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Cognitive and Linguistic Underpinnings of Orthographic Learning: Beyond the Effects of Phonological Decoding

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Cognitive and Linguistic Underpinnings of Orthographic Learning:

Beyond the Effects of Phonological Decoding

by

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Professor Anne E. Cunningham, Chair

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Abstract

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Many words in English resemble each other in multiple ways. When these words have similar spelling, they are referred to as *orthographic* neighbors. The purpose of this within-subject experimental study was to examine the effect of orthographic neighbors on the acquisition of spelling, more specifically constructing orthographic representations of words. Five questions will be addressed in the study: (1) Is there an effect of orthographic neighbors on the acquisition of orthographic representations? (2 Is there an effect of phoneme-to-grapheme consistency on spelling acquisition? (3) Is there an effect of delay on spelling acquisition? (4) Can participants' ability to learn spelling improve without specific instruction? (5) Are there interactions between the effects of orthographic processing ability and the effects of rime, substitution, and transposition neighbors on participants' spelling acquisition?

Seventy-one second grade students in northern California participated in the study. Following assessment of participants' cognitive ability, five sessions of a computer-based experiment were conducted. In each session, the participants were shown two base words and attempted to learn seven new words. The seven new words included control words (without orthographic neighbors: no connection with the corresponding base word) and target words (representing various types of connections with the corresponding base word). Each new word was presented three times for five seconds in random order. Orthographic choice and spelling tasks were used to assess orthographic learning via the orthographic choice and spelling tasks. Each task was administered twice: immediately after the experiment and two days after the experiment.

Three-level logistics regression with random effects for sessions and participants were used to analyze the data. The model allows between-student variation in learning outcomes due to the individual differences among participants and contextual effects at the session level. The outcome variable was participants' performance on the orthographic choice and spelling tasks. Level 1 included the words' characteristics, Level 2 the sessions' characteristics, and Level 3 the participants' characteristics. In addition, random coefficients of effects of neighbors (Rime, Substitution, Transposition) and the cross-level interaction between orthographic neighbors and the participants' orthographic processing ability were considered.

The effect of rime neighbors on participants' performance were found in both the orthographic choice and the spelling tasks. The effects of substitution and transposition neighbors existed only for participants' performance on the orthographic choice tasks. The facilitative effect of phoneme-to-grapheme consistency was found in the orthographic choice tasks, but not in the spelling tasks. The effect of delay was found both in the orthographic choice tasks and the spelling tasks. Orthographic processing was as a significant predictor for participants' performance on all four posttests. A significant interaction between orthographic processing and rime neighbors was observed in both spelling tasks. The findings demonstrate that second-grade students can use orthographic analogies to facilitate their orthographic learning and that orthographic processing is an important cognitive ability for spelling acquisition.

Keywords: orthographic neighbors, orthographic learning, spelling acquisition

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Chapter 1 Introduction

Orthographic learning, the acquisition and development of orthographic knowledge, provides a gateway for beginning readers to transition from laborious and taxing word recognition to more automatic, efficient, and fluent word recognition. Although many reading scientists have attempted to model this transition, one approach that is central in explaining the development of orthographic knowledge is the self-teaching hypothesis (Jorm & Share, 1983; Share, 1995). The self-teaching hypothesis posits that "phonological recoding acts as a self-teaching mechanism or built-in teacher, enabling a child to independently develop both specific and general orthographic knowledge" (Share, 1995 p. 155). According to this position, the acquisition of orthographic knowledge entails not only the rote memorization of a word's graphemes, but also includes the correspondence between phonological and orthographic codes. In this way, the process of associating phonological and orthographical codes, known as phonological recoding or decoding, supports the construction of an orthographic representation of a word (Share, 1995).

Numerous studies have consistently demonstrated the importance of phonological decoding in constructing orthographic representation (Cunningham, 2002; 2006; de Jong, Bitter, van Setten, & Marinus, 2009; Kyte & Johnson, 2006; Share, 1999; 2008). Yet, despite the abundant research on phonological decoding in orthographic learning, there remain several unresolved foundational issues. These outstanding issues include (a) detangling the differences between orthographic knowledge and orthographic processing and operationalizing a working definition of each construct, (b) designing an appropriate assessment of orthographic processing, (c) exploring factors beyond phonological decoding that affect or contribute to orthographic learning, (d) investigating instruction that facilitates children's acquisition of orthographic knowledge, and (e) operationalizing the developmental trajectory of orthographic knowledge.

Although the ultimate goal of this dissertation is to address the third issue, defining the factors beyond phonological decoding that may contribute to the process of orthographic learning, we must address the first two outstanding issues. In order to examine the factors that affect or contribute to orthographic learning, it is essential to *define* orthographic learning. But because orthographic learning is the acquisition and development of orthographic knowledge, operationalizing orthographic knowledge must occur prior to defining orthographic learning. Yet, one of the many challenges in defining orthographic knowledge is that orthographic knowledge and orthographic processing have been used interchangeably within the field, and no clear distinction has been drawn between these two constructs. As a result, a necessary first step in any investigation of orthographic learning is to detangle the differences between orthographic knowledge and orthographic processing.

Orthographic processing has been theorized as a factor contributing to orthographic learning. However, to date, no empirical evidence has demonstrated its role in orthographic learning. It is argued that this gap is due largely to a lack of suitable assessments that tap orthographic processing. Thus, an appropriate assessment of orthographic processing must be availed to researchers. Designing a valid and reliable assessment of orthographic processing is therefore an essential step before exploring the factors beyond phonological decoding that affect or contribute to orthographic learning.

Two arrays of variables are examined in this dissertation: individual differences and word variations. Individual differences refer to individuals' previous knowledge and cognitive ability. Word variations refer to the differences in word characteristics. In this dissertation, the variables that tap into individual differences include print knowledge, oral vocabulary, decoding ability, phonological processing, and orthographic processing. The variables that tap into word variations include word frequency, word length, the degree of phoneme-to-grapheme consistency, and orthographic neighbors. These variables have been either empirically examined or theoretically posited as factors affecting orthographic learning.

Among these variables, the effects of orthographic neighbors are of particular interest, because of both their practical contribution to literacy education and their theoretical contribution to information processing by learners. More specifically, helping students analyze features or patterns of words is among the effective ways to teach children to recognize and spell words. A common method used to facilitate students' analysis of words is to introduce words through the concept of word families, i.e., groups of words that have a common feature or pattern. In this way, students make analogies to acquire new words that share the same features. When words have similar spellings, they are referred to as orthographic neighbors. Grouping words that share the same rhyme (e.g., *cat*, *bat*, *rat*), called rime orthographic neighbors, is the most well-known way to categorize words into families. However, in addition to sharing the same rhyme, words can be similar in other ways. For example, a word becomes similar to another when the position of the certain letters is switched (e.g., *abroad*, *aboard*); these are called transposition orthographic neighbors. Words also are similar when one letter is omitted (e.g., *over*, *overt*), called deletion orthographic neighbors. Finally, words become similar when one letter is changed and they do not share the same rhyme (e.g., *cot*, *cat*); these are substitution orthographic neighbors.

Although words can be similar in many different ways, the evidence supporting the facilitative effect of orthographic neighbors on reading and spelling acquisition is limited to only one category: rime neighbors (Goswami, 1988, 1990a, 1990b, 1992). It remains unknown whether the simultaneous inclusion of the other categories (substitution, and transposition neighbors) would facilitate students' orthographic learning. Thus, a key question to address is whether these three types of orthographic neighbors should be taught together.

To address this issue, I examine rime, substitution, and transposition neighbors , while adjusting for the phoneme-to-grapheme consistency, word length, and word frequency. Yet the literature has demonstrated that individual differences in cognitive ability account for a considerable amount of variation in all types of learning. In order to account for these difference in children's word learning, the Word Attack subset of the Woodcock-Johnson III Test of Achievement (2007), the Peabody Picture Vocabulary Test-Fourth Edition (2007), the prior orthographic knowledge task developed by Olson, Kliegl, Davidson, and Foltz (1985), the Elision and Blending subtests of the Comprehensive Test of Phonological Processing (1999), and a self-designed assessment of orthographic processing (Chen, Wilson, & Irey in preparation) will be used as covariates. Finally, as part of this sophisticated and complex design, as a means to account for variation in learning outcomes due to the individual differences among the participants, contextual differences among the five experimental sessions, and word variations among the 35 stimuli, a three-level logistic regression was employed to analyze the data.

