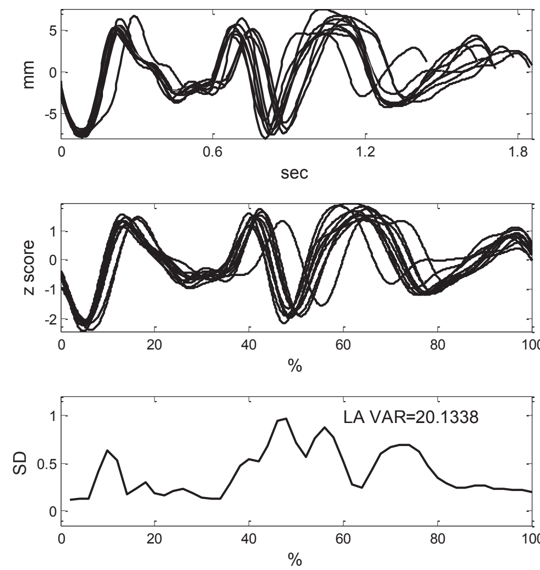

Figure 3. *Examples of extracted movement sequences from the utterance, "Bob saw a /mʌnfik/ before."*

Kinematic analyses were conducted at the sentence level, because effects of language load often appear in multi-movement contexts. Each production was extracted from the /b/ in "Bob" to the /b/ in "before". Analyses included both the LA index values and, as a more direct index of learning, the pretest/posttest difference scores.

Statistical Analyses

All variables were analyzed using a repeated measures analysis of variance (ANOVA). The between-participant factors were group (Adult-Typ, child, and Adult-LP). The within-participant factors were condition (auditory only, transparent spelling, opaque spelling), phase (pretest and posttest), and nonword (first or second nonword). Follow-up ANOVAs were used for pairwise comparisons when effects were present. Because by definition data expressed as proportions are not normally distributed, an arcsin transformation was applied to the PCC and TTR data (Rucker, Schwarzer, Carpenter, & Olkin, 2009). The alpha level was set to .05.

Individual differences were also analyzed. A sign test was conducted for the TTR data to determine in which direction the changes occurred (i.e., whether participants experienced facilitative or disruptive effects of viewing the nonwords' orthography). Linear regression was also used to determine whether a relationship exists between articulatory stability and two highly distinct aspects of reading skill. The first aspect is decoding, as quantified by each participant's performance on the word attack subtest of the Woodcock Reading Mastery Tests. The second, comprehension, assesses a different component of reading and is quantified by performance on the word comprehension subtest of the Woodcock Reading Mastery Tests. For the correlations, the alpha level was changed to 0.025 using a Bonferroni adjustment. This adjustment accounts for the potentially inflated Type I error inherent in conducting multiple correlations on related dependent variables (Tabachnick & Fidell, 2007).

RESULTS

Analytic Issues

Transcription Reliability

An independent coder transcribed 20% of the sessions in order to establish reliability of phonetic transcription. The two coders' transcriptions were in agreement for 98% of the consonants for the Adult-Typ group, 96% for the child group, and 97% for the Adult-LP group.

Missing Data

Data were excluded from kinematic analysis for several reasons, including interruptions in the speech signal (such as laughing, pausing, or producing disfluencies), incomplete or inaccurate sentences (e.g., several participants frequently substituted the name "Paul" for "Bob" when producing the sentence containing the nonword *"pulvoot"*), or a participant silently opening his or her mouth in the middle of the sentence. Productions were also excluded when an IRED was missing from the cameras' view. In these cases, articulatory trajectories could not be extracted from the speech stream.

However, these data were included in the PCC and TTR analyses. Approximately 4% of the kinematic data were excluded from the Adult-Typ group, 16% from the child group, and 8% from the Adult-LP group. In addition, some data were missing from kinematic analysis because the participant did not produce at least five consistent productions for each nonword. For this reason, five participants were missing from the Adult-Typ group; five from the child group; and four from the Adult-LP group. Because missing cells are problematic for ANOVA, this resulted in some participants being excluded from aspects of statistical analysis of the kinematic, but not the PCC or TTR, data.

Dependent Measures

Segmental Accuracy

Because these data are proportions, to avoid ceiling effects, an arcsin transform was applied prior to completing statistical analysis. There was a main effect of group, $F(2, 49) = 24.21$, $p < .001$. Post hoc analysis using Tukey's HSD indicated that all three groups were different, with the Adult-Typ group demonstrating the most accuracy, the child group demonstrating the least accuracy, and the Adult-LP group in the middle, all ps $\leq .05$. There was no main effect of condition, $F(2, 98) = 2.05$, $p = .13$. There was a main effect of phase, $F(1, 49) = 100.14$, $p < .001$, as participants became more accurate from the pretest to the posttest phase. There was no main effect of nonword, $F(1, 49) = .62$, $p = .43$. Phonetic accuracy data are reported on Figure 4.

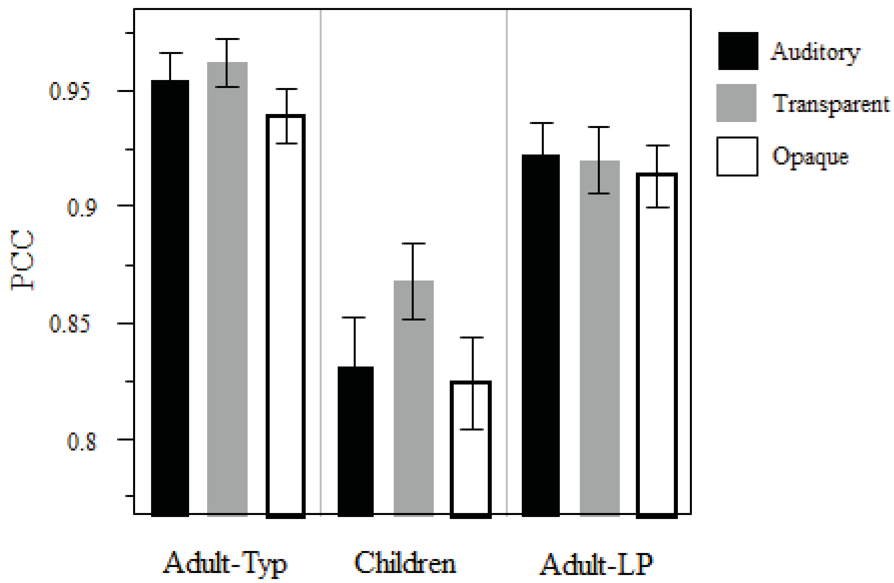

Figure 4. PCC data.

There was an interaction of condition by phase, $F(2, 98) = 13.90$, $p < .001$. To clarify this interaction, follow-up ANOVAs were conducted. These analyses indicated that participants became more accurate from pretest to posttest in the transparent condition, $F(1, 51) = 52.09$, $p < .001$, and the opaque condition, $F(1, 51) = 38.45$, $p < .001$, but not in the auditory condition, $F(1, 51) = 3.60$, $p = .06$ (Figure 5). There were no other interactions, all Fs < 3.82, all ps > .06.

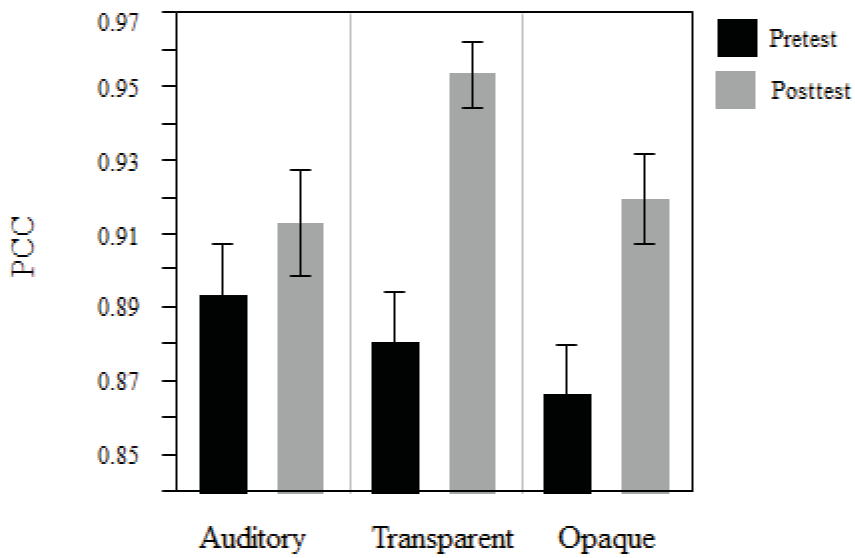

Figure 5. PCC condition by phase interaction.

To directly assess learning, pretest/posttest difference scores for segmental accuracy (PCC) were calculated. There was no main effect of group, $F(2, 49) = 1.37$, $p = .26$. There was a main effect of condition, $F(2, 98) = 7.54$, $p < .001$. Post hoc analyses using Tukey's HSD indicated that participants showed greater difference scores (reflecting increased learning from pretest to posttest) in the two written conditions, both *p*s < .04, as compared to the auditory condition, $p = .41$ (Figure 6). There was no main effect of nonword, $F(1, 49) = .94$, $p = .34$. There were no interactions, all *F*s < 1.70, all *p*s > .16.

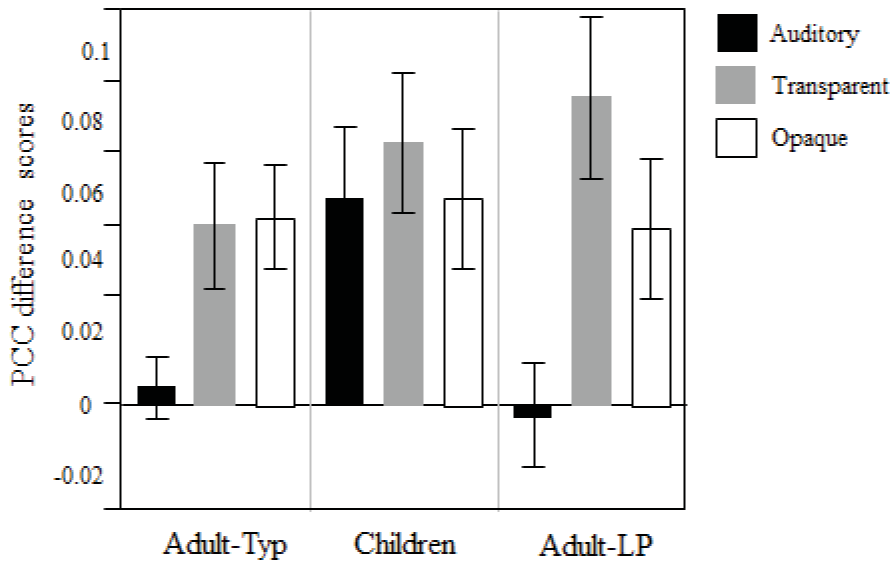

Figure 6. PCC pretest/posttest difference scores.

Segmental Variability

The TTR data were analyzed for both group and individual effects. First, the TTR data were analyzed for group effects after applying the arcsin transform. There was a main effect of group, $F(2, 49) = 25.18$, $p < .001$. Post hoc analysis using Tukey's HSD indicated that all three groups were different, with the typical adult group demonstrating the least variability, the child group demonstrating the most variability, and the low-proficiency adult group in the middle, all *p*s < .02. There was no main effect of condition, $F(2, 98) = 1.05$, $p = .35$. There was a main effect of phase, $F(1, 49) = 69.73$, $p < .001$, as participants' productions became more stable from the pretest to the posttest phase. There was no main effect of nonword, $F(1, 49) = 2.31$, $p = .13$. There was a significant interaction of group by nonword, $F(2, 49) = 3.31$, $p = .04$. There were no other significant interactions, all Fs < 2.44, all ps > .09. Segmental variability data are reported on Figure 7.