Chapter 2 discusses the literature on orthographic learning. The constructs of orthographic knowledge, orthographic processing and orthographic learning are discussed. Subsequently, a review of the factors that affect or contribute to orthographic learning is presented.

Chapter 3 addresses the methodology employed in this study and explicates the study's research questions and hypotheses. A detailed description of the sample, experimental design, and generation of the stimuli are described, followed by the assessments employed to measure individual differences and orthographic learning among the second grade students. Of particular note is the section on the self-designed assessment of orthographic processing, which includes a report of the reliability and validity, as well as item-fit statistics. To conclude, the multifaceted data-analysis plan is described in greater detail, including the identification of data outliers, how composited scores were formed, the standardization of the raw scores, and modeling three-level logistic regressions.

Chapter 4 reports the findings of this study. Beginning with descriptive statistics, the participants' performance on a series of assessments and their performance on the five sessions of experiments is summarized. Inferential statistics, multiple statistical tests of learning outcomes by the types of posttests (i.e. immediate or delayed; choice or spelling) and the types of neighbors are addressed. Finally, three-level logistic regressions with random effects for sessions and participants are reported, and the methods for identifying the final model are discussed.

Chapter 5 begins with a summary and interpretation of the effects of orthographic neighbors on the participants' spelling acquisition. The relations between word features (phoneme-to-grapheme consistency, word frequency, and word length) and spelling acquisition is considered in addition to the role of several cognitive and literacy abilities in orthographic learning. Among the factors of individual differences, orthographic processing received a particular focus: its interaction with the different types of neighbors is interpreted. The constraints in the selection of word stimuli is deliberated upon and the applications and contributions of the study to research and instruction is described.

Chapter 2 Literature Review

Orthographic learning, orthographic knowledge, and orthographic processing are three frequently used terms in the spelling research. Although these three terms are strongly connected to one another, each has its own unique meaning. Orthographic learning, the larger umbrella construct, is defined as the acquisition and development of orthographic knowledge. It has clear boundaries in which to characterize its nature. Essentially it is the learning, acquisition, and development of orthographic knowledge. Empirically, researchers operationalize orthographic learning as the incremental improvement of orthographic knowledge from pretest to posttest in assessments.

Yet there has been much confusion in the literature regarding the difference between these three components of spelling fluency. The central cause can be attributed to the various definitions of orthographic knowledge and orthographic processing that have been presented and examined in the research literature. The vague nature and lack of operationalization of orthographic knowledge versus orthographic processing obscures our ability to examine their independent contribution to orthographic learning. Over, twenty-five years ago, Wagner and Baker (1994) argued that the varied and discrepant definitions reflect a major problem confronting the field in the attempt to define and operationalize orthographic knowledge. They argued that the first issue is the confusion between orthographic knowledge and processing, and the second issue pertains to the entanglement or intersection of phonological representations within orthographic knowledge. This remains an underlying issue in the field. Thus, prior to elaborating on a definition of orthographic knowledge and orthographic processing and then examining their measurement, the intricacies of these two issues will be first addressed.

Unclear Distinctions Between Orthographic Knowledge and Orthographic Processing

As argued, the terms orthographic knowledge and orthographic processing are frequently confused in the literature. One of the distinctive differences between orthographic knowledge and orthographic processing is that orthographic knowledge is the static database of stored information, whereas orthographic processing is the on-going access, retrieval, and manipulation of information. Static, crystalized orthographic knowledge is composed of two dimensions: (a) an individual's specific and accurate memory of orthographic representations and (b) his or her understanding of the rules for permissible letter combinations (orthographic patterns). Accurate memory of orthographic representations has been described as word-specific orthographic knowledge, whereas understanding the rules for permissible letter combinations has been labeled general orthographic knowledge (Conrad, Harris, & Williams, 2012; Share, 1995).

In contrast, on-line processing can be characterized by an individual's ability to perceive, manipulate, and store orthographic representations. An example of on-line processing is found in Stanovich and West's (1989) original conceptualization of orthographic processing, which they operationalized as "the ability to form, store, and access orthographic representations" (p.404). Two decades later, Apel (2011) pointed out that many studies employ measures of orthographic knowledge to assess orthographic processing. Measuring orthographic processing via tasks of orthographic knowledge is problematic because these tasks do not assess on-line processes, but instead measure static knowledge (Burt, 2006; Castles & Nation, 2008; Chalmers & Burt, 2008).

The Contribution of Phonological Representation to Orthographic Knowledge

In their attempt to understand orthographic knowledge and processing, numerous researchers have attempted to examine the relation between phonological decoding and orthographic learning (e.g., Ehri, 1980, 2005; Cunningham et al., 2001; Stanovich & West, 1989). For example, Ehri (1980, 2005) suggested that orthographic learning involves not only rote memorization of graphemes, but also includes memorization/recognition of the correspondence between phonological codes and orthographic codes. Similarly, de Jong, Bitter, van Setten, and Marinus (2009) defined orthographic knowledge as “a system of associations between phonology and orthography” (p.267). Both perspectives maintain that phonological decoding supports the construction of an orthographic representation of a word (Share, 1995). Indeed, Ehri (2005; 2014) argued that it is the amalgamation of phonological and orthographic representations stored in an individual’s memory that enables one to quickly identify a word. Despite this relation between phonology and orthography, a central point of this dissertation is that their amalgamation does not necessarily imply that phonological representations are an integral and inherent part of orthographic knowledge. That is, knowledge of letter-sound correspondence (the alphabetic principle) and awareness of phonological representations each serve as distinct resources to help children learn orthographic knowledge rather than being an integral aspect of it (Ehri, 2005, 2014; Kyte & Johnson, 2006; Share, 1995, 1999, 2004).

Defining and Measuring Orthographic Knowledge

Orthographic knowledge is the retention of graphemic representations of words and the understanding of permissible letter combinations. The “and” is significant because it signifies that this construct is multi-dimensional (Conrad, Harris, & Williams, 2012), consisting of both word specific graphemic representations *and* permissible letter combinations. However, because the construct and subsequent definition of orthographic knowledge has varied in the past (Apel, 2011; Beringer, 1994; Geva & Willows, 1994), the measurements used to assess it have varied. Nonetheless, one or both dimensions of orthographic knowledge have been measured in each of the relevant studies, and it is possible to divide these assessment tools into two categories: measures of specific orthographic representations and measures of orthographic patterns.

Specific orthographic representations. Specific orthographic representations are graphemic representations of a written word in one’s long-term memory, which Apel (2011; 2012) refers to as mental graphemic representations and Share (1995) as word-specific orthographic knowledge. Studies that refer to orthographic knowledge as specific orthographic representations commonly use orthographic choice tasks or homophone choice tasks to assess orthographic knowledge (for review see Apel, 2011; Cunningham, Nathan, & Raher, 2011). In orthographic choice tasks, an individual is required to choose the correctly spelled word from a stimulus of two orthographically-similar written words (e.g., *rain* and *rane*). In homophone choice tasks, an individual is required to choose the correctly spelled word from two phonologically similar words (e.g., *read* and *reed*). Because the stimuli in these tasks have the same phonological representations or pronunciation, the choice of the target word requires and activates the memory of a specific orthographic representation.

Orthographic patterns. Orthographic pattern knowledge includes how letters can and cannot be combined (e.g., *gzp* is not a permissible string in English), and how positional and contextual constraints affect the letters in a word (e.g., *c* always comes before *o* but *k* rarely does) (Goulandris, 1994; Ouellette & Senechal, 2008). Share (1995) employed the term general orthographic knowledge to refer to this concept. This concept is the same as the orthographic cues referenced in Rayner’s (1988) study, which he defined as the sensitivity to a letter sequence that enables an individual to identify common letter sequences and differentiate permitted from non−permitted spelling patterns (Ashby, 2012). This aspect of orthographic knowledge has often been considered independent of phonological decoding because individuals are required to select the letter string that looks like a real word in English from a pair of pronounceable non-words (e.g., *filk–filv*). This type of assessment is usually called a non-lexical choice task or letter-string choice task (Cassar & Treiman, 1997; Treiman, 1993). Although it is generally accepted that non-lexical choice or letter-string tasks are independent of phonological decoding, a factor analytic study conducted by Hagiliassis, Pratt, and Johnston (2006) demonstrated that these assessments have significantly moderate loadings on orthographic (0.49) and phonologic (0.36) factors. This finding suggests that completing non-lexical choice or letter string tasks might also involve phonological skills. Even so, non-lexical choice or letter string tasks continue to be the most commonly used assessment when attempting to measure orthographic pattern knowledge.