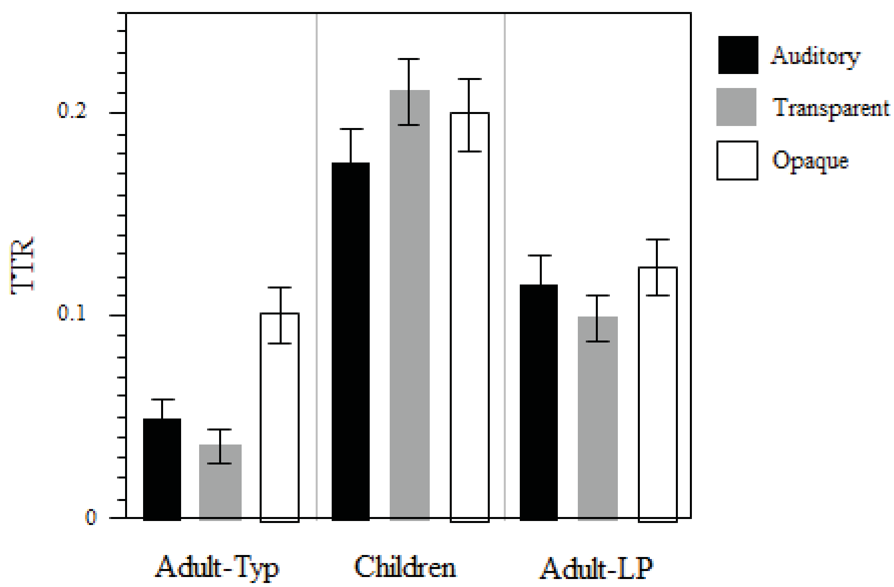

Figure 7. TTR data.

Next, the TTR data were analyzed for individual effects. Some individuals experienced a facilitative effect of orthography, as demonstrated by a decrease in TTR (i.e., the participants' productions became more stable) from the pretest phase to the learning phase. Others experienced a disruptive effect of orthography, as demonstrated by an increase in TTR (i.e., the participants' productions became more variable) from the pretest to the learning phase. Examples of these participants are presented in Table 12.

Table 13. Examples of participants who improved or worsened with exposure to orthography in the transparent spelling condition.

Participant	Target	Productions in pretest phase	Productions in learning phase	Direction of change
Child2	/bɑɪnvet/	/bɑɪnvet/	/bɑɪnvet/ /bΛn/ /bΛnwet/ /bΛti/ /bɪtiv/	Worsened with learning
Child5	/fΛlvæʃ/	/fΛlvæʃ/ /pΛlvæʃ/ /fΛlbæʃ/ /pΛlbæʃ/ /vΛlpæʃ/ /bevæʃ/ /vΛlbəvæʃ/	/fΛlvæʃ/ /fΛlfæʃ/	Improved with learning

To quantify facilitative versus disruptive effects, a descriptive statistic regarding percent change was conducted for the three conditions. The TTR of the two nonwords in the pretest phase within each condition was compared to the TTR of the two nonwords in the learning phase within each condition. See Table 13 for these results.

Table 14. Descriptive statistic for TTR; percent of participants who improved from the pretest to the learning phase.

Group	Auditory	Transparent	Opaque
Adult-Typ	61.54	83.33	66.67
Child	83.33	52.17	40.62
Adult-LP	78.95	73.19	66.67

Speech Movement Stability

For the LA index, there was a main effect of group, $F(2, 35) = 18.19$, $p < .001$. Post-hoc analyses using Tukey's HSD indicated that all three groups were different, with the Adult-Typ group demonstrating the greatest stability, the child group demonstrating the least stability, and the Adult-LP group in the middle, all *p*s < .02. There was no main effect of condition, $F(2, 70) = .66$, $p = .52$. There was a main effect of phase, $F(1, 35) = 24.25$, $p < .001$, as participants became more stable from the pretest to the posttest phase. There was no main effect of nonword, $F(1, 35) = .29$, $p = .60$. There were interactions of group by condition by phase, $F(4, 70) = 2.64$, $p = .04$, and group by condition by word, $F(4, 70) = 3.16$, $p = .02$. There were no other interactions, all *F*s < 2.89, all *p*s > .06. Articulatory stability data are reported on Figure 8.

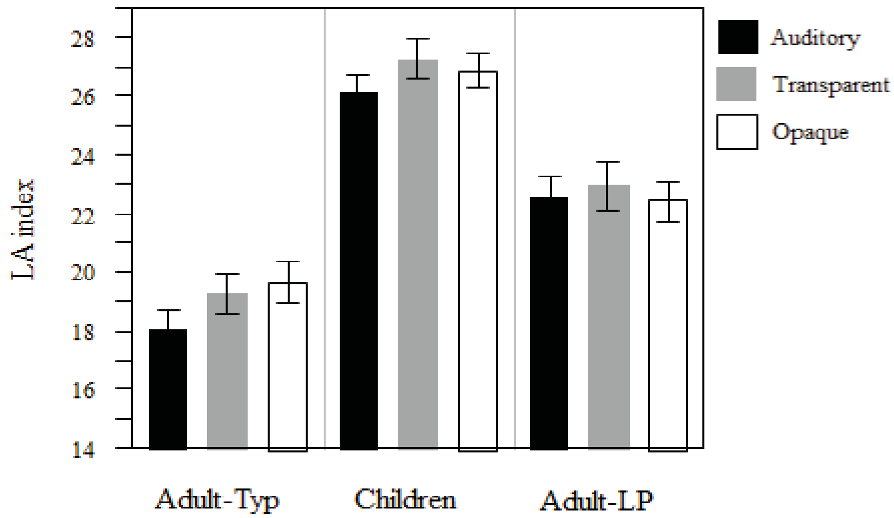

Figure 8. *LA index data.*

Because of the number of missing cells, a follow-up analysis which included all participants was completed. In this case, the LA index values were averaged across the two nonwords within each condition. The results were similar, with a main effect of group, $F(2, 49) = 21.04$, $p < .001$. Again, post-hoc analyses using Tukey's HSD indicated that all three groups were different, with the Adult-Typ group demonstrating the greatest stability, the child group demonstrating the least stability, and the Adult-LP group in the middle, all *p*s < .006. There was no main effect of condition, $F(2, 98) = 1.26$, $p = .29$. There was a main effect of phase, $F(1, 49) = 16.76$, $p < .001$, as participants became more stable from pretest to posttest. There were no interactions, all *F*s < 1.94, all *p*s > .11.

To directly assess learning, pretest/posttest difference scores for the LA index values were calculated. In difference scores, there were no main effects, all *F*s < 1.64, all *p*s > .21. There was an interaction of group by condition, $F(4, 70) = 3.09$, $p = .02$. Follow-up ANOVAs indicated that the Adult-LP group drove this interaction, as there was an effect of condition which approached significance for this group, $F(2, 26) = 3.25$, $p = .055$. Post hoc analysis using Tukey's HSD indicated that for the Adult-LP group, the two written conditions differed from one another, with the transparent condition associated with the greatest positive change and the opaque condition associated with the least change, $p = .04$. In contrast, the articulatory stability of the Adult-Typ group did not change by condition, all *F*s < 2.49, all *p*s > .11, and the articulatory stability of the child group did not change by condition, all *F*s < 2.91, all *p*s > .12. There were no other interactions, all *F*s < 2.36, all *p*s > .10. LA index difference scores are stated in Figure 9.

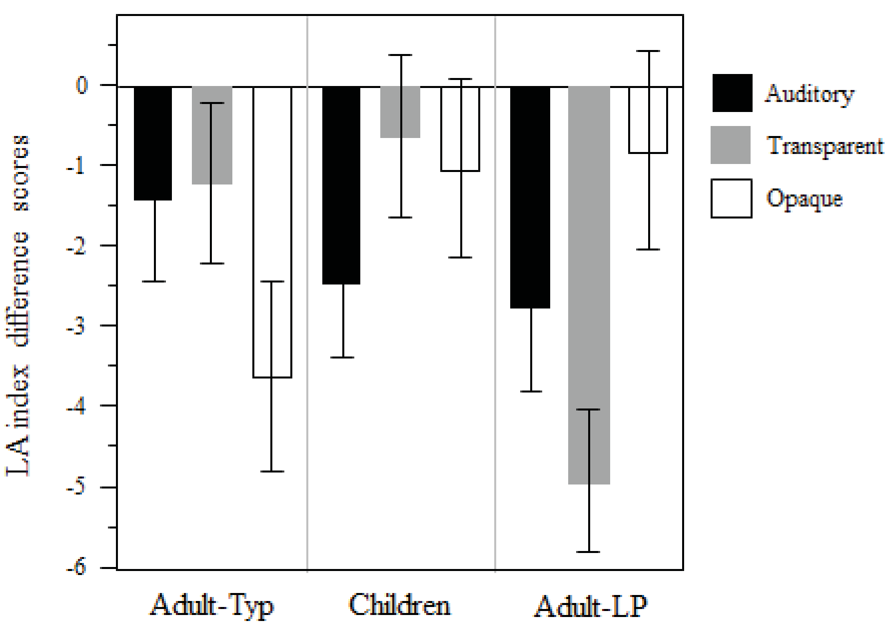

Figure 9. LA index pretest/posttest difference scores.

Relationship between Reading Skills and Performance on the Experimental Task

A linear regression was conducted to determine whether reading skills – specifically, the word attack and word comprehension subtests of the Woodcock Reading Mastery Tests – predicted articulatory stability. It was anticipated that the children's inherently weaker reading skills would drive the results if they were included in the regression; therefore, the regressions were run using only the two adult groups. The regressions indicated that articulatory stability was correlated with both decoding, $F(1, 33) = 8.31$, $p < .01$, $R^2 = .20$ (Figure 10), and comprehension, $F(1, 33) = 7.45$, $p = .01$, $R^2 = .18$ (Figure 11). Given the *p*-value of .025 based on the Bonferroni type adjustment, these results were significant.

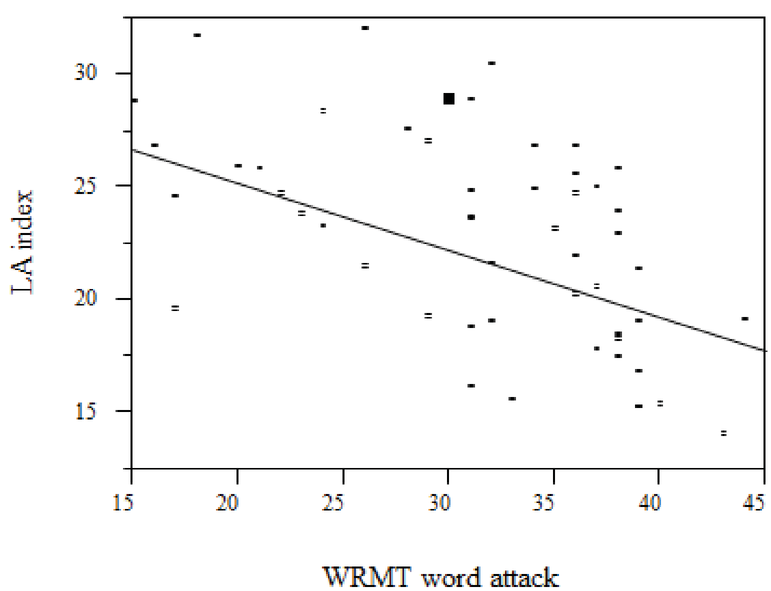

Figure 10. Relationship between articulatory stability and decoding.

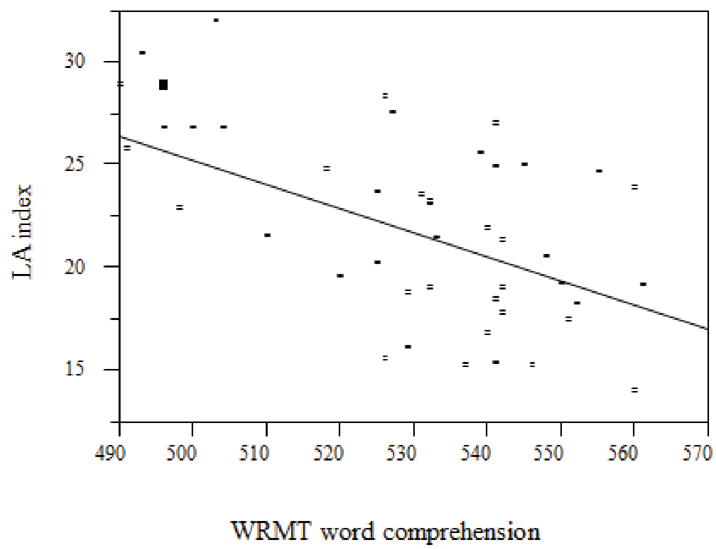

Figure 11. Relationship between articulatory stability and comprehension.

DISCUSSION

The aim of this study was to quantify readers' processing of the orthographic characteristics of nonwords. Participants heard and read aloud nonwords which systematically varied in modality of presentation (auditory and written) and orthographic transparency. Segmental accuracy, segmental variability, and articulatory stability were used to quantify orthographic effects on speech production. Findings indicated that the three groups of participants differed from one another on every dependent measure – a result which was not predicted based on previous studies of adults. Practice effects were apparent throughout the study. The PCC and LA index results revealed that changes occurred to individuals' speech production as the result of exposure to the words in written form and, in the case of the Adult-LP group, as the result of exposure to the transparent orthography. Significantly, these changes were observed in the phase of the task which occurred after the reading phase. This suggests that changes to accuracy and stability occurred as a consequence of exposure to orthography, and persisted after the removal of the written text; these changes did not simply happen in the course of the reading task itself.