These two components of orthographic knowledge--specific orthographic representations and orthographic pattern awareness—have been widely discussed in the literature. However, the majority of the research on orthographic learning via the self-teaching paradigm focuses solely on the acquisition of specific orthographic representations (e.g., Bowey & Miller, 2007; Bowey & Muller, 2005; Cunningham, 2006; Cunningham, Perry, Stanovich, Share, 2002; de Jong et al., 2009; de Jong & Share, 2007; Share, 1999; Sprenger-Charolles, Siegel, Béchennec, & Serniclaes, 2003). When considering orthographic patterns, most studies (e.g., Cassar & Treiman, 1997; Pacton, Perruchet, Fayol & Cleeremans, 2001; Treiman, 1993) examine the development of orthographic patterns by investigating whether and when beginning readers are sensitive to certain orthographic patterns, such as a double letter combination. As a result of this imbalance, further research is needed to illuminate the factors affecting the development of orthographic patterns. Even more, researchers need to specify the particular aspects of orthographic knowledge they seek to examine and choose appropriate means to assess it. Reconciling which factors contribute to the learning of specific orthographic representations versus those that contribute to learning orthographic patterns is necessary for the advancement of the field.

Environmental, Cognitive and Linguistic Factors Affecting Orthographic Learning

A framework is used to elucidate the factors that contribute to orthographic learning, previously defined as the acquisition of orthographic knowledge. The framework serves to define and limit the domain of discussion, and to organize and stratify the hypothesized and confirmed factors. The framework that is utilized in this dissertation accounts for the impact of environment, individual's cognitive capacity, and additionally considers word features.

Environmental Factors that Affect Orthographic Learning

Environmental factors influencing orthographic learning range from micro-level factors, such as print exposure, to macro-level factors, such as socioeconomic status or cultural capital. Currently, studies have explored only the microsystem of orthographic learning in English, with a focus on print exposure. Although critical to understanding the complex ecology of children's orthographic learning, because of the lack of data examining macro-level factors, this dissertation will focus only upon the existing microsystem evidence examining the role of print exposure in orthographic learning.

Print exposure. An individual's previous exposure to print (reading volume) has an important and specific impact on the acquisition of specific orthographic representations and orthographic patterns (Cunningham & Stanovich, 1990; Stanovich & West, 1989). In fact, the frequency of exposure to print is the primary condition for the growth of orthographic knowledge, for both specific orthographic representation and orthographic pattern acquisition (Bowers, Golden, Kennedy, & Young, 1994; Cassar & Treiman, 1997; Pacton, Perruchet, Fayol & Cleeremans, 2001), especially in a deep orthography language such as English (Nation, Angell, & Castles, 2007). The orthographic sensitivity hypothesis, as proposed by Share (2004), asserts that a critical volume of experience with print elicits a fundamental change in orthographic sensitivity. This orthographic sensitivity allows more experienced and skilled readers to be aware of the subtle nuances of letter patterns within words, which further facilitates the accurate construction of specific orthographic representations.

A number of empirical studies have explored the impact of print exposure to target words on the learning of specific orthographic representations for those target words (e.g., Booth, Perfetti, & MacWhinney, 1999; Nation et al, 2007; Share, 1999, 2004). Here, researchers employed self-teaching experiments to examine the impact of print exposure on the acquisition of orthographic representation. Beginning readers were asked to read stories in which the target words were embedded throughout the story. In order to manipulate the number of times a beginning reader saw a target word in each story, the word was embedded multiple times, varying by experimental conditions (e.g., students in a group who saw a specific target word six times as opposed to those in a group who were exposed to it only once in a story). For example, Share (1999) embedded the target word *Akunia* six times in a story by using *Akunia* as a name of a place (e.g., "In the middle of Australia is the hottest town in the world. This town is called *Akunia* and it's right in the middle of the desert. In *Akunia*, the temperature can reach 60 degrees.") Orthographic learning, as a function of the varying number of exposures to target words, was compared across groups.

Although a number of studies have observed differences across groups based on exposure amount, the threshold and approximate number of exposures required for constructing orthographic representations remain unclear. The inconclusive findings regarding the requisite number of exposures for orthographic learning are most likely related to the variation of the orthography of the word stimuli in each study (Cunningham et al., 2011), as well as the variation of participants' backgrounds. Share (1999) suggested that four or fewer exposures to Hebrew orthographic representations were sufficient to facilitate second graders' orthographic learning, and the difference between four and six exposures was not statistically significant for performance on both the orthographic choice task and the spelling task. Share (2004) further explored the difference between one, two, and four exposures on third-grade students' accurate memorization of orthographic representations and found that there was no difference between these numbers of exposures. De Jong and Share (2007) replicated Share's findings and found that there was no difference between two and four exposures of Dutch orthographic representations for second graders' orthographic learning. Yet Nation et al. (2007) examined Year 3 and Year 4 children in England and found that orthographic learning in English was significantly greater following four exposures as compared to one exposure. These discrepant findings illustrate the fact that the field lacks conclusive evidence regarding the influence of the quantity of print exposure on the acquisition of specific orthographic representations.

Cognitive Factors that Affect Orthographic Learning

One of the key arguments in understanding how children acquire orthographic knowledge has been that individual differences in cognition underlie most complex learning tasks and that differences in spelling may be largely due to constitutional factors rather than the constraints of the orthography. Challenging this hypothesis, Cunningham et al. (2002) demonstrated that general cognitive ability--a composite of the Peabody Picture Vocabulary Test (Dunn & Dunn, 1981), the Raven Progressive Colored Matrices (Raven, 1962), the Digit Span Subtest in Wechsler Intelligence Scales for Children (Wechsler, 1991), and the Woodcock Reading Mastery Test (Woodcock, 1987--did not explain additional variance in acquiring orthographic representations beyond that explainable by previous orthographic knowledge and phonological decoding ability. Thus, it is worthwhile to review other studies that examined the role of cognitive factors in orthographic learning. These cognitive factors include prior (crystalized) knowledge, decoding, and rapid automatized naming (RAN).

Prior (crystalized) knowledge. The acquisition of specific orthographic representations does not merely rely on successful decoding but also depends on prior orthographic knowledge (Cunningham et al., 2002; Tucker, Castle, Laroche, Deacon, 2016). Prior knowledge refers to the knowledge that individuals have accumulated before current learning. In an orthographic learning situation, prior orthographic knowledge is the previous knowledge of orthographic representations and patterns that one has acquired.

Young readers develop sensitivity to orthographic pattern knowledge as they progress in reading ability (Ashby, 2012; Rayner, 1988) largely because they acquire related alphabetic, morphologic, and orthographic knowledge, which in turn supports the development of sensitivity to orthographic patterns. Drawing from Goswami's (1994, 1998) research on orthographic analogy, the positive influence of prior knowledge on the acquisition of orthographic representations can be observed when individuals learn words with many orthographic neighbors (e.g., *clam*-*calm* or *stop*-*shop*). Constructing the orthographic representation of *shop* could be easier for individuals who have the crystalized orthographic representation of *stop* than those who do not, because they only need to substitute *h* for *t* to construct *shop*. In contrast, individuals who do not already have an orthographic representation of a neighbor for *shop* have nothing from which to make an analogy or build from when constructing *shop* (Goswami, 1994, 1998).