While lexical and phonological factors have been extensively studied in speech production, the influence of orthographic factors has not been previously investigated. This study's findings also contribute to the literature as they corroborate and expand upon earlier theoretical accounts of language processing. Specifically, they support the view of reading as an interactive process, the idea that spoken and written language processing are reorganized throughout development, and the theoretical perspective that word- and phonological-level factors and articulatory stability are connected. Below, these results will be interpreted within the context of the groups' responses to the manipulations in the task. The ways in which measures of speech production can index implicit processing will then be discussed. While articulatory stability has previously been used to explore sentence-, word-, and phonological-level effects such as syntactic, semantic and prosodic factors, the current study establishes that this measure can also be used to provide insight into orthographic effects.

Differences in Phonetic and Articulatory Factors Across Groups

On all three dependent measures, the Adult-Typ group demonstrated the best performance, the child group the worst performance, and the Adult-LP group intermediate performance. This indicates that the groups do not cluster in such a way as to relate the two adult groups to one another, or to relate the two typical groups to one another. Rather, the three groups showed distinct performance. Alternatively, these results can be interpreted as representing a continuum of performance which reflects the influences of both typical and atypical development. Both of these explanations speak to group differences which were unexpected in relation to previous studies of adult speakers. In addition, the results of the regression indicated that reading skills were correlated with overall articulatory stability in the two adult groups. This finding further emphasizes that even individuals with typical nonverbal cognition and oral language skills may be separated by reading proficiency.

Particularly surprising was the case of group differences in speech motor stability. The Adult-LP group was globally weaker in articulatory stability. This was true even in the auditory condition, when reading did not play any role in the task. These findings differ from those reported by Chakraborty, Goffman, and Smith (2008), who found that even relatively low proficiency bilingual speakers showed a high degree of consistency in speech motor production in their second language. Their results indicated that when producing sentences in English, speakers with low English proficiency who acquired English as a second language relatively late in life demonstrated LA index values which were similar to those of monolingual English speaking adults. These individuals depended on highly stable motor patterns in their speech production. In contrast, the Adult-LP group in the current study displayed LA index values which were significantly different from those of the two typical groups, despite demonstrating similar oral language functioning. It appears that atypical developmental history, not language proficiency, results in increased articulatory variability.

Modality and Transparency Influence Phonological and Motor Learning

Effects of Modality on Phonological Learning

A central question examined in the current study was how manipulations of modality would influence the three groups of readers. This question is best addressed by the PCC data, which reflect phonological learning. All three groups became more accurate with practice in the two written conditions, but not in the auditory condition. That is, all groups benefited from the addition of written cues, in contrast to auditory cues alone. This verifies that readers of all skill levels respond to manipulations of modality.

Two conflicting hypotheses, both based on empirical data, were proposed in the Introduction. One prediction was that poorer readers would be more influenced by manipulations of modality, because they depend to a greater extent upon the visual characteristics of written words than upon phonological factors (Lavidor, Johnston, & Snowling, 2006). Alternatively, more skilled readers may be more influenced by these manipulations, because they rely upon holistic visual processing to a greater extent than upon phonological mediation (Kamhi & Catts, 2012).

Ultimately, the data obtained in the current study do not support either view, but actually present a third option. In the present study, participants were sensitive to manipulations of modality, as they demonstrated greater accuracy when they were exposed to the nonword stimuli in written form. This was true for adults who were skilled readers, children who were developing reading skills typically, and adults who were poor readers. Thus, even individuals who demonstrated a relatively low level of literacy experienced facilitative effects of the exposure to writing.

It may be the case that all three groups benefited from the presentation of written cues because they were able to use orthography intentionally as a mnemonic device to support phonological learning (which is consistent with the supposition of Alario et al., 2007). Even the individuals with lower reading skills were able to use these cues, perhaps because of two reasons. Meta-linguistic strategies are taught as a component of even the very earliest reading and language arts instruction. In addition, most of the participants in the Adult-LP group had also received language and/or reading intervention as children or adults, which may have strengthened their ability to perform the nonword repetition task. It may be due to these types of instruction that all three groups experienced a facilitative effect of reading the nonword stimuli.

These data support the concept of reading as an interactive process. That is, the reorganization of spoken language processing and the reorganization of written language processing are interrelated. In the current study, PCC practice effects were discovered in the two written conditions, in that participants consistently demonstrated superior performance in the posttest phase as compared to the pretest phase. What is most significant about this finding is that during the posttest phase, participants were no longer able to read the words. Therefore, the discovery of practice effects in the two written conditions indicates that participants must have been able to integrate the nonwords' orthographic factors into their lexical representations. In contrast, participants did not become significantly more accurate from pretest to posttest in the auditory condition. This indicates that practice alone did not advance phonological learning, but that participants' accuracy improved due to the specific experience of reading.

Effects of Transparency on Motor Learning

The next focus of the current study was more specifically about how manipulations of orthographic transparency, as operationalized by neighborhood density, would influence speech production in high and low proficiency readers. This question is best addressed by the LA index data, which reflect motor learning. All three groups became more stable with practice. However, difference scores, which directly assess learning within the experimental task, indicated that the Adult-LP group experienced the greatest positive change in the transparent condition and the least change in the opaque condition. In contrast, the two typical groups became more stable regardless of orthographic transparency. The differences between phonological and motor learning will be explored in depth below.

The effects of orthographic transparency may be interpreted in relation to two competing hypotheses that were proposed and reviewed in the Introduction. In one hypothesis, it was suggested that poorer readers may be more influenced by manipulations of orthographic word-level factors because they experience difficulties in processing sublexical factors in spoken or written language (Fowler, 1991) and in automatically identifying written words (Ventura et al., 2007). In a competing view, more skilled readers may be particularly influenced by these manipulations, because they are more likely to demonstrate orthographic neighborhood density effects (Ziegler et al., 2003; Ziegler & Muneaux, 2007) and to be affected by phonological/orthographic inconsistencies (Bolger et al., 2008).

The data obtained in the current study support the first of these two views. The Adult-LP group demonstrated differences in articulatory stability as an outcome of the manipulation of orthographic transparency. This finding is in accord with the defining characteristics of dyslexia – a language disorder which manifests differently in languages with orthographies of varying depths, in that individuals with reading disabilities are unduly influenced by the transparency of a given writing system (Catts & Kamhi, 2005;

Jiménez-González & Hernández-Valle, 2000; Kamhi & Catts, 2012; Serrano & Defior, 2008; Ziegler & Goswami, 2005). Consistent with this definition, individuals who experienced reading difficulties were more affected by the orthographic transparency of the written stimuli in the current study.

Orthographic neighborhood density did influence poor readers, in that this group became more stable from pretest to posttest (as quantified by difference scores) in their production of higher-density words in contrast to their production of lower-density words. Ziegler and colleagues (2003) found a similar result (i.e., a facilitatory orthographic neighborhood effect) in typical adults, and concluded that this was caused by the consistency of the relationship between phonology and orthography at the sublexical level. Ziegler's paradigm was similar to that of the current study, which involved some stimuli with consistent phonological-orthographic mappings and others with inconsistent mappings. Taken together, the results of both studies indicate that spoken words containing a common (transparent) orthographic structure are processed more efficiently than spoken words with a less common (opaque) orthographic structure (Zeigler et al., 2007). In the current study, only less proficient adult readers were impacted by transparency, suggesting that they apply a unique strategy to the processing of these factors.

These data are also consistent with research which has shown that orthographic representations may be activated by perceiving a word in any modality (Miller & Swick, 2003); that listeners and readers respond to manipulations of a new word's spelling (Damian & Bowers, 2003; Fiez, Balota, Raichle, & Petersen, 1999); and that a word's representation in the mental lexicon includes information about its orthography (Morton, 1969). Like experience with words' phonological and semantic properties in previous studies, the experience of reading in the current study influenced participants' speech output in subsequent productions. It therefore appears that literacy acquisition and speech production skills are related across development. Children reorganize both their spoken and written language processing as a consequence of maturation and instruction. If a child fails to perform this reorganization successfully, there will be a disconnect between his or her phonological representations and the increasing segmentation of his or her lexical representations. Consequently, the child may experience deficits in phonological awareness, and ultimately may develop reading difficulties. The paradigm used in the current study provides a tool with which to begin to explore the ways in which this atypical development proceeds.

These data also speak to the difference in learning styles between children who are developing typically and adults with poor reading skills. If these individuals had used the same strategies, the data would have indicated that these two groups were more similar to each other than to the typical adults. However, all three groups actually performed differently. This provides evidence that adults with low levels of reading skill do not use the same strategies as younger people who are at a relatively low reading level. This finding is crucial to the design of interventions for individuals with reading difficulties. It may not be sufficient to conduct reading instruction which strictly follows the developmental sequence. Rather, individuals who develop reading skills atypically may need interventions which reflect their specific pattern of strengths and weaknesses.

The auditory condition involved nonword repetition – a task which may be especially difficult for individuals with poor reading skills (Munson et al., 2005; Nation

& Hulme, 2011). A nonword repetition task engages the phonological pathway, which develops in concert with literacy skills (Castro-Caldas et al., 1998; Castro-Caldas & Reis, 2003; Pattamadilok et al., 2008). Consequently, the Adult-LP group struggled more, and therefore showed more dramatic improvement, than the typical readers. Similarly, the classic psycholinguistic framework of Coltheart (1978) states that readers may engage the rules of grapheme-phoneme correspondence to read infrequent and regularly-spelled words (*indirect route*), and may bypass the use of these phonological cues to read frequent and irregularly-spelled words (*direct route*). The reading task in the current study introduced participants to nonwords which were spelled either regularly or irregularly; therefore, presumably, participants would have had to access both pathways at some point during their performance of the task. Because the Adult-LP group may have experienced difficulties in accessing either or both routes, their motor learning may have been more disrupted than that of the stronger readers.

In summary, all three groups showed phonological learning related to orthographic manipulations, demonstrating systematic improvements in PCC for the nonwords which they were able to read as opposed to the nonwords which they were only able to hear (even with the same amount of exposure). Crucially, this difference was apparent in the posttest phase – i.e., even when participants were no longer able to read the nonword. These data suggest that phonological learning occurred as a direct result of the reading process, as participants integrated the nonwords' orthography into their mental representations. In contrast, only the Adult-LP group showed differences in motor learning related to orthographic manipulations. This group demonstrated particular improvements in articulatory stability in the transparent condition, whereas the

Adult-Typ and child groups demonstrated this type of improvement with practice, regardless of condition.

The question remains as to why the three groups performed differently in motor learning, but performed similarly in phonological learning. It is therefore crucial to define some differences between phonological learning and motor learning. One important component which varies between these two types of knowledge is the influence of meta-linguistic awareness. That is, meta-linguistic strategies can be applied to aid phonological, but not motor, learning. In the current study, when participants read the nonwords in the learning phase, they could make a conscious decision to use the orthographic cues to improve their phonetic accuracy. Knowing how to spell the nonwords indicated to the participants how they should pronounce them, which minimized any ambiguity related to their auditory presentation. Indeed, some participants explicitly commented that seeing the nonwords made the task easier. In motor learning, however, meta-linguistic strategies do not play a role. One can look at a word and think about how to say it more accurately, but one cannot look at a word and think about how to produce it with greater stability or how to otherwise influence one's articulatory kinematics.

The segmentation hypothesis discussed above also relates to the differences between phonological and motor learning. This hypothesis states that children's processing of spoken language shifts from holistic to segmental methods as they develop vocabulary and language skills (Dodd & McIntosh, 2009; Nittrouer et al., 1989). It may therefore be the case that adults who struggle with reading do not progress beyond the phonological stage in explicit learning. However, the data indicate that they do change in implicit or motor learning. Only fine-grained analyses of implicit learning, such as measures of articulatory stability, are sensitive enough to reveal these subtle changes. These analyses are explored in depth in the following section.

Speech Production Measures Index Implicit Processing

This study employed the production measures of segmental accuracy, segmental variability, and articulatory stability to explore the effects of modality and transparency. Many previous investigations addressing the influences of identical or similar orthographic factors on language processing used meta-linguistic tasks, which speak to an explicit level of processing. Studies examining meta-linguistic skills exclusively may be limited in their application to individuals with reading or language difficulties (Morais et al., 1979; Read et al., 1986). In contrast, this study went beyond the limitations imposed by strictly meta-linguistic tasks in order to target an implicit level of linguistic processing. The use of speech production measures can contribute more subtle and fine-grained analyses of the influences of orthographic factors on language processing. The correlation between articulatory stability and reading skills in the two adult groups further supports this application, as it indicates that changes in the processing of written language may be reflected in individuals' speech production.