Decoding ability. Theoretically, the acquisition of orthographic knowledge is related to, or affected by, decoding ability, the ability to map phonology onto orthography, which is also known as phonological recoding (see Ehri, 2005; Share, 1995, 2008; Perfetti, 2007). Share's (1995) self-teaching hypothesis posits that "phonological recoding acts as a self-teaching mechanism or built-in teacher, enabling a child to independently develop both specific and general orthographic knowledge" (p. 155). Similarly, Ehri proposed the idea that the connection between orthographic representations and phonological representations constitutes a more powerful mechanism for constructing orthographic representations than the connection between orthographic representations and semantic representations. In other words, both Share and Ehri suggest that beginning readers can acquire an orthographic representation of a word via phonological decoding. Perfetti's (2007) lexical quality hypothesis also stresses the importance of the linkage between orthography, phonology, and semantics. Although Perfetti did not directly state that the spelling-sound connection plays a primary role in the acquisition of orthographic representations, the link between orthography and phonology implicitly reflects the importance of decoding ability.

Ziegler, Perry and Zorzi (2014) used a computational model to justify the theoretical foundation of phonological decoding in orthographic learning. They simulated Share's (1995) self-teaching mechanism by creating a model trained on a small number of grapheme and phoneme correspondences. They found that with initial training, the model was able to learn up to 80% of the orthographic representations through phonological decoding, yielding strong evidence to support the role of phonological decoding in orthographic learning.

Beyond the simulation evidence, self-teaching experiments have consistently demonstrated the importance of decoding ability in constructing orthographic representations. Cunningham et al. (2002) and Cunningham (2006) used the orthographic choice task, the spelling task, and the target-naming task to measure first and second graders' acquisition of orthographic representations. In the orthographic choice task, four alternative spellings of target words were shown to beginning readers, who were asked to choose the correct spelling of the target word. In the spelling task, beginning readers were asked to write the spelling of an orally provided target word. Cunningham found that that the acquisition of an accurate orthographic representation displayed moderate to strong correlations (r =. 52 in the 2002 study and r =.66 in the 2006 study) with an individual's decoding ability. Cunningham (2006) also provided empirical evidence that accurate decoding during reading predicted subsequent learning of orthographic representation.

Moreover, strong and reliable evidence exists that the degree of phonological decoding differentially supports an individual's construction of orthographic representation (de Jong, Bitter, van Setten, & Marinus, 2009; Kyte & Johnson, 2006; Share, 1999). Specifically, in the condition in which phonological decoding was maximized, participants were shown a word and asked to read it aloud. In the minimization condition, students were prompted to pronounce an irrelevant nonsense word while silently reading a list of real words (e.g., the nonsense word DUUBA). The condition designed to maximize phonological recoding led to a stronger construction of a given orthographic representation (de Jong, Bitter, van Setten, & Marinus, 2009; Kyte & Johnson, 2006; Share, 1999).

A series of studies analyzing phonological decoding during silent reading also provides strong evidence that decoding ability is critical for the acquisition of orthographic representations (Bowey & Miller, 2007; Bowey & Muller, 2005; de Jong et al., 2009; de Jong & Share, 2007; Sprenger-Charolles, Siegel, Béchennec, & Serniclaes, 2003). In these studies, researchers found that beginning readers who did not read aloud the story still selected the target spelling more than their homophone foils in an orthographic choice task. Moreover, when considering the homophone foils and their visually similar foil counterparts, homophone foils were more likely to be chosen. In sum, strong and converging evidence exists that decoding ability is an essential factor when accounting for individual differences in the construction of specific orthographic representations of words.

Rapid automatic naming. Theoretically, there are strong arguments for the assertion that rapid automatic naming (RAN) accounts for individual differences in the acquisition of orthographic knowledge, both for specific representations as well as patterns (Bowers et al., 1994; Bowers & Wolf, 1993). After reviewing studies exploring developmental dyslexia and the speed of symbol-naming, Bowers and Wolf (1993) hypothesized that the speed of letter or digit naming is a predictor of the formation of orthographic representations rather than an indicator of phonological processing. Bowers et al. (1994) also proposed that the time it takes to name simple visual symbols, such as single digits or letters, has a significant and independent effect on acquiring orthographic patterns.

Although there is strong theoretical support for the influence of RAN on the acquisition of orthographic representations, the empirical findings are inconsistent (Torgesen, Wagner, Rashotte, Burgess, & Hecht, 1997). Based on her longitudinal-correlational study, Bowers (1995) found evidence suggesting that naming speed contributed to the variance of second through fourth grade students' construction of orthographic representations. Manis, Doi, and Bhadha (2000) also found that second graders' letter and digit naming speed independently contributed additional variance (ranging from 9% to 19%) to their performance on an orthographic choice task when vocabulary knowledge, and either elision or blending ability, had been partialled. Georgiou, Parrila, and Kirby (2009) followed children from Grade 3 to Grade 4 and found that RAN was more strongly linked to accurate performance on orthographic choice tasks than phonological tasks.

In contrast, Torgesen et al. (1997) found that performance on rapid naming tasks (digits and letters) did not explain variability in fourth- and fifth-grade students' acquisition of orthographic representations, after accounting for reading skills in the earlier grade. Similar to Torgesen et al.'s finding, Cunningham et al. (2002) found that second graders' construction of orthographic representations displayed a correlation of .35 with the RAN composite score. However, after adjusting for decoding ability, RAN failed to significantly predict the learning of orthographic representations at the five percent level. Bowey and Miller (2007) also found a similar pattern with third-grade children.

Powell, Stainthorp, and Stuart (2014) compared the learning of orthographic representations between a low RAN group and controls matched on phonological awareness and memory, verbal and nonverbal ability, exposure to print, and age. Intriguingly, they found that among second and third grade students, the low RAN group significantly outperformed the high RAN group when constructing orthographic representations. In short, the field does not yet have enough evidence to conclusively determine the nature of the influence of RAN on the acquisition of orthographic knowledge.

Word Features that Affect Orthographic Learning

Four word features – semantics, morphology, orthographic neighbors, and orthographic consistency – are highlighted in this section and their individual contributions to orthographic learning are considered. These four features represent the meaning of the words, prefixes, suffixes, and roots of words, the common spelling of words, and the grapheme and phoneme connection of the words.

Semantic knowledge. Theoretically, semantic information plays a role in the acquisition of orthographic knowledge (Share, 1995). Contextual information helps an individual resolve decoding ambiguity and select the correct word among a set of competitors (Ziegler, Perry, & Zorzi, 2014). This assertion acknowledges the potential role of semantics within orthographic learning (Ouellette & Fraser, 2009) and suggests a potential interaction between phonology, orthography, and semantics (Wang, Castles, Nickels, & Nation, 2011).

Empirical evidence of the influence of semantic information on the acquisition of specific orthographic representations, however, is mixed. In an effort to test this relation, Cunningham (2006) conducted an experimental study during which she provided two types of reading material with the same target words to two groups of first grade participants: one with and one without semantic and syntactic information. The learning of the orthographic representation of the target words was then assessed. She found that reading with the support of semantic information and syntactic structure facilitated a reader's accuracy when decoding target words, but these contextual clues did not further enhance the memorization of the orthographic representations of target words. Consistent with Cunningham's findings, Nation et al. (2007) used the same design to examine the influence of contextual clues and found that there was no significant difference in seven- and eight- year old children's learning of orthographic representations between experimental groups with and without contextual clues. Interestingly, Landi, Perfetti, Bolger, Dunlap, and Foorman (2006) suggested that learning a new word with semantic information may have a negative effect on first and second graders' acquisition of an orthographic representation of that word. They argued that that presence of semantic information causes the reader to focus less on orthographic and phonological features because they consequently become less crucial for meaning making. In contrast, in a non-word learning context, Ouellette and Fraser (2009) found that semantic information was a significant predictor of fourth graders' construction of orthographic representations. Wang et al. (2011) also found that semantic information was central to second graders' construction of orthographic representations when words had irregular letter-sound correspondence. Thus, the role of semantic information in the acquisition of orthographic representation is far from conclusive.

Morphological knowledge. Morphological knowledge has been viewed as a potential factor supporting orthographic learning, under the supposition that an individual can more easily memorize orthographic representations using morphological codes, such as prefixes and suffixes (Frost, Kugler, Deutsch, & Forster, 2005). The unit of orthographic representation expands from letter-by-letter to word chunk-by-word chunk with increased reading experience and print exposure. This chunking process can be based on the morphological structure of words (McCormick, Rastle, & Davis, 2008; Rastle, Davis, & New, 2004).