The results of the current study indicate that kinematic analyses are effective tools for investigating the impact of orthography on the phonological representations of individuals with varying levels of reading skill. Because the task in the current study involved simply speaking and reading, without the necessity of making conscious judgments (Hoff, 2011; Snow et al., 1998), it is a valuable tool to explore implicit learning, as predicted. This is especially important in investigating populations such as individuals with dyslexia, as well as more broadly in assessing the influence of orthography on speech production (rather than speech perception) – domains which have not been previously explored in depth. Consistent with this goal, the nonword production task was sensitive to individual and group differences in reading skill and to subtle responses to manipulations of modality and orthographic transparency.

The findings of the current study support those of previous investigations which indicate that speech movement stability changes in response to linguistic load (e.g., Goffman et al., 2006, 2007; Heisler et al., 2010; Maner et al., 2000; Wohlert & Smith, 1998). For instance, Saletta and colleagues (in revision) found that sentences containing more complex syntax were produced with greater articulatory variability than sentences containing simpler structures. Goffman and Saletta (in preparation) and Saletta and Goffman (in preparation) found similar results in children with typical development and specific language impairment. Both groups of children demonstrated greater articulatory variability when generating sentences and recalling words (high linguistic load) than when repeating sentences and words (low linguistic load). The current study was similar in structure to these previous works, but focused on the manipulation of orthography as a unique type of linguistic load.

Expanding Upon Previous Models of Language-Motor Interactivity

Researchers (e.g., Hickok, 2012; Smith & Goffman, 2004) have taken the idea of language-motor interactivity a step further by uniting the study of speech motor control with that of higher-level linguistic output. Previous works (such as Abbs, 1986; Barlow & Farley, 1989; Moll, Zimmermann, & Smith, 1977; and Smith, 1992) have applied the principles of the general motor control literature to examine the control and coordination of speech motor output. These studies have focused on lower-level processes including kinematic forces, movement trajectories, and feedback control. Other works (such as Bock, 1995; Levelt, 1989; Levelt, Roelofs, & Meyer, 1999; and Shattuck-Hufnagel, 1987) have examined psycholinguistics, focusing on higher-level linguistic processing as being independent from the motor implementation system.

What is innovative about Smith and Goffman's premise is that they combine the study of motor control with that of linguistic processing. These authors state that low-level physiological events are influenced by the speaker's goals and language skills; similarly, these physiological events have bottom-up influences on higher-level language processing. Indeed, these processes co-develop in both children who are typically and atypically developing. This is demonstrated by studies of infant's babbling, which is thought to begin as a biologically grounded movement pattern initially unrelated to speech, but which later becomes associated with linguistic representations based on culturally mediated cognitive demands (MacNeilage & Davis, 2000). Similarly, children's development of sound production is influenced by both the perceptual salience of the given sound as well as its movement complexity (Green, 2002; Kent, 1992).

One model which is particularly important, but highly discrete in contrast to these findings of interactivity, is that of Levelt (1989; 1999). In this model, processing components and knowledge stores each receive input and produce a certain output – thus, levels are conceptualized as being independent and generally unidirectional. Linguistic levels of processing, including conceptual, lexical (lemma), and grammatical, ultimately result in a phonetic or articulatory plan – the internal representation of how the utterance should be articulated. Finally, the musculature of the respiratory, laryngeal, and supralaryngeal systems executes the phonetic plan.

In Levelt's proposed model, each of the above processing components is relatively autonomous and specialized within the system. This means that only one level can perform a given task; that its mode of operation is minimally affected by the output of other components; and that there is no feedback from lower processors. According to Levelt, one of the only circumstances in which a given component can be affected by information other than its characteristic input involves the influence of executive control on higher levels of processing. This highly controlled processing enables attention to be paid to the many varied components of fluent speech (such as considering alternatives, being reminded of relevant information, etc.).

Smith and Goffman (2004) extended standard and largely unidirectional and serial models to incorporate the direct interactions of the higher processing levels with motor planning and execution. Speaking control processes must operate over different sizes of temporal and spatial units, including speech breathing cycles which occur over many seconds, articulatory movements which continue over several hundred milliseconds, and voicing onset and offset which last tens of milliseconds. Thus, there is not a single level of linguistic processing or a single level of motor planning at the language-motor interface. Furthermore, as speech motor learning develops, the bidirectional influences of both factors change. For example, during babbling, prosodic frames such as fundamental frequency contours and syllables may be the units which shape the motor process. Older children, who are able to produce longer and more complex utterances, experience word- and phrase-level mappings. Finally, over time, highly stable synergies (collectives of muscles including the upper lip, lower lip, and jaw muscles) do not map directly onto a unit, but rather, respond to multiple levels of linguistic processing.

Recent experimental paradigms which manipulate linguistic factors and measure acoustic or speech motor output provide further evidence for this interactivity. For instance, Baese-Berk and Goldrick (2009) measured changes in voice onset time which occurred in the phonetic realization of words as a function of word-specific properties (specifically, whether or not the word had a minimal pair neighbor in the mental lexicon). Goldrick and Blumstein (2006) examined the relationship between phonological planning and articulatory processes by means of a tongue twister paradigm. Participants' speech errors had traces of the intended target, in that the articulatory and acoustic properties of the error – for instance, the realization of [k] for the target /g/ – were different from those produced for a [k] which was the intended target. This provided evidence that partially activated phonological representations of the target influence the articulation of the error. Specifically related to the present study, influences of neighborhood density and phonotactic probability change in concert with children's developing lexicons, indicating that semantic knowledge and segmental variables interact (Hollich, Jusczyk, & Luce, 2002; Storkel, 2001). Adding lexical representation to a novel word, as for example by accompanying the word with a visual referent, causes speech motor stability to change (Heisler et al., 2010). Finally, adding semantic depth to nonwords by embedding them in a story enhances word learning in preschool-aged children (Gladfelter & Goffman, 2013).

The current study extends the language-motor interface to include another level of processing – namely, the influence of words' orthographic characteristics. In reference to Levelt's (1989) model, these findings suggest the addition of the orthographic representation as another processing component. Theoretically, words containing less consistent grapheme-phoneme correspondences may be subjected to an additional "step" in their processing. Opaque representations are thus associated with a less direct relationship between phonology and orthography. More specifically, the neighborhood density of a given word intersects the knowledge store of the lemma/lexicon and the processing component of phonological encoding. This factor thus influences both the preceding and following levels of language processing.

Finally, it is crucial to note that these types of interactivity occur even when they are not strictly necessary for a given task. That is, phonological, semantic, and orthographic representations all impact one another as words are spoken, even if each of these domains do not need to be activated (as for instance, orthography does not need to be activated in a task involving speaking alone). Thus, even if the task does not require the use of semantics or spelling, as was true regarding the nonword repetition task in the current study, orthographic characteristics will still influence speech production and should still be a component of the interactive model.

Individual Differences

When completing the experimental task, some individuals seemed to experience a facilitative effect of orthography, as they became more consistent in their productions of the nonwords when they were able to read them. In contrast, other individuals seemed to experience a disruptive effect of orthography, as they became more variable in their errors when they were required to read the stimuli. High TTR values in the learning phase may indicate that the participant's strategy involves substantial online segmental reorganization.

A descriptive statistic quantified the percent of individuals in each group who improved in TTR (i.e., became less variable in their productions) from the pretest to the learning phase. Results indicated that individuals in each of the three groups used different strategies when exposed to the nonwords' spellings. Over 83% of the Adult-Typ group improved in the transparent condition, but about two-thirds of the participants improved in the other two conditions. Over 83% of the children improved with practice alone (auditory condition), but when exposed to writing in the learning phase, about half of the children improved and half worsened. The Adult-LP group showed the most consistent pattern of the three, as two-thirds or more of the participants improved in all three conditions. Again, these three groups did not pattern similarly; rather, each group applied different strategies. The Adult-Typ group received the most benefit from orthographic transparency. The child group was the most disrupted by exposure to orthography, perhaps because six- to eight-year-old children may still be transitioning from their earlier reliance on spoken phonology when processing and producing new words. The Adult-LP group was the least influenced by modality and transparency.

This is an exploratory analysis which reflects differences in the strategies applied by individuals with varying levels of reading skill. Future studies should examine these differences in greater depth. To this end, it would be informative to perform a more detailed case history and additional behavioral measures than were included in the current study, as this may clarify additional individual differences. For example, it would be helpful to learn which types of reading strategies – and in particular, which types of remedial reading strategies – were taught to an individual. These types of strategies could have included the application of phonics and decoding strategies, as opposed to the identification of whole words. It may be that readers who were not adept at the experimental task did not have the opportunity to practice applying phonetic rules to the learning of new words. Also, looking more specifically at different strategies experimentally – as for instance, specifying to the participant that he or she should try to remember the word as a whole versus trying to sound it out phonetically – may provide insight into which approaches are most helpful to poor readers.

Future Directions

These data point to several outstanding questions. The next step is to examine a fourth group: children with reading disabilities. This would be followed by groups of children who experience language, phonological, and/or motor impairments (either speech motor or limb motor) as well. This type of inquiry is crucial in order to learn more about the developmental course of learning disabilities. Investigating reading disabilities across the lifespan will allow researchers to disambiguate which components of these difficulties have their source in childhood and later resolve, as opposed to other components which become exacerbated and magnified as academic demands increase. What is the origin of the differences between young good and poor readers? How do children approach learning to read if their language development is proceeding atypically? Do children with a language or phonological impairment as preschoolers consistently develop reading impairments? Obviously, this is not always the case; why do these problems persist for some and resolve for others? How do older children who experience reading difficulties develop as a result of intervention or maturation? Does the severity level of the reading impairment remain consistent throughout the lifespan of the individual? The findings of the current study speak to the introduction of more effective methods of intervention for struggling readers. These therapies may emphasize the developmental course by teaching struggling readers in the same sequence as experienced in typical literacy acquisition. Alternatively, future works may support the finding that poor readers do not pattern similarly to younger children. If so, it may be necessary to design interventions which more directly target the specific patterns produced by poor readers.

A second remaining problem is the issue of why the task was so easy for some participants and so difficult for others. Which strategies are used by various individuals, and which of these strategies is the most effective? The current study began to explore this issue by using TTR values to indicate whether participants experienced orthographic facilitation or disruption. High TTR values may indicate that the participant's strategy involves a great deal of online segmental reorganization. However, there may be a host of other approaches used by readers when encountering new words. It is important to note that reading disorders are not unitary. This is evidenced even in the current study by the very different strategies employed by the relatively homogeneous individuals in each group. Multiple factors can lead to reading difficulties, and co-morbid conditions, such as attention deficit disorder or depression, often exist in a given individual. Future work should include a broader range of participants, especially adults who have fewer years of formal education and perhaps lower levels of cognition. Additional participants who fit categories other than strict dyslexia would enable the researcher to examine these factors more carefully.

A third key issue for future studies is to further explore the issue of motor stability versus variability. Traditionally, the kinesiology literature has considered variability to be a negative process. For instance, many researchers have explored quiet stance on a forceplate, measuring changes in the participants' center of pressure or center of mass in the anterior/posterior and medial/lateral planes. In these cases, increased sway was thought to represent postural instability, while decreased sway was thought to be indicative of greater stability (Woollacott, Shumway-Cook, & Nashner, 1986).

However, it is possible that increased variability may actually be an adaptive process. In conditions of learning, such as a child's system developing, or an adult's system changing due to healthy aging or pathological changes to his or her neuromuscular system, motor variability can act as a crutch. One example involves the differences in infants' reaching trajectories, which according to Thelen and colleagues (1993) are evidence for flexibility and learning. As another example, Waddington and

Adams (2003) discovered that wearing textured insoles improved soccer players' ability to discriminate ankle inversion, thus potentially diminishing the risk of lower limb injury. From this paradigm, Davids, Shuttleworth, Button, Renshaw, and Glazier (2003) make the case that the presence of noise (i.e., variability of motor output) is essential for individuals to adapt to dynamic environments. Returning to the quiet stance paradigm described above, increased sway may actually mean that the individual is more adaptable and better able to overcome perturbations to his or her balance. While viewing motor variability as an adaptive process may be more intuitive than applying this concept to speech variability, it is important to note that increased variability in speech production is not always a function of a disordered system. Rather, this type of variability may actually aid developing speech and language learners in finding the optimal production patterns. Perhaps participants' speech movements became more variable when they were exposed to orthography because they were reorganizing their representations of the nonword and learning how to best integrate this new information.

A fourth factor which may be emphasized in future works is to examine other aspects of reading in addition to decoding. For instance, individuals' reading comprehension, awareness of text macrostructure, and use of contextual cues are all important components of being a successful reader. Longer strings of read words may be used to increase cognitive load. The interactions of various word-level components, including semantics and orthographic characteristics, could be further explored from the perspective of these other aspects of reading. For instance, previous studies have investigated the impact of introducing new words in semantically rich versus semantically sparse contexts (Gladfelter & Goffman, 2013; Heisler et al., 2010). The same paradigm could be applied to investigations of reading, in two main ways. First, researchers could attempt to understand the best ways of teaching reading. Researchers could quantify learning by an increase (or perhaps decrease, as explored above regarding the complexities of variability) in articulatory stability, as in the current study, or they could use other measures such as better memory for read text or increased reading fluency. Second, researchers could attempt to understand the best ways of teaching new words. Is it more helpful to present words within a meaningful narrative or in isolation? The above model which probes semantically rich versus semantically sparse contexts may be adapted to probe orthographically rich versus orthographically sparse contexts. That is, introducing new words in writing, in addition to (or, instead of) verbally or in pictures, may support word learning in typical and clinical populations. Furthermore, it is important to compare the potentially facilitative effects of reading aloud versus reading silently, or performing a combination of reading, listening, and repeating, as in reading along with a speaker.

Conclusions

This study provides an important contribution to our knowledge of the relationship between modality, orthographic transparency, and language production. Fine-grained analyses, including measures of segmental accuracy, segmental variability, and articulatory stability, allow researchers to quantify implicit linguistic processing. The findings of this study indicate that modality and transparency impact speech accuracy and efficiency, and that these effects vary according to reading skill. Exposure to the orthographic representations of new words alters speakers' and readers' phonological representations and, consequently, their speech production. These data support models of speech production which emphasize interactivity between a word's lexical, phonological, and orthographic characteristics. This work represents an important first step in designing and improving methods of identification and intervention for children and adults who experience reading difficulties.

LIST OF REFERENCES

LIST OF REFERENCES

Abbs, J. H. (1986) Invariance and variability in speech production: A distinction between linguistic intent and its neuromotor implementation. In J. Perkell & D. Klat (Eds.), *Invariance and variability in speech processes* (pp. 202-225). Mahwah, NJ: Lawrence Erlbaum.

Adams, M. J. (1990). *Beginning to read: Thinking and learning about print*. Cambridge, MA: MIT Press.

Alario, F. X., Perre, L., Castel, C., & Ziegler, J. C. (2007). The role of orthography in speech production revisited. *Cognition, 102,* 464-475. doi: 10.1016/j.cognition.2006.02.002.

Arciuli, J., & Cupples, L. (2006). The processing of lexical stress during visual word recognition: Typicality effects and orthographic correlates. *Quarterly Journal of Experimental Psychology, 59*(5), 920–948.

Atteveldt, N. V., Formisano, E., Goebel, R., & Blomert, L. (2004). Integration of letters and speech sounds in the human brain. *Neuron, 43*, 271-282.

Augur, J. (1985). Guidelines for teachers, parents, and learners. In M. J. Snowling (Ed.), *Children's Written Language Difficulties* (p. 147). Slough, United Kingdom: NFER-Nelson.

Bailey, T., & Hahn, U. (2001). Determinants of wordlikeness: Phonotactics or lexical neighborhoods. *Journal of Memory and Language, 44*, 568-591.

Bapi, R. S., Miyapuram, K. P., Graydon, F. X., & Doya, K. (2006). fMRI investigation of cortical and subcortical networks in the learning of abstract and effector-specific representations of motor sequences. *Neuroimage, 32*, 714-727.

Barlow, S. M., & Farley, G. R. (1989). Neurophysiology of speech. In D. P. Kuehn, M. L. Lemme, & J. M. Baumgartner (Eds.) *Neural Bases of speech, hearing, and language* (pp. 146-200). Boston: College Hill Press.

Barton, D. (1992). The emergence of sounds: Parallels between learning to read and learning to speak. In C. A. Ferguson, L. Menn, & C. Stoel-Gammon (Eds.), *Phonological development: Models, research, implications* (pp. 539-552). Timonium, MD: York Press.

Baese-Berk, M., & Goldrick, M. (2009). Mechanisms of interaction in speech production. *Language and Cognitive Processes, 24*, 527-554.

Baumgaertner, A., Buccino, G., Lange, R., McNamara, A., & Binkofski, F. (2007). Polymodal conceptual processing of human biological actions in the left inferior frontal lobe. *European Journal of Neuroscience*, *25*(3), 881-889. doi:10.1111/j.1460-9568.2007.05346.x.

Benton, A. L. (1978). Some conclusions about dyslexia. In A. L. Benton & D. Pearl (Eds.), *Dyslexia: An appraisal of current knowledge* (p. 451). Oxford: Oxford University Press.

Bischoff-Grethe, A., Goedert, K. M., Willingham, D. T., & Grafton, S. T. (2004). Neural substrates of response-based sequence learning using fMRI. *Journal of Cognitive Neuroscience, 16*, 127-138.

Bishop, D. V. M., & Snowling, M. J. (2004). Developmental dyslexia and specific language impairment: Same or different? *Psychological Bulletin, 130*(6), 858-886. doi: 10.1037/0033-2909.130.6.858.

Blumstein, S. E., & Stevens, K. N. (1980). Perceptual invariance and onset spectra for stop consonants in different vowel environments. *Journal of the Acoustical Society of America, 67*, 648-662.

Bock, K. (1995). Sentence production: From mind to mouth. In J. L. Miller & P. D. Eimas (Eds.), *Speech, Language, and Communication: Handbook of Perception and Cognition, Second edition* (pp. 191-216). San Diego, CA: Academic Press.

Bolger, D. J., Hornickel, J., Cone, N. E., Burman, D. D., & Booth, J. R. (2008). Neural correlates of orthographic and phonological consistency effects in children. *Human Brain Mapping, 29*, 1416-1429. doi: 10.1002/hbm.20476.

Borgwaldt, S. R., Hellwig, F. M., & de Groot, A. M. B. (2004). Word-initial entropy in five languages. *Written Language and Literacy, 7*(2), 165-184.

Browman, C. P., & Goldstein, L. M. (1986). Towards an articulatory phonology. *Phonology Yearbook, 3,* 219-252.

Bruck, M. (1990). Word-recognition skills of adults with childhood diagnose of dyslexia. *Developmental Psychology, 26*(3), 439-454.

Brown, L., Sherbenou, R. J., & Johnsen, S. K. (2010). *Test of Nonverbal Intelligence, Fourth Edition*. Austin, TX: Pro-Ed.

Buccino, G., Binkofski, F., Fink, G. R., Fadiga, L., Fogassi, L., Gallese, V., et al. (2001). Action observation activates premotor and parietal areas in a somatotopic manner: An fMRI study. *European Journal of Neuroscience, 13*(2), 400-404.

Buccino, G., Binkofski, F., & Riggio, L. (2004). The mirror neuron system and action recognition. *Brain and Language, 89*(2), 370-376.

Burns, M. S., & Fahy, J. (2010). Broca's area: Rethinking classical concepts from a neuroscience perspective. *Topics in Stroke Rehabilitation*, *17*(6), 401-410. doi:10.1310/tsr1706-401.

Castro-Caldas, A., Petersson, K. M., Reis, A., Stone-Elander, S., & Ingvar, M. (1998). The illiterate brain: Learning to read and write during childhood influences the functional organization of the adult brain. *Brain, 121*, 1053-1063. doi:10.1093/brain/121.6.1053.

Castro-Caldas, A., & Reis, A. (2003). The knowledge of orthography is a revolution in the brain. *Reading and Writing*, *16*(1-2), 81-97. doi: 10.1023/A:1021798106794.

Catts, H. W., Adlof, S. M., & Ellis Weismer, S. (2006). Language deficits in poor comprehenders: A case for the simple view of reading. *Journal of Speech, Language, and Hearing Research, 49*, 278-293. doi: 1092-4388/06/4902-0278.

Catts, H. W., Adlof, S. M., Hogan, T. P., & Weismer, S. E. (2005). Are specific language impairment and dyslexia distinct disorders? *Journal of Speech, Language, and Hearing Research, 48*, 1378-1396. doi: 1092-4388/05/4806-1378.

Catts, H. W., &Kamhi, A. G. (2005). Classification of reading disabilities. In H. W. Catts & A. G. Kamhi (Eds.), *Language and reading disabilities, Second edition* (pp. 72-79). Boston, MA: Pearson.

Catts, H. W., Kamhi, A. G., & Adlof, S. M. (2012). Defining and classifying reading disabilities. In H. W. Catts & A. G. Kamhi (Eds.), *Language and reading disabilities, Second edition* (pp. 45-76). Boston, MA: Pearson.

Chakraborty, R., Goffman, L., & Smith, A. (2008). Physiological indices of bilingualism: Oral-motor coordination and speech rate in Bengali-English speakers. *Journal of Speech, Language, and Hearing Research, 51,* 321-332.

Clerget, E., Poncin, W., Fadiga, L., & Olivier, E. (2012). Role of Broca's area in implicit motor skill learning: Evidence from continuous theta-burst magnetic stimulation. *Journal of Cognitive Neuroscience*, *24*(1), 80-92. doi:10.1162/jocn_a_00108.

Coltheart, M. (1978). Lexical access in simple reading tasks. In G. Underwood (Ed.), *Strategies of information processing* (pp. 151-216). New York: Academic Press.

Coltheart, M., Davelaar, E., Jonasson, J. T., &Besner, D. (1977). Access to the internal lexicon. In S. Dornic (Ed.), *Attention and performance IV* (pp. 535-555). Hillsdale, NJ: Erlbaum.

Damian, M., & Bowers, J. (2003). Effects of orthography on speech production in a form-preparation paradigm. *Journal of Memory and Language*, *49*(1), 119-132. doi:10.1016/S0749-596X(03)00008-1.

Davids, K., Shuttleworth, R., Button, C., Renshaw, I., & Glazier, P. (2003). “Essential noise” – Enhancing variability of informational constraints benefits movement control: A comment on Waddington and Adams (2003). *British Journal of Sports Medicine, 38*, 601-605.

Davis, C. J., Perea, M., &Acha, J. (2009). Re(de)fining the orthographic neighborhood: The role of addition and deletion neighbors in lexical decision and reading. *Journal of Experimental Psychology: Human Perception and Performance, 35*(5), 1550-1570. doi: 10.1037/a0014253.

Diamond, A. (2000). Close interrelation of motor development and cognitive development and of the cerebellum and prefrontal cortex. *Child Development, 71*(1), 44-56. doi: 0009-3920/2000/7101-0006.

Dodd, B., & McIntosh, B. (2009). Two-year-old phonology: Impact of input, motor, and cognitive abilities on development. *Journal of Child Language, 37*(5), 1027-1046. doi:10.1017/S0305000909990171.

Dowling, W. J. (1993). Procedural and declarative knowledge in music cognition and education. In T. J. Tighe & W. J. Dowling (Eds.), *Psychology and music: The understanding of melody and rhythm* (p. 5-18). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Dunn, L. M., & Dunn, D. M. (2007). *Peabody Picture Vocabulary Test, Fourth Edition.* San Antonio, TX: Pearson.

Eckert, M. A., Leonard, C. M., Richards, T. L., Aylward, E. H., Thomson, J., & Berninger, V. W. (2003). Anatomical correlates of dyslexia: Frontal and cerebellar findings. *Brain, 126*(2), 482-494.

Ehri, L. C. (1991). Development of the ability to read words. In R. Barr, M. Kamil, P Mosenthal, & P. Pearson (Eds.), *Handbook of reading research, Volume II* (pp. 1-417). White Plains NY: Longman.

Ehri, L. C., &Wilce, L. S. (1980). The influence of orthography on readers' conceptualization of the phonemic structure of words. *Applied Psycholinguistics, 1,* 371-385.

Fawcett, A. J., Nicolson, R. I., & Dean, P. (1996). Impaired performance of children with dyslexia on a range of cerebellar tasks. *Annals of Dyslexia, 46*, 259-283.

Ferguson, C. A., & Farwell, C. B. (1975). Words and sounds in early language acquisition. *Language, 51*, 419-439.

Fiez, J. A., Balota, D. A., Raichle, M. E., & Petersen, S. E. (1999). Effects of lexicality, frequency, and spelling-to-sound consistency on the functional anatomy of reading. *Neuron, 24*, 205-218.