In the field of psycholinguistics, several studies have shown that related morphemes prime the recognition of target words (e.g., McCormick, Rastle, & Davis, 2008; Rastle, Davis, & New, 2004; Rastle, Davis, Marslen-Wilson, & Tyler, 2000). In their study, Rastle et al. (2000) utilized a lexical decision task, a task that requires one to judge whether a lexical stimulus is a real word or a pseudoword, to assess adult readers' ability to judge if a letter string constituted a word or a non-word. Rastle et al. created two word lists for a lexical decision task. Half of the words or non-words were presented after corresponding primes (e.g., prime-words or prime-non-words) and the other half were presented without primes. Within the priming condition, the prime-words or prime-non-words were presented in five different conditions: (a) morphologically related, semantically related, and orthographically related primes (e.g., departure–DEPART; +M+S+O); (b) morphologically related, semantically unrelated, and orthographically related primes (e.g., apartment–APART; +M–S+O); (c) morphologically unrelated, semantically related, and orthographically unrelated primes (e.g., cello–VIOLIN; –M+S–O); (d) morphologically unrelated, semantically unrelated, and orthographically related primes (e.g., typhoid–TYPHOON; –M–S+O); and (e) completely same primes (e.g., church–CHURCH). It was observed that lexical decisions were made more rapidly when words were primed with related words than when words were not primed. Most importantly, morphologically related primes (+M+S+O) provided greater priming effects than *only* semantically related (–M+S–O) and *only* orthographic related primes (–M–S+O). Thus, Rastle et al. concluded that morphological structure plays a significant role in the recognition of an English word.

In addition to its contribution to word recognition, morphological knowledge can also resolve encoding ambiguity (Bourassa, Beaupre, & MacGregor, 2011). When an individual encounters encoding challenges, morphological knowledge may assist the speller to produce written morphemes (Bourassa, Treiman, & Kessler, 2006). Additional studies have also demonstrated that morphological knowledge can support an individual's invented spelling (e.g., Ouellette & Senechal, 2008; Chliounaki & Bryant, 2007). Although one could argue that these findings do not directly support the facilitative effects of morphological knowledge in the acquisition of orthographic representation because invented spelling is not a pure measure of orthographic learning, it does capture some aspects of constructing orthographic representations.

Although few studies have examined the influence of morphological knowledge on the acquisition of orthographic representations and pattern knowledge, MacEachron (2008) argued that an understanding of morphology should facilitate first-graders' construction of an orthographic representation. In a follow-up experiment, Callahan (2011) found that the acquisition of an orthographic representation was facilitated when an individual had knowledge of a morphemic part of a word. Although there is a lack of research examining how morphological knowledge affects readers' construction of the orthographic representations of words, the potential benefits of morphological information to expand the unit of orthographic codes is theoretically justified by Grainger and Ziegler's (2011) dual route model of orthographic processing. This model hypothesizes that processing occurs via a coarse-grain route and a fine-grain route. The coarse grain optimizes word identification by using a minimal subset of letters while accessing the meaning; on the other hand, the fine-grain route represents recognition of letter order and their position within a word. Thus, the fine-grain route allows for chunking words based on morphemes.

Orthographic neighborhood effect. Orthographic neighbors refer to words that differ by one letter (e.g., *stop*/*shop*). The orthographic neighborhood effect includes the effect of neighborhood size and the effect of neighbor frequency. The former refers the number of neighbors that a word has and the later to the frequency of a neighboring word. For example, using the Cross-Linguistic Easy-Access Resource for Phonological and Orthographic neighborhood densities database (CLEARPOND), yields the finding that the word *cat* has 33 neighbors[1] and the average frequency of a neighboring word is 33 per million, whereas the frequency of cat is 66.33 per million (Marian, Bartolotti, Chabal & Shook, 2012).

The orthographic neighborhood effect has been widely studied since the 1980s, but findings regarding neighborhood effect on word recognition are contradictory (Andrews, 1997; Davis & Taft, 2005; Forster & Shen, 1996). Contradictory findings are most evident when considering whether neighborhood size and/or neighbor frequency has a facilitatory effect on the performance of lexical decision tasks (LDTs) or naming tasks. Andrews (1997) reviewed 16 experimental studies that assessed the reaction time and/or accuracy for a single presentation of a word utilizing neighborhood size and/or frequency as the control. She found evidence that large neighborhood size facilitates performance on LDTs and naming tasks, even if the targets have higher frequency neighbors. Moreover, Andrews argued that neighborhood size rather than neighbor frequency exerts influence on LDTs. These results are inconsistent, however, with the findings of Grainger, O'Regan, Jacobs, and Segui (1989) who found that frequency, rather than size, is the critical variable (for a detailed discussion about these contradictory findings see Grainger, 1992).

Still, there are multiple studies indicating that large neighborhoods inhibit adults' performance on LDTs and naming tasks. Davis and Taft (2005) examined the influence of

[1]can, car, eat, cut, fat, hat, cab, rat, sat, bat, cap, Pat, Cal, Cam, Nat, mat, Kat, cot, vat, tat, cad, gat, oat, Cag, caw, at, coat, cast, cats, chat, cart, cant, Scat

deletion neighbors (a word that overlaps with all but one deleted letter of the target word; e.g., *overt* vs. *over*) on lexical decision and found an inhibitory effect for reaction time and accuracy when target words had high frequency deletion neighbors. Most importantly, they observed significant differences in reaction time between initial overlap deletion neighbors (e.g., *overt* vs. *over*), final overlap deletion neighbors (e.g., *blast* vs. *last*), and outer overlap deletion neighbors (e.g., *drown* vs. *down*). Inhibitory effects were stronger for the outer overlap condition, which suggests that outer representations of words are more easily detected by the reader, while inner representations of words are more easily ignored. Relatedly, Christianson, Johnson, and Rayner (2005) examined the letter transposition effect and determined that letter transposition within a morpheme resulted in more of a priming effect (operationalized as shorter reaction time on LDTs) than letter transposition across morphemes, after controlling for the influence of syllabic characteristics. These researchers concluded that people are more sensitive to letter transposition across morpheme boundaries than they are to transposition within a morpheme.

Cortese, Watson, Wang, and Fugett (2004) and Glanc and Green (2007), who operationalized orthographic neighbors as words that have the same orthographic and phonologic rime as a target word (e.g., *bat*: *mat*, *cat*, and *tat*), found that a larger rime-orthographic neighborhood size causes interference when recognizing and recalling target words. This finding suggests that larger rime-orthographic neighborhood size causes an inhibitory effect because of the co-activation of phonological and orthographic codes. Yet, rime-orthographic neighborhood size has a faciliatory effect on *associative* recognition tasks (Glanc & Greene, 2009). In the associative recognition tasks, participants were required to recognize pairs of words after the presentation of the list of target words. The words with high rime-orthographic neighborhood size were easier to remember in pairs, due to relational processing. These studies suggest that the effect of orthographic neighbors can be faciliatory or inhibitory, depending on the processing demand(s) of the task.

With regard to beginning readers, Castles and colleagues (1999) used identity primes (e.g., *ball* vs. *BALL*) and form primes (*dall* vs. *BALL*) to examine the effect of neighborhood size on Grade 2, 4, and 6 children. They found that children demonstrated a priming effect on LDTs for both large and small neighborhood size words. Castles and colleagues (2007) further examined the effect of substitution and transposition neighbors on LDTs. They found that Grade 3 children demonstrated a priming effect for both substitution and transposition neighbors. When they conducted a follow-up testing session with the same group of children in Grade 5, the priming effect of the substitution neighbors disappeared, but the priming effect of the transposition neighbors remained statistically significant. Seemingly, the various types of orthographic neighbors function differentially among skilled readers and those developing word recognition ability.

A series of experiments conducted by Goswami (1988, 1990a, 1990b, 1992) provides evidence that seven-to-nine-year-old children can use analogies from the earliest stages of learning to read rime-orthographic neighbors. The number of target words that were correctly pronounced or spelled by participants was higher when participants were exposed to the rime-orthographic neighbors of the target words before learning the target words. This finding suggests that rime-orthographic neighbors allow children to use orthographic analogy to recognize new words (Goswami, 1994; Goswami 1998). Thus, children may be able to utilize rime-orthographic neighbors that exist in their vocabulary to construct orthographic representations of new words.

Consistent with Goswami's findings, Laxon, Coltheart, and Keating (1988) also found benefits to orthographic learning due to the presentation of orthographic neighbors. However, Laxon et al. did not use orthographic neighbors as priming stimuli as in Goswami's studies. Instead, they selected 39 real words and 39 non-words and asked second and third grade students to name the words and make a decision about whether or not they were real. Laxon et al. categorized these real and not real words into two types according to their orthographic neighborhood size: Friendly (Mean no. of neighbors = 11.18) vs. Not Friendly (Mean no. of neighbors = 2.00). One month later, they used an orthographic choice task to assess participants' learning of the orthographic representations of the real words. A spelling task was employed for assessing participants' learning of non-words. Laxon et al. found that performance on the orthographic choice task was lower when the words had fewer orthographic neighbors. This pattern was even more evident in the spelling task. Thus, Laxon et al. argued that orthographic neighbors are an important factor for young readers when acquiring orthographic representations.

Through a series of studies, Apel and colleagues extended findings of the effect of neighborhood size on the acquisition of orthographic representations by manipulating nonwords with high or low orthographic statistical regularities (Apel, 2010; Apel, Thomas-Tate, Wilson-Fowler, & Brimo, 2012; Wolter & Apel, 2010). They used high orthotactic probabilities to represent orthographic patterns that appear frequently in English and low orthotactic probabilities to represent the orthographic patterns that appear infrequently in English. Similar to the self-teaching paradigm, these nonwords were embedded in stories for children to read. They then measured Kindergarten children's acquisition of orthographic representations with both a spelling and an orthographic choice task. They found that high orthotactic probability nonwords were spelled more accurately than low orthotactic nonwords.

Despite the inconclusive findings regarding the effect of orthographic neighbors on skilled readers' visual word recognition and beginning readers' word recognition and learning, current research has demonstrated that that the size and the frequency of orthographic neighbors, as well as the type of neighbor should be considered when examining factors affecting orthographic learning.

Orthographic consistency effect. Orthographic consistency is the degree of correspondence between grapheme (letter) and phoneme (sound). Languages are considered deep or shallow orthographies based on their degree of letter-sound consistency. A language that has a higher degree of orthographic consistency is a shallow orthography (e.g., Spanish); conversely, a language in which there is a lower degree of orthographic consistency is called a deep orthography. In cross language comparisons, English is considered to have a deep orthography because it has a lower degree of orthographic consistency at the one-to-one grapheme to phoneme level (Besner & Smith, 1992), although this is relationship is less opaque at the morphophonemic level (Abbott, Fayol, Zorman, Casalis, Nagy, & Berninger, 2016). It is generally agreed that less transparent orthographies make less reliable use of the letter–sound or grapheme-phoneme connection to recognize words (Wimmer & Goswami, 1994), and phonological decoding is more difficult in less transparent orthographies (Aro & Wimmer, 2003; Landerl & Wimmer, 2008).

Yet, even within English, words differ in their degree of orthographic consistency (e.g., *cat* vs. *eye*; *brunch* vs. *island*) (Johnston, MaGeown & Moxon, 2013). Since orthographic representations of words are retained in memory when their letters become bonded to phonemes and syllables (Ehri, 2014), it is easier to retain the orthographic units for words with a higher degree of orthographic consistency (e.g., *cat*) because they are more easily bonded to their pronunciation. In contrast, it is often more difficult to retain the orthographic code for a word with a lower degree of orthographic consistency because the letter–sound correspondence is not transparent and straightforward and thus does not as easily map onto its pronunciation (e.g., *two*). Therefore, the orthographic consistency effect is another potential factor affecting the construction of orthographic representation.

Orthographic consistency has been demonstrated to influence spelling development and word recognition. Caravolas, Kessler, Hulme, and Snowling (2005) indicated the degree of orthographic consistency of vowels in words significantly predicts four to seven years old children's vowel spelling accuracy and later vowel spelling development. In the field of word recognition, the orthographic consistency effect is bidirectional, including feedforward consistency and feedback consistency (Lacruz & Folk, 2004; Stone, Vanhoy, & Van Orden, 1997). Feedforward refers to spelling-to-phonology consistency, whereas feedback refers to the phonology-to-spelling consistency. Utilizing visual LDTs and the word naming tasks, Lacruz & Folk (2004) found that there are strong feedforward and feedback consistency effects in adult word recognition for both high and low frequency monosyllabic words, after controlling for word length and orthographic neighbors. Participants responded more slowly when the words had an inconsistent letter–sound relationship; this effect was more evident for monosyllabic words. However, Stone, Vanhoy, and Van Orden (1997) found this effect for only low-frequency words. Ziegler, Montant, and Jacobs (1997) replicated Stone et al.'s (1997) experiment and concluded that lexical-decision latencies and errors increase when a word's phonological rime has multiple corresponding orthographic representations. A more recent study conducted by Ziegler, Petrova, and Ferrand, (2008, Exp. 1 & 2), did not yield convincing evidence for the existence of feedback consistency effects in adults' performance on LDTs. The inconsistent findings of the *feedback* consistency effect on word recognition largely attribute to various "levels" of consistency, such as the phoneme to grapheme or syllable (Perry, 2003).

Despite the inconsistent findings in feedback consistency, it is generally agreed that the higher the degree of the letter-sound (feedforward) consistency, the stronger the facilitatory effect of lexical access and word naming. Although the field lacks of sufficient studies of degree orthographic consistency in constructing orthographic representation, the strong connection between orthography and phonology and the significant role that phonological decoding plays in the acquisition of orthographic representations aligns with the proposition that orthographic consistency influences the acquisition of orthographic representation.

Research Gaps to be Addressed

Previous empirical studies have rarely examined the factors that affect or contribute to the acquisition of orthographic patterns. So far, our best hypothesis is that orthographic patterns develop as reading volume improves. Beyond this, there is much to be explored regarding how children acquire orthographic patterns and what factors affect this learning process. Although empirical studies have examined the acquisition of orthographic representations, the findings are far from conclusive.

Current research has demonstrated consistent evidence that phonological decoding and prior crystalized knowledge are two critical factors for constructing orthographic representation. However, the evidence is mixed regarding the quantity of print exposure and rapid automatic naming. Moreover, additional research is needed to explore, in more depth, the role of semantic and morphologic information when acquiring orthographic representations. Studies have demonstrated the orthographic neighborhood effect and its influence on learning orthographic representations. Nevertheless, the fine-grained effect of neighborhood size, frequency, and type of neighbors when constructing orthographic representations is far from determined. The field lacks adequate evidence regarding the consistency effect and its role in constructing orthographic representations.

Researchers in this field have made great strides in attempting to ascertain how orthographic knowledge influences the development of fluent word recognition and have highlighted the relative contribution of orthographic knowledge to word recognition above and beyond phonology. Nevertheless, orthographic learning still represents an understudied frontier (McClung et al., 2012). Our understanding of orthographic learning will be advanced if (1) orthographic knowledge is teased apart from processing and is redefined; (2) assessments that are designed to tap into the construct of orthographic processing are reconsidered and clearly delineated; and (3) potential theoretical and empirical factors that contribute to orthographic learning are further examined. Each of these steps is necessary to provide stronger, explicit, and more stable evidence that will help verify the unique and most influential elements that contribute to orthographic learning.

Redefining orthographic knowledge

As maintained throughout this dissertation, there has not been sufficient emphasis in the literature on operationalizing and defining the nature of orthographic knowledge. Orthographic knowledge must be redefined. For example, it has been argued that phonological representation and the alphabetic principle are not components of orthographic knowledge. Rather, it has been argued that phonological decoding is a factor that explains individual differences in orthographic learning for beginning readers and lays the foundation for orthographic learning (Ehri, 2005, 2004; Share, 1995, 1999, 2004).

Designing accurate assessments for orthographic processing

Most existing studies use extant or breadth of orthographic knowledge to assess orthographic processing (e.g., Cunningham et al., 2001) because no comprehensive measure of orthographic processing is available. Thus, the current empirical evidence supports only the conclusion that "orthographic knowledge" independently contributes to individual differences in word learning. As a result, strong and specific evidence that orthographic processing independently accounts for individual differences in orthographic learning is rare because of the misalignment or lack of appropriate assessments designed to tap into orthographic processing *per se*. In order to bridge this gap, designing more accurate probes for measuring orthographic processing is necessary for future studies (Conard, Harris, & Williams, 2012).