Frith, U. (1995). Beneath the surface of developmental dyslexia. In K. Patterson, J. Marshall, & M. Coltheart (Eds.), *Surface dyslexia* (pp. 1-30). London: Erlbaum.

Frith, U. (1998). Editorial: Literally changing the brain. *Brain, 121*, 1051-1052.

Floel, A., Ellger, T., Breitenstein, C., & Knecht, S. (2003). Language perception activates the hand motor cortex: Implications for motor theories of speech perception. *European Journal of Neuroscience, 18*(3), 704-708.

Fowler, A. E. (1991). How early phonological development might set the stage for phoneme awareness. In S. Brady & D. Shankweiler (Eds.), *Phonological processes in literacy: A tribute to Isabelle Y. Liberman.* (pp. 97-117). Hillsdale, NJ: Lawrence Erlbaum Associates.

Frisch, S. A., Large, N. R., & Pisoni, D. B. (2000). Perception of wordlikeness: Effects of segment probability and length on processing of non-word sound patterns. *Journal of Memory and Language, 42*, 481-496.

Gladfelter, A., & Goffman, L. (2013). The influence of prosodic stress patterns and semantic depth on novel word learning in typically developing children. *Language Learning and Development, 9*, 151-174. doi: 10.1080/15475441.2012.684574.

Goffman, L., Gerken, L., &Lucchesi, J. (2007). Relations between segmental and motor variability in prosodically complex nonword sequences. *Journal of Speech, Language, and Hearing Research, 50,* 444-458. doi:10.1044/1092-4388(2007/031).

Goffman, L., Heisler, L. & Chakraborty, R. (2006). Mapping of prosodic structure onto words and phrases in children's and adults' speech production. *Language and Cognitive Processes, 21*(1), 25-47.

Goffman, L., & Saletta, M. (In preparation). *Picture naming and word repetition influence speech production processes in children with SLI.*

Goffman, L., & Smith, A. (1999). Development and phonetic differentiation of speech movement patterns. *Journal of Experimental Psychology, 25*(3), 649-660. doi: 0096-1523/99/S3.00.

Goffman, L., Smith, A., Heisler, L. & Ho, M. (2008). The breadth of coarticulatory units in children and adults. *Journal of Speech, Language, and Hearing Research, 51*, 1424-1437. doi: 1092-4388/08/5106-1424.

Goldrick, M., Baker, H. R., Murphy, A., & Baese-Berk, M. (2011). Interaction and representational integration: Evidence from speech errors. *Cognition, 121*, 58-72. doi:10.1016/j.cognition.2011.05.006.

Goldrick, M., & Blumstein, S.E. (2006). Cascading activation from phonological planning to articulatory processes: evidence from tongue twisters. *Language and Cognitive Processes, 21*, 649-683.

Gough, P., & Turner, W. (1986). Decoding, reading, and reading disability. *Remedial and Special Education, 7*, 6-10.

Grainger, J., Diependaele, K., Spinelli, E., Ferrand, L., & Farioli, F. (2003). Masked repetition and phonological priming within and across modalities. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 29*(6), 1256-1269.

Grainger, J., &Ferrand, L. (1994). Phonology and orthography in visual word recognition and naming: Effects of masked homophone primes. *Journal of Memory and Language, 33*, 218-233.

Grainger, J., Muneaux, M., Farioli, F., & Ziegler, J. C. (2005). Effects of phonological and orthographic neighbourhood density interact in visual word recognition. *Quarterly Journal of Experimental Psychology, 58A*, 981-998.

Green, J. R., More, C. A., & Reilly, K. J. (2002). The sequential development of jaw and lip control for speech. *Journal of Speech, Language, and Hearing Research, 45*, 66-79.

Hammill, D. D., Brown, V. L., Larsen, S. C., &Wiederholt, J. L. (2011). *Test of adolescent and adult language (Third edition).* San Antonio, TX: Pearson.

Haslum, M. (1989). Predictors of dyslexia? *Irish Journal of Psychology, 10*, 622-630.

Hay, J., Pierrehumbert, J., & Beckman, M. (2004). Speech perception, well-formedness, and the statistics of the lexicon. In J. Local, R. Ogden, & R. Temple (Eds.), *Papers in laboratory phonology VI* (pp. 58-74). Cambridge, U.K.: Cambridge University Press.

Heisler, L., Goffman, L., & Younger, B. (2010). Lexical and articulatory interactions in children's language production. *Developmental Science, 13*(5), 722-730. doi: 10.1111/j.1467-7687.2009.00930.x.

Hickok, G. (2012). Computational neuroanatomy of speech production. *Nature Reviews Neuroscience,* Advanced Online Publication. doi: 10.1038/nrn3158.

Hoff, E. (2011). *Language development.* Belmont, CA: Wadsworth.

Hollich, G., Jusczyk, P., & Luce, P. (2002). Lexical neighborhood effects in 17-month-old word learning. *Proceedings of the 26th Annual Boston University Conference on Language Development* (pp. 314-323). Boston, MA: Cascadilla Press.

Hollingshead, A. B. (1975). *Four Factor Index of Social Status.* Unpublished manuscript, Yale University, Department of Sociology, New Haven, CT.

Hoover, W. A., & Gough, P. B. (1990). The simple view of reading. *Reading and Writing, 2*, 127-160.

Hoover, J. R., Storkel, H. L., & Hogan, T. P. (2010). A cross-sectional comparison of the effects of phonotactic probability and neighborhood density on word learning by preschool children. *Journal of Memory and Language, 63*, 100-116. doi:10.1016/j.jml.2010.02.003.

Ingram, D. (1976). *Phonological disability in children*. London: Cole and Whurr.

Ivry, R.B., & Keele, S.W. (1989). Timing functions of the cerebellum. *Journal of Cognitive Neuroscience, 1*, 136-152.

Jacobs, A. M., & Grainger, J. (1994). Models of visual word recognition: Sampling the state of the art. *Journal of Experimental Psychology, Human Perception and Performance, 20*(6), 1311-1334.

James, K. (2010). Sensori-motor experience leads to changes in visual processing in the developing brain. *Developmental Science*, *13*(2), 279-288. doi:10.1111/j.1467-7687.2009.00883.x.

James, K.H., & Atwood, T.P. (2009). Active motor experience changes neural activation patterns to letter-like symbols. *Cognitive Neuropsychology, 26*, 91-110.

James, K.H., & Gauthier, I. (2006). Letter processing automatically recruits a sensori-motor network. *Neuropsychologia, 44*, 2937-2949.

James, K.H., James, T.W., Jobard, G., Wong, C.N., & Gauthier, I. (2005). Letter processing in the visual system: Different activation patterns for single letters and strings. *Cognitive, Affective and Behavioral Neuroscience, 5*, 452-466.

Jancke, L., Siegenthalaer, T., Preis, S., &Stienmetz, H. (2007). Decreased white-matter density in a left-sided fronto-temporal network in children with developmental language disorder: Evidence for anatomical anomalies in a motor-language network. *Brain and Language, 102*, 91-98. doi: 10.1016/j.bandl.2006.08.003.

Jiménez González, J. E., & Hernández-Valle, I. (2000). Word identification and reading disorders in the Spanish language. *Journal of Learning Disabilities, 33*(1), 44-60.

Johnson, E. P., Pennington, B. F., Lowenstein, J. H., & Nittrouer, S. (2011). Sensitivity to structure in the speech signal by children with speech sound disorder and reading disability. *Journal of Communication Disorders, 44*, 294-314. doi: 10.1016/j.jcomdis.2011.01.001.

Jones, A. C., Folk, J., R., & Rapp, B. (2009). All letters are not equal: Subgraphemic texture in orthographic working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35*(6), 1389-1402. doi: 10.1037/a0017042.

Kamhi, A. G., & Catts, H. W. (2012). Language and reading: Convergences and divergences. In A. G. Kamhi & H. W. Catts (Eds.), *Language and Reading Disabilities, Third Edition* (pp. 1-23). Boston, MA: Pearson.

Kamhi, A. G., & Catts, H. W. (2012). Reading development. In A. G. Kamhi & H. W. Catts (Eds.), *Language and Reading Disabilities, Third Edition* (pp. 24-44). Boston, MA: Pearson.

Kent, R. (1992). The biology of phonological development. In C. A. Ferguson, L. Menn, & C. Stoel-Gammon (Eds.), *Phonological development: Models, research, implications* (pp. 65-90). Timonium, MD: York Press.

Koechlin, E., & Jubault, T. (2006). Broca's area and the hierarchical organization of human behavior. *Neuron, 50*, 963-74.

Lavidor, M., Johnston, R., &Snowling, M. J. (2006). When phonology fails: Orthographic neighbourhood effects in dyslexia. *Brain and Language, 96*, 318-329. doi:10.1016/j.bandl.2005.06.009.

Leonard, L. B. (1998). *Children with specific language impairment*. Cambridge, MA: MIT Press.

Levelt, W. J. M. (1989). *Speaking: From intention to articulation*. Cambridge, MA: The MIT Press.

Levelt, W. J. M., Roelofs, A., & Meyer, A. S. (1999a). A theory of lexical access in speech production. *Behavioral and Brain Sciences, 22*, 1-75.

Levelt, W. J. M., Roelofs, A., & Meyer, A. S. (1999b). The time course of lexical access in speech production: A study of picture naming. *Psychological Review, 98*, 122-142.

Luce, P. A., & Pisoni, D. B. (1998). Recognizing spoken words: The neighborhood activation model. *Ear and Hearing, 19*, 1-36.

Lyon, G. R., Shaywitz, S. E., & Shaywitz, B. A. (2003). Defining dyslexia, comorbidity, teachers' knowledge of language and reading. *Annals of Dyslexia, 53*, 1-14. doi: 0736-9387.

MacNeilage, P. F., & Davis, B. D. (2000). On the origin of internal structure of word forms. *Science, 288*(5465), 527-532. doi: 0036-8075.

Maner, K. J., Smith, A., & Grayson, L. (2000). Influences of utterance length and complexity on speech motor performance in children and adults. *Journal of Speech, Language, and Hearing Research, 43*, 560-573. doi: 1092-4388/00/4302-0560.

Masonheimer, P., Drum, P., & Ehri, L. (1984). Does environmental print identification lead children into word learning? *Journal of Reading Behavior, 16*, 257-271.

McMillen, C. T., Corley, M., & Lickley, R. J. (2009). Articulatory evidence for feedback and competition in speech production. *Language and Cognitive Processes, 24*(1), 44-66. doi: 10.1080/01690960801998236.

Menghini, D., Hagberg, G. E., Caltagirone, C., Petrosini, L., & Vicari, S. (2006). Implicit learning deficit in dyslexic adults: An fMRI study. *NeuroImage, 33*(4), 1218-1226.

Menn, L. (1983). *Language acquisition, aphasia, and phonotactic universals.* Paper presented at the 12th Annual University of Wisconsin-Milwaukee Linguistics Symposium, Milwaukee, WI.

Miles, T. R. (1983). *Dyslexia: The Pattern of Difficulties*. Oxford: Blackwell.

Miller, K. M., & Swick, D. (2003). Orthography influences the perception of speech in alexic patients. *Journal of Cognitive Neuroscience, 15*, 981-990.

Moe-Nilssen, R., Helbostad, J. L., Talcott, J. B., & Toennessne, F., E. (2003). Balance and gait in children with dyslexia. *Experimental Brain Research, 150*, 237-244. doi: 10.1007/s00221-003-1450-4.

Moll, K., Zimmermann, G., & Smith, A. (1977). The study of speech production as a human neuromotor system. In M. Sawashima & F. S. Cooper (Eds.), *Dynamic Aspects of Speech Production* (pp. 107-127). Tokyo: University of Tokyo.

Morais, J., Cary, L., Alegria, J., & Bertelson, P. (1979). Does awareness of speech as a sequence of phones arise spontaneously? *Cognition, 7,* 323-331.

Morton, J. (1969). Interaction of information in word recognition. *Psychological Review, 76,* 165-178.

Munson, B. (2001). Phonological pattern frequency and speech production in adults and children. *Journal of Speech, Language, and Hearing Research, 44,* 778-792.

Munson, B., Kurtz, B. A., & Windsor, J. (2005). The influence of vocabulary size, phonotactic probability, and wordlikeness on nonword repetitions of children with and without specific language impairment. *Journal of Speech, Language, and Hearing Research, 48*, 1033-1047. doi: 1092-4388/05/4805-1033.

Munson, B., Swenson, C. L., & Manthei, S. C. (2005). Lexical and phonological organization in children: Evidence from repetition tasks. *Journal of Speech, Language, and Hearing Research, 48*, 108-124. doi: 1092-4388/05/4801-0108.