One way to address this is to add a response latency component into orthographic choice tasks, homophone choice tasks, letter string choices tasks, and spelling tasks. The response time for answering these test items correctly could be considered as an indicator of orthographic processing. Hagiliassis, Pratt, and Johnston (2006) utilized this method and their factor analysis of response latency data suggested there are three factors. However, the three factors were difficult to interpret and did not strongly link to the concept of orthographic processing. An innovative approach to overcome the limitations of current orthographic processing assessments is an urgent need in the field.

Comprehensively Exploring Existing and Potential Factors and Their Interactions

Given that individual differences in orthographic learning cannot be fully explained by phonological decoding, other potential factors need to be comprehensively explored. As put forth in this dissertation, existing evidence is inconsistent regarding the role of rapid automatized naming, limited for the role of morphology, inconclusive for the semantic factor, and insufficient for orthographic characteristics of words. More studies are needed to understand the complete array of potential predictors for constructing orthographic representations and acquiring orthographic patterns.

Understanding the contribution of orthographic processing to orthographic learning is a central issue for the field. The importance of orthographic processing has been proposed in many previous studies (e.g., Braker et al. 1992; Cunningham, 2001, 2002, 2006; Stanvoich & West, 1989). However, its precise contribution to orthographic learning has not been fully specified due to the previously reviewed measurement issues and lack of accurate indices tapping into orthographic processing.

Finally, although several previous studies have demonstrated a causal relationship between print exposure and the construction of orthographic representations, the evidence is inconsistent due to variation in the characteristics of word stimuli. Further studies are needed to investigate the quantity and quality of print exposure(s) that are sufficient for constructing solid orthographic representations of words, while controlling for existing phonological, semantic, morphological, and contextual information, and while holding the effect of orthographic characteristics constant.

To date, empirical evidence has bolstered our understanding that although phonological decoding is the primary contributor to variance in individual differences in word learning, phonological skills do not single-handedly explain the development of skilled word recognition (Cunningham, Nathan, & Raher, 2011). Precise and solid orthographic representations that securely link to phonological, semantic, and morphological information allow children to easily recognize printed words. Therefore, continued investigation of the factors and limitations laid out in this review are necessary in order to have a more fully developed model and understanding of word recognition.

Chapter 3 Methodology

The goal of this dissertation study is to explore factors beyond phonological decoding that affect or contribute to orthographic learning. Two arrays of variables are examined: individual differences and word variations. Individual differences refer to individuals' previous knowledge and cognitive ability, including print knowledge, oral vocabulary, decoding ability, phonological processing, and orthographic processing. Word variations refer to differences in word characteristics, including word frequency, word length, degree of phoneme-to-grapheme consistency, and orthographic neighbors. Among these variables the effects of orthographic neighbors are of particular interest, and thus orthographic neighbors are the primary factor when considering the experimental design and the selection of stimuli.

Research Questions and Hypothesis

Five questions are posed:

1. Is there an effect of orthographic neighbors on spelling acquisition?

Does the recollection of the *rime neighbor* of a target word facilitate the construction of the orthographic representation of the target word, compared to words with no neighbors, with transposition neighbors, or with substitution neighbors, after controlling for word variations and individual differences?

Does the recollection of the *transposition neighbor* of a target word facilitate the construction of the orthographic representation of the target word, compared to words with no neighbors, with rime neighbors, or with substitution neighbors, after controlling for word variations and individual differences?

Does the recollection of the *substitution neighbor* of a target word facilitate the construction of the orthographic representation of the target word, compared to words with no neighbors, with rime neighbors, and with transposition neighbors, after controlling for word variations and individual differences?

2. Is there an effect of phoneme-to-grapheme consistency on spelling acquisition?

3. Is there an effect of delay on the participants' performance on the assessments of orthographic learning?

4. Can the participants' ability to learn spelling acquisition improve without specific instruction?

a. Does the participants' ability to learn the spelling of words (assessed by the orthographic choice and spelling tasks) improve across sessions?

5. Are there interactions between the effects of orthographic processing ability and the effects of rime, substitution, and transposition neighbors on the participants' spelling acquisition?

a. Is there a significant interaction between rime neighbors and orthographic processing ability?

b. Is there a significant interaction between substitution neighbors and orthographic processing ability?

c. Is there a significant interaction between transposition neighbors and orthographic processing ability?

Based on the literature review, I hypothesize that there are differences in the effects of the three types of neighbors in the construction of orthographic representations of target words. I hypothesize that all types of orthographic neighbors will facilitate the construction of target words. Given Goswami's work (1988, 1990a, 1990b, 1992) and Castles and colleagues' work (1999, 2007), I hypothesized that rime neighbors will have the strongest facilitating effect, while substitution neighbors will have the weakest.

With respect to Research Question 2, based on the findings of Caravolas, Kessler, Hulme, and Snowling (20005), I hypothesize that the degrees of orthographic consistency can predict the participants' spelling acquisition. The participants are more likely to acquire the spelling of the words with a higher degree of phoneme-to-grapheme correspondence than those with a lower degree of grapheme-to-phoneme correspondence.

Regarding Research Question 3, based on Nation and colleagues' work (2007), I hypothesize that there is an effect of delay on the participants' performance on both the orthographic choice task and the spelling task. Pertinent to Research Question 4, I hypothesize that without specific instructions, the participants' ability to learn the spelling of the words and to use orthographic analogy will not improve from Session 1 to Session 5. Regarding RQ5, due to the nature of the rime neighbors (rime neighbors rhyme with each other), I hypothesize the effect of orthographic processing is less evident for rime neighbors.

Participants

Seventy-one second-grade students (38 boys and 33 girls) from five classrooms in two elementary schools in the San Francisco Bay Area participated in this study. The mean age was 96.15 (*SD* = 3.96) months at the time of beginning data collection. All the participants completed all five sessions of the computer-based experiment. The schools are located in two middle class communities. The participants' cognitive and literacy ability is summarized in Chapter 4 (Results).

Experiment

The experiment consisted of three stages. The first stage was designed to provide the base words as the foundation on which the participants made analogies. The second stage allowed the participants to learn to spell target words with which they were unfamiliar. The control words used as a baseline condition were presented in the second stage. The third stage was designed to assess the participants' orthographic learning.

Prior to Stage 1, the participants were told that they were going to learn some new words, and that they would be quizzed on the spelling of the words after the session. They were also told that they would see each new word three times for five seconds.

In the first stage, the participants viewed base words and selected one picture from four options, in which one corresponded to the meaning of each base word. The participants were required to press a number key (1-4) to answer. This procedure was designed to verify that the participants knew the base words and to prime the base words.

During the second stage, the participants saw the words to be learned and their corresponding pictures. Two types of learning words were used: those that are neighbors of the base words (target words) and those without a neighbor (control words). Each word was presented 3 times for 5 seconds in random order.

In the third stage, the participants completed the posttests both immediately after the computer-based experiment and two days after the experiment. The posttests were orthographic choice and spelling tasks. In the orthographic choice task, the participants saw a picture of a target word that was presented in the experiment, and then chose a target spelling from four options: a target (e.g., *veal*), its alternative homophone (*veel*), its visually similar stimulus (*vael*), and another unrelated word (*vite*). In the spelling task, the participants saw a picture of a target word and then used a pencil to spell the word. In the immediate posttest, the orthographic choice task came before the spelling task. In the delayed posttest, the spelling task came before the orthographic choice task.

Generation of word lists

The CLEARPOND database was used to select the base words and their corresponding neighbors (target words), except for the transposition neighbors, for which data are not included in CLEARPOND. CLEARPOND provides a number of important psycholinguistic measures, such as neighborhood density and neighborhood frequency, both for within-language neighbors and foreign-language neighbors (Marian, Bartolotti, Chabal & Shook, 2012). Transposition neighbors were found in Johnson's (2009) transposition neighbor list.

Base words. Base words had to be words that second grade students had already acquired, so that they could use them as a foundation in making analogies. Three procedures were used to verify the base words were selected well. First, the words had to appear in the Children's Printed Word database (Stuart, Masterson, Dixon & Quinlan, 2002), which consists of words that appear in books for children aged 5–9 years old. Second, the list of base words was provided to the schoolteachers. They circled the words that they believed second grade students must know and crossed out any words that they believed they did not know. Third, the participants completed a pretest two weeks before the experiment to confirm that they recognized the base words.