Nation, K., & Hulme, C. (2011). Learning to read changes children's phonological skills: evidence from a latent variable longitudinal study of reading and nonword repetition. *Developmental Science, 14*(4), 649-659. doi: 10.1111/j.1467-7687.2010.01008.x.

Nicolson, R. I., & Fawcett, A. J. (1990). Automaticity: A new framework for dyslexia research? *Cognition, 35*, 159-182.

Nicolson, R. I., & Fawcett, A. J. (1994). Comparison of deficits in cognitive and motor skills among children with dyslexia. *Annals of Dyslexia, 44*, 147-164.

Nicolson, R. I., & Fawcett, A. J. (2007). Procedural learning difficulties: Reuniting the developmental disorders? Trends in Neurosciences, 30(4), 135-141. doi: 10.1016/j.tins.2007.02.003

Nicolson, R. I., & Fawcett, A. J. (2011). Dyslexia, dysgraphia, procedural learning and the cerebellum. *Cortex, 47*, 117-127. doi: 10.1016/j.cortex.2009.08.016.

Nicolson, R.I., Fawcett, A.J., & Dean, P. (1995). Time estimation deficits in developmental dyslexia: Evidence of cerebellar involvement. *Proceedings of the Royal Society of London. Series B: Biological Sciences, 259*, 43-47.

Nittrouer, S. (1996). The relation between speech perception and phonemic awareness: Evidence from low-SES children and children with chronic OM. *Journal of Speech and Hearing Research, 39*, 1059-1070.

Nittrouer, S., Manning, C., & Meyer, G. (1993). The perceptual weighting of acoustic cues changes with linguistic experience. *Journal of the Acoustical Society of America, 94*, S1856.

Nittrouer, S. (1993). The emergence of mature gestural patterns is not uniform: Evidence from an acoustic study. *Journal of Speech and Hearing Research, 36*, 959-972.

Nittrouer, S., Studdert-Kennedy, M., & McGowan, R. S. (1989). The emergence of phonetic segments: Evidence from the spectral structure of fricative-vowel syllables spoken by children and adults. *Journal of Speech and Hearing Research, 32*, 120-132.

Ohala, D. K. (1996). *Cluster reduction and constraints on acquisition*. Unpublished doctoral dissertation, University of Arizona, Tucson, AZ.

Pattamadilok, C., Perre, L., Dufau, S., & Ziegler, J. (2009). On-line orthographic influences on spoken language in a semantic task. *Journal of Cognitive Neuroscience*, *21*(1), 169-179. doi:10.1162/jocn.2009.21014.

Pierrehumbert, J. (2002). Word-specific phonetics. In C. Gussenhoven & N. Warner (Eds.), *Laboratory phonology VII* (pp. 101–140). Berlin: Mouton.

Ramus, F., Pidgeon, E., &Frith, U. (2003). The relationship between motor control and phonology in dyslexic children. *Journal of Child Psychology and Psychiatry, 44*(5), 712-722.

Rastle, K., McCormick, S. F., Bayliss, L., & Davis, C. J. (2011). Orthography influences the perception and production of speech. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 37*(6), 1588-1594. doi: 10.1037/a0024833.

Read, C., Zhang, Y.-F., Nie, H.-Y., & Ding, B.-Q. (1986). The ability to manipulate speech sounds depends on knowing alphabetic spelling. *Cognition, 24,* 31-44.

Roelofs, A. (2006). The influence of spelling on phonological encoding in word reading, object naming, and word generation. *Psychonomic Bulletin & Review, 13*(1), 33-37. doi: 10.3758/BF03193809.

Rucker, G., Schwarzer, G., Carpenter, J., & Olkin, I. (2009). Why add anything to nothing? The arcsine difference as a measure of treatment in a meta-analysis with zero cells. *Statistics in Medicine, 28*, 721-738. doi: 10.1002/sim.3511.

Saletta, M., Darling White, M., Ryu, J. H., Haddad, J. M., Goffman, L., Francis, E. J., & Huber, J. E. (In revision). *Dual speech and balance task performance in individuals with Parkinson's disease.*

Saletta, M., & Goffman, L. (In preparation). *Influences of grammatical and lexical demands on speech production in children with SLI.*

Saletta,. M., Goffman, L., & Brentari, D. (In revision). *Orthography and reading proficiency influence speech movement stability.*

Schwartz, M., Leikin, M. & Share, D. L. (2005). Bi-literate bilingualism versus mono-literate bilingualism: A longitudinal study of reading acquisition in Hebrew (L2) among Russian-speaking (L1) children. *Written Language and Literacy, 8*, 179-207.

Schwartz, M., Share, D. L., Leikin, M., & Kozminsky, E. (2008). On the benefits of bi-literacy: Just a head start in reading or specific orthographic insights? *Reading and Writing, 21*, 905-927. doi: 10.1007/s11145-007-9097-3.

Seidenberg, M. S., & Tanenhaus, M. K. (1979). Orthographic effects on rhyme monitoring. *Journal of Experimental Psychology: Human Learning and Memory, 5*, 546-554.

Seidenberg, M. S., & McClelland, J. L. (1989). A distributed, developmental model of word recognition and naming. *Psychological Review, 96*(4), 523-568.

Semel, E., Wiig, E. H., & Secord, W. A. (2003). *Clinical Evaluation of Language Fundamentals, Fourth Edition.* San Antonio, TX: Pearson.

Serrano, F., & Defior, S. (2008). Dyslexia speed problems in a transparent orthography. *Annals of Dyslexia, 58*, 81-95. doi: 10.1007/s11881-008-0013-6.

Shankweiler, D., Mencl, W. E., Braze, D., Tabor, W., Pugh, K. R., & Fulbright, R. K. (2008). Reading differences and brain: Cortical integration of speech and print in sentence processing varies with reader skill. *Developmental Neuropsychology, 33*(6), 745-775. doi: 10.1080/87565640802418688.

Shattuck-Hufnagel, S. (1987). The role of word onset consonants in speech production planning: New evidence from speech error patterns. In E. Keller & M. Gopnik (Eds.), *Motor and Sensory Processing in Language* (pp. 17-51). Hillsdale, NJ: Erlbaum.

Shulman, H., Hornak, R., & Sanders, M. (1978). The effects of graphemic, phonetic, and semantic relationships on access to lexical structures. *Memory and Cognition, 6,* 115-123.

Shriberg, L. D., Austin, D., Lewis, B. A., McSweeny, J. L., & Wilson, D. L. (1997a). The Percentage of Consonants Correct (PCC) metric: Extensions and reliability data. *Journal of Speech, Language, and Hearing Research, 40*, 708-722.

Smith, A. (1992). The control of orofacial movements in speech. *Critical Reviews in Oral Biology and Medicine, 3*, 233-267.

Smith, A., & Goffman, L. (1998). Stability and patterning of speech movement sequences in children and adults. *Journal of Speech, Language, and Hearing Research, 41,* 18-30.

Smith, A., & Goffman, L. (2004). Interaction of motor and language factors in the development of speech production. In B. Maasen, R. Kent, H. Peters, P. van Lieshout, & W. Hulstijn (Eds.) *Speech Motor Control in Normal and Disordered Speech* (pp. 227-252). New York: Oxford University Press.

Smith, A., Johnson, M., McGillem, C., & Goffman, L. (2000). On the assessment of stability and patterning of speech movements. *Journal of Speech, Language, and Hearing Research, 43*, 277-286. doi: 1092-4388/00/4301-0277.

Snow, C. E., Burns, M. S., & Griffin, P. (Eds.). (1998). *Preventing reading difficulties in young children.* Washington, DC: National Academy Press.

Snowling, M. J. (2000). *Dyslexi*a. Oxford: Blackwell.

Snowling, M. J. (2013). Early identification and interventions for dyslexia: A contemporary view. *Journal of Research in Special Educational Needs, 13*(1), 7-14. doi: 10.1111/j.1471-3802.2012.01262.x.

Snowling, M. J., Bishop, D. V. M., Stothard, S. E., & Kaplan, C. (2006). Psychosocial outcomes at 15 years of children with a preschool history of speech-language impairment. *Journal of Child Psychology and Psychiatry, 47*, 759-765. doi: 10.1111/j.1469-7610.2006.01631.x.

Sommers, M., (2002). Washington University in St. Louis Speech and Hearing Lab Neighborhood Database. Last accessed April 28, 2014 from http://128.252.27.56/neighborhood/Home.asp.

Stanovich, K. E., & Seigel, L. S. (1994). Phenotypic performance profile of children with reading disabilities: A regression-based test of the phonological-core variable-difference model. *Journal of Educational Psychology, 86*, 24-53.

Stoodley, C. J., Harrison, E. P. D., & Stein, J. F. (2006). Implicit motor learning deficits in dyslexic adults. *Neuropsychologia, 44*, 795-798. doi: 10.1016/j.neuropsychologia.2005.07.009.

Storkel, H. L. (2001). Learning new words: Phonotactic probability in language development. *Journal of Speech, Language, and Hearing Research*, *44*, 1321-1337.

Storkel, H. L. (2004). The emerging lexicon of children with phonological delays: Phonotactic constraints and probability in acquisition. *Journal of Speech, Language, and Hearing Research, 47*, 1194-1212.

Storkel, H. L., Maekawa, J., & Hoover, J. R. (2010). Differentiating the effects of phonotcatic probability and neighborhood density on vocabulary comprehension and production: A comparison of preschool children with versus without phonological delays. *Journal of Speech, Language, and Hearing Research, 53*, 933-949. doi:10.1044/1092-4388(2009/09-0075).

Studdert-Kennedy, M. (1987). The phoneme as a perceptuomotor structure. In A. Allport, D. MacKay, W. Prinz, & E. Scheerer (Eds.), *Language perception and production* (pp. 67-84). London: Academic Press.

Thelen, E., Corbetta, D., Kamm, K., Spencer, J., Schneider, K., & Zermicke, R. F. (1993). *A dynamic systems approach to the development of cognition and action.* Cambridge, MA: MIT Press.

Tokimura, H., Tokimura, Y., Oliviero, A., Asakura, T., & Rothwell, J. C. (1996). Speech-induced changes in corticospinal excitability. *Annals of Neurology, 40*(4), 628-634.

Tomblin, J. B., Mainela-Arnold, E., & Zhang, X. (2007). Procedural learning in adolescents with and without specific language impairment. *Language Learning and Development, 3*(4), 269-293.

Tomblin, J. B., Records, N., Buckwalter, P., Zhang, X., Smith, E., & O'Brien, M. (1997). Prevalence of specific language impairment in kindergarten children. *Journal of Speech, Language, and Hearing Research, 40*, 1284-1294.

Torgesen, J., Wagner, R., & Rashotte, C. (2011). *Test of Word Reading Efficiency, Second Edition (TOWRE-2).* San Antonio, TX: Pearson.

Ullman, M. T, & Pierpont, E. I. (2005). Specific language impairment is not specific to language: The Procedural Deficit Hypothesis. *Cortex, 41*, 399-433.

Vellutino, F. R., Fletcher, J. M., Snowling, M. J., & Scanlon, D. M. (2004). Specific reading disability (dyslexia): What have we learned in the past four decades? *Journal of Child Psychology and Psychiatry, 45*(1), 2-40.

Ventura, P., Morais, J., Pattamadilok, C., & Kolinsky, R. (2004). The locus of the orthographic consistency effect in auditory word recognition. *Language and Cognitive Processes, 19*, 57-95.

Ventura, P., Morais, J., & Kolinsky, R. (2007). The development of the orthographic consistency effect in speech recognition: From sublexical to lexical involvement. *Cognition, 105*, 547-576. doi:10.1016/j.cognition.2006.12.005.

Vitevitch, M. S. (1997). Phonotactics and spoken word recognition. Unpublished doctoral dissertation, University at Buffalo, Buffalo, NY.

Vitevitch, M. S. (2002). The influence of phonological similarity neighborhoods on speech production. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *28*(4), 735-747. doi:10.1037/0278-7393.28.4.735.

Vitevitch, M. S., & Luce, P. A. (1998). When words compete: Levels of processing in spoken word perception. *Psychological Science, 9*, 325-329.

Vitevitch, M. S., & Luce, P. A. (1999). Probabilistic phonotactics and neighborhood activation in spoken word recognition. *Journal of Memory and Language, 40,* 374-408. doi: jmla.1998.2618.

Vitevitch, M. S., & Luce, P. A. (2004). A Web-based interface to calculate phonotactic probability for words and nonwords in English. *Behavioral Research Methods, Instruments, and Computers, 36*(3), 481-487.

Vitevitch, M. S., & Luce, P. A. (2005). Increases in phonotactic probability facilitate spoken nonword repetition. *Journal of Memory and Language, 52*, 193-204. doi:10.1016/j.jml.2004.10.003.

Vitevitch, M. S., Luce, P. A., Charles-Luce, J., & Kemmerer, D. (1997). Phonotactics and syllable stress: Implications for the processing of spoken nonsense words. *Language and Speech, 40*(1), 47-62.

Vitevitch, M. S., Luce, P. A., Pisoni, D. B., & Auer, E. T. (1999). Phonotactics, neighborhood activation, and lexical access for spoken words. *Brain and Language, 68*, 306-311.

Vogel Sosa, A.,& Stoel-Gammon, C.(2006). Patterns of intra-word phonological variability during the second year of life. *Journal of Child Language, 33*, 31-50.

Washington University in St. Louis Speech and Hearing Lab Neighborhood Database as a web-based implementation of the 20 000-word Hoosier Mental Lexicon. http://neighborhoodsearch.wustl.edu/Neighborhood/NeighborHome. asp.

Watkins, R., Kelly, D., Harbers, H., & Hollis, W. (1995). Measuring children's lexical diversity: Differentiating typical and impaired language learners. *Journal of Speech and Hearing Research, 38,* 1349-1355.

Wohlert, A. B., & Smith, A. (1998). Spatiotemporal stability of lip movements in older adult speakers. *Journal of Speech, Language, and Hearing Research, 41*, 41-50.

Woodcock, R. W. (2011). *Woodcock reading mastery tests - Revised-Normative update.* San Antonio, TX: Pearson.

Woollacott, M., Shumway-Cook, A., & NAshner, L. (1986). Aging and posture control: Changes in sensory organization and muscular organization. *International Journal of Aging and Human Development, 23*, 97-114.

Yang, Y., & Ho-Yan, B. (2011). Unilateral implicit motor learning deficit in developmental dyslexia. *International Journal of Psychology, 46*(1), 1-8. doi: 10.1080/00207594.2010.509800.

Zecker, S. G. (1999). The orthographic code: Developmental trends in reading-disabled and normally-achieving children. *Annals of Dyslexia, 41*, 178-192. doi: 10.1007/BF02648085.

Zelaznik, H. N., & Goffman, L. (2010). Generalized motor abilities and timing behavior in children with specific language impairment. *Journal of Speech, Language, and Hearing Research, 53*, 383-393.

Ziegler, J. C., & Ferrand, L. (1998). Orthography shapes the perception of speech: The consistency effect in auditory word recognition. *Psychonomic Bulletin & Review, 5*(4), 683-689.

Ziegler, J. C., Ferrand, L., & Montant, M. (2004). Visual phonology: The effects of orthographic consistency on different auditory word recognition tasks. *Memory & Cognition, 32*(5), 732-741.

Ziegler, J. C., & Goswami, U. (2005). Reading acquisition, developmental dyslexia, and skilled reading across languages: A psycholinguistic grain size theory. *Psychological Bulletin, 131*(1), 3-29.

Ziegler, J. C., & Goswami, U. (2006). Becoming literate in different languages: Similar problems, different solutions. *Developmental Science, 9,* 429-453.

Ziegler, J. C., Jacobs, A. M., & Klueppel, D. (2001). Pseudohomophone effects in lexical decision: Still a challenge for current word recognition models. *Journal of Experimental Psychology: Human Perception and Performance, 27*(3), 547-559.

Ziegler, J. C., & Muneaux, M. (2007). Orthographic facilitation and phonological inhibition in spoken word recognition: A developmental study. *Psychonomic Bulletin & Review, 14,* 75-80.

Ziegler, J. C., Muneaux, M., & Grainger, J. (2003). Neighborhood effects in auditory word recognition: Phonological competition and orthographic facilitation. *Journal of Memory and Language, 48*, 779-793.

Ziegler, J. C., Van Orden, G. C., & Jacobs, A. M. (1997). Phonology can help or hurt the perception of print. *Journal of Experimental Psychology: Human Perception and Performance, 23*(3), 845-860.

Zoccolotti, P., De Luca, M., Di Pace, E., Judica, A., Orlandi, M., & Spinelli, D. (1999). Markers of developmental surface dyslexia in a language (Italian) with high grapheme-phoneme correspondence. *Applied Psycholinguistics, 20*, 191-216.

VITA

VITA

Education:

- **2009-2014.** Doctor of Philosophy: Purdue University, West Lafayette, IN. Speech, Language, and Hearing Sciences.
- **2006-2008.** Master of Science: Rush University, Chicago, IL. Communication Disorders Sciences.
- **2004-2006.** Bachelor of Arts: Hebrew Theological College, Chicago, IL. Double major: Special Education and Judaic Studies; minor: Speech Pathology.

Publications:

Master's thesis:

- Saletta, M. (2008). *Speech and language changes associated with motor asymmetry in Parkinson's disease: A pilot study.* (Master's thesis). Rush University, Chicago, IL.

To appear:

- Saletta, M., Gladfelter, A., Vuolo, J., & Goffman, L. (To appear). Interaction of motor and language factors in the development of speech production. Invited chapter in R. H. Bahr & E. R. Silliman (Eds.), *Handbook of Communication Disorders.*

In revision:

- Saletta, M., Darling White, M., Ryu, J. H., Haddad, J. M., Goffman, L., Francis, E. J., & Huber, J. E. (In revision). Dual speech and balance task performance in individuals with Parkinson's disease. *Journal of Communication Disorders.*
- Saletta, M., Goffman, L., & Brentari, D. (In revision). Orthographic factors influence speech production. *Applied Psycholinguistics.*

In preparation:

- Chagdes, J. R., Haddad, J. M., Rietdyk, S., Zelaznik, H. N., Huber, J. E., Saletta, M., Darling White, M., & Raman, A. (In preparation). Limit cycle oscillations in standing human posture.
- Goffman, L., & Saletta, M. (In preparation). Picture naming and word repetition influence speech production processes in children with SLI.
- Saletta, M., & Goffman, L. (In preparation). Influences of grammatical and lexical demands on speech production in children with SLI.

Presentations:

- Goffman, L., Saletta, M., Gladfelter, A., & Vuolo, J. (June, 2013). *Shifts in production variability as a function of input and learning in typical and disordered language development.* Poster presented at the annual meeting of the Linguistic Institute, University of Michigan, Ann Arbor, MI.
- Saletta, M., & Goffman, L. (June, 2013). *Grammatical and lexical demands influence speech movement stability in children with SLI.* Poster presented at the annual Symposium on Research in Child Language Disorders, Madison, WI.
- Vuolo, J., Goffman, L., Zelaznik, H., Berlin, J., & Saletta, M. (June, 2013). *The production of manual rhythmic sequences in children with specific language impairment.* Poster presented at the annual Symposium on Research in Child Language Disorders, Madison, WI.
- Vuolo, J., Saletta, M., & Goffman, L. (May, 2013). *Musical and prosodic sequencing in children with specific language impairment.* Poster presented at the Center for Research on the Brain, Language, and Music Inaugural Symposium on Language and Music, Montreal, QC.
- Goffman, L., Gladfelter, A., Vuolo, J., & Saletta, M. (November, 2012). *Underpinnings of the motor deficit in children with SLI.* Presentation at the annual meeting of the American Speech-Language-Hearing Association, Atlanta, GA.
- Saletta, M., Goffman, L., & Brentari, D. (November, 2012). *Orthography and reading proficiency influence speech movement stability.* Presentation at Purdue University's weekly departmental colloquium, West Lafayette, IN.
- Goffman, L., Saletta, M., & Miller, D. (June, 2012). *Automaticity in sentence production in children with SLI: Assessment of a component of the procedural deficit hypothesis.* Poster presented at the annual Symposium on Research in Child Language Disorders, Madison, WI.
- Saletta, M., Goffman, L., & Brentari, D. (June, 2012). *Development of a new paradigm relating orthographic transparency and reading proficiency to speech movement stability.* Poster presented at the annual Symposium on Research in Child Language Disorders, Madison, WI.
- Saletta, M., Darling, M., Ryu, J. H., Haddad, J. M., Goffman, L., Francis, E. J., & Huber, J. E. (February-March, 2012). *Interaction of syntactic complexity, memory load, and balance in Parkinson's disease.* Presentation at the biennial Motor Speech Conference, Santa Rosa, CA.
- Darling, M. Huber, J. E., Saletta, M. Haddad, J. M., Ryu, J. H., & Francis, E. J. (November, 2011). *Effects of Parkinson's disease on breath pausing during balance tasks.* Presentation at the annual meeting of the American Speech-Language-Hearing Association, San Diego, CA.
- Saletta, M., Darling, M., Ryu, J. H., Haddad, J. M., Goffman, L., & Francis, E. J. (November, 2011). *Interaction of syntactic complexity, memory load, and balance in Parkinson's disease.* Presentation at Purdue University's weekly departmental colloquium, West Lafayette, IN.

- Francis, E. J., Saletta, M., Huber, J. E., Darling, M., & Haddad, J. M. (January, 2011). *Effects of age, Parkinson's disease, syntactic complexity, and balance on sentence production.* Poster presented at the annual meeting of the Linguistic Society of America, Pittsburgh, PA.
- Saletta, M. (February, 2008). *Speech and language changes associated with motor asymmetry in Parkinson's disease: Preliminary data.* Presentation at the annual meeting of the Illinois Speech, Language, and Hearing Association, Rosemont, IL.

Teaching Experience:

- **Summer, 2010, 2011, and 2013.** Clinical supervisor, Purdue University, West Lafayette, IN. Supervised graduate clinicians working with young children with specific language impairment in an integrated clinical and research program.
- **Fall, 2012.** Guest lecturer, Purdue University, West Lafayette, IN; SLHS 519, Speech Science. Presented academic lectures on research methods in this graduate-level course.
- **Fall, 2009 and Spring, 2010.** Teaching assistant and instructor of course laboratory sections, Purdue University, West Lafayette, IN; SLHS 306, Introduction to Phonetics. Planned and taught laboratory sections.

Employment History:

- **2010-current.** Research assistant, Purdue University, West Lafayette, IN; Developmental Speech Production Laboratory (research supported by the National Institutes of Health/National Institute on Deafness and Other Communication Disorders, R01 DC04826), under the direction of Dr. Lisa Goffman. Mentored undergraduate laboratory assistants, helped to design experimental protocols, collected data from child and adult participants, analyzed and interpreted data, disseminated research.
- **2008-2009.** Clinical fellow in speech-language pathology, Proviso Area for Exceptional Children, Maywood, IL. Assessed and treated speech and language disorders in elementary and high school students with intellectual disabilities and/or autism spectrum disorders.
- **2006-2008.** Graduate clinician, Rush University, Chicago, IL. Assessed and treated speech and language disorders in individuals ranging in age from pre-K (Head Start) and elementary school (Gesher Day School, Rush Day School) to high school (Stevenson Public High School), as well as adult rehabilitation and acute care (Rush University Medical Center).
- **2003-2007.** Instructor, Lubavitch Chabad of Illinois, Chicago, IL. Designed and implemented an extracurricular literacy program for elementary school children.

Service:

- **2010-2013.** Musician, Purdue Musical Organizations, All Campus and Community Chorale, West Lafayette, IN.
- **2009-2013.** Musician, Purdue Bands and Orchestras, Concert Band, West Lafayette, IN.
- **2011.** Tutor, Lafayette Adult Resource Academy, Lafayette, IN.
- **2008-2009.** Coach, Special Olympics Illinois, Maywood, IL.

Grants and Other Research Awards:

- **2013.** NIH/NIDCD F31 submitted. Impact score: 30.
- **2012.** Indiana Lions McKinney Outreach Program Award.
- **2012.** Doctoral Purdue Research Foundation Grant, Purdue University.
- **2012.** Wilson Travel Grant: Awarded for travel to Santa Rosa, CA, to give a presentation at the biennial Motor Speech Conference.
- **2011.** NIH/NIDCD T32, Laurence Leonard, PI.
- **2011.** Robert L. Ringel Research Endowment Award: Awarded to support work regarding the impact of orthography on speech movement stability.
- **2011.** Weinberg Travel Grant: Awarded for travel to Pittsburgh, PA, to present a poster at the annual meeting of the Linguistic Society of America.
- **2006-2008.** Research Scholarship: Awarded for conducting research in the Master of Science program in Communication Disorders Sciences at Rush University, Chicago, IL.

Professional Memberships:

- **2010-current.** Certificate of Clinical Competence in speech-language pathology, American Speech, Language, and Hearing Association.
- **2010-current.** Licensed speech-language pathologist, state of Indiana.
- **2010-current.** Licensed speech-language pathologist, state of Illinois.