Target words. Target words had to be words that second grade students could not yet spell, so that their ability to recognize and spell the target words could be considered evidence of learning. In addition, a target word had to be an orthographic neighbor of a base word.

Similar procedures were used to verify that the target words were selected well. First, the list of target words was provided to the teachers, who crossed out the words that they believed second grade students did not know. The participants completed a pretest to verify that they could not recognize the target words.

Control words. Control words are those that have no neighbors. The same procedure was applied to the selection of the control words in order to confirm that their selection was appropriate.

Ideally, target words and control words should not be recognized by the participants in the pretest. Nevertheless, this goal was constrained. Finding words with various types of neighbor words and without neighbors limited the options. Not much freedom was left after setting the rules for finding orthographic neighbors. As mentioned in the beginning of Chapter 3, orthographic neighbors are the primary factor when considering the experimental design and the selecting of words. As a result, a statistical method was applied to overcome this limitation: Use pretest accuracy as a word-level covariate in three-level logistic models. This method, used by Elleman, Steacy, Olinghouse, and Compton (2017), can partial the influence of each individual's pretest accuracy on spelling acquisition.

Words in the experiment

This study includes five sessions of the experiment. In each session, the participants see two base words and seven learning words (including target and control words). More than one type of neighbor was manipulated in each session. Appendix A provides a table that summarizes the words by sessions, effects, and base words.

Session 1. The first base word is *couch*. The target words include *pouch* [rime neighbor], *crouch* [rime neighbor] and *conch* [substitution neighbor]. The control word is *tulip*.
The second base word is *lion*. The target words include *loin* [transposition neighbor] and *Zion* [rime neighbor]. The control word is *yeti*.

Session 2. The first base word is *rain*. The target words include *rein* and *ruin* [substitution neighbors] and *vain* [rime neighbor]. The control word is *okra.*
The second base word is *clam*. The target word is *calm* [transposition neighbor]. The non-neighbor target is *slam* [rime neighbor]. The control word is *envy*.

Session 3. The first base word is *witch*. The target words include *hitch* and *switch* [rime neighbors]. The control words are *vicar* and *whimsy.*
The second base word is *able*. The target words include *albe* [transposition neighbor] that was assigned to the meaning of an alien creature, and *axle* [substitution neighbor]. The pseudoword *albe* is used in this study because the limited number of transposition neighbors in English.

Session 4. The first base word is *camp*. The target words include *champ*, *clamp*, and *cramp* [rime neighbors]. The control word is *vomit*.
The second word is *step.* The target words include *stew* [substitution neighbor] and *strep* [rime neighbor]. The control word is *ibex*.
Session 5. The first base word is *state*. The target words include *estate* and *statue* [rime neighbors], and *skate* [substitution neighbor]. The control word is *musket.*
The second base word is *stain*. The target words include *satin* [transposition neighbor] and *stein* [substitution neighbor]. The control word is *abbey*.

Measures for individual differences

Participants were assessed using three standardized tests, one non-standardized test, and one self-designed assessment of orthographic processing. These assessments are designed to measure the participants' decoding ability, oral language ability, print knowledge, and phonological and orthographic processing ability.

Decoding ability. Decoding was assessed by the Word Attack subset of the Woodcock-Johnson III Test of Achievement (WJ-III: Woodcock, McGrew, & Mather, 2007). This subtest is designed to assess children's ability to phonologically decode pseudowords, such as *gusy* or *sluke*. It has 32 items. For respondents aged 7-10 years, the split-half reliability ranged from .88 to .92. The score was transformed into z-scores when used in three-level logistic regression analyses.

Oral language ability. This was assessed by the Peabody Picture Vocabulary Test-Fourth Edition (PPVT: Dunn & Dunn, 2007). This assessment is designed to assess both children's receptive and expressive vocabulary and includes 228 items. In this study, PPVT was used to measure receptive vocabulary. For respondents aged 7-10 years, the test-retest reliability was .91, the split-half reliability ranged .90 to .95, and the Cronbach's alpha is .94 to .97. The score was transformed into z-scores when used in three-level logistic regression analyses.

Print knowledge. This was assessed by the Letter and Word Identification subtest of WJ-III (Woodcock, McGrew, & Mather, 2007) and a non-standardized test, the prior orthographic knowledge task, the latter developed by Olson, Kliegl, Davidson, and Foltz (1985). The Letter and Word Identification subtest is designed to assess children's ability to recognize letters and words in print. It has 75 items, including letters (e.g., *P*, *E*), one syllable words (e.g., *car, must*), and morphologically complex words (e.g., *achieved*, *domesticated*). The participants were required to pronounce the items aloud. The reliability of this test for various age groups was reported in McCrew et al. (2007). The reliability for respondents aged 7-10 years ranged from .93 to .97. The prior orthographic knowledge task is designed to assess children's ability to pick the correct spelling between two homophones (e.g., *rain* vs. *rane*) in English. A composite score formed by averaging the z-scores of these two tests was used in three-level logistic regression analyses.

Phonological processing. This variable was assessed by the Elision and Blending subtests of the Comprehensive Test of Phonological Processing (CTOPP: Wagner, Torgesen, & Rashotte, 1999). The Elision task requires children to delete a sound from a stimulus word and state the resulting word. For example, *winter* without the /t/ sound is *winner*. The Blending task requires children to blend phonemes together. For example, once blended together the isolated sounds /s/ /t/ / æ/ /m/ /p/ form the word *stamp*. Both subtests have 20 items. Reliability for these measures were reported in Wagner et al. (1999). The Elision reliability ranged from .89 to .91 for respondents aged 7-10 years. The Blending reliability ranged from .79 to .87 for respondents aged 7-10 years. A composite score that was formed by averaging the z-scores of these two tests was used in three-level logistic regression analyses.

Orthographic processing. This variable was assessed by a self-designed tool, using the software E-Prime 2.0 Professional (Psychology Software Tools, 2013). This tool assesses the participants' ability to perceive, store and retrieve, add and remove, and arrange orthographic representations (English letters) and orthographic patterns (American English spelling rules). This assessment comprises of six different tasks. Each task has 9 to 12 actual items plus 1 to 4 practice items. The first five tasks require a fixed response, and the sixth task requires an open-ended response. The assessment includes 60 actual items. The instructional statements and questions were presented in New Courier 36 in black. Stimuli and choices were presented in Arial 42 in blue and shown on a 12-inch screen. The participants used a keyboard to respond (choosing number 1, 2, 3 or 4). For detailed information, please see Appendix B.

One hundred and forty participants (66 boys and 74 girls) were administered the computer-based orthographic processing assessment. Thirty-four participants were third to sixth grade students in Taiwan, and 106 students were elementary students from four schools in the San Francisco Bay area. These 140 participants' responses on the orthographic processing assessment were used in a Rasch model analysis to examine the reliability of this assessment and design of items.

Reliability. The item separation reliability was .93, suggesting that the items were sufficiently well separated by the participants. The person separation reliability was .93, suggesting that the participants' ability was sufficiently well measured by the items. Most items had .30 or lower standard errors, except Item 58 [*create*] with a standard error of .42. Item 58 was used to assess the children's ability to rearrange six letters: *a, c, e, e, r, t*; this is the most difficult item of the orthographic processing assessment. The larger standard error might emanate from the finding that only two out of 140 respondents answered this item correctly.

Measures for Word Characteristics

Word Frequency. Word Frequency was calculated by using the Corpus of Contemporary American English (COCA) dataset (Davies, 2015). It represents the number of time that a word appears out of 520 million words in 220,225 texts, including 20 million words each year from 1990-2015.

Number of Letters. It represents the number of letters in a word.

Phoneme-to-Grapheme Consistency. Phoneme-to-grapheme consistency was calculated by using the method proposed by Berndt, Reggia, and Mitchum (1987). Each phoneme could be spelled in various ways, and the percentage of a given letter or letters to present a phoneme was calculated. A ratio was generated by taking the ratio between the percentage that a given letter was used to present a phoneme divided by the percentage of the most frequent letter to present the phoneme. The phoneme-to-grapheme consistency of a word was the average of the ratios of phonemes. The percentage of times that a given letter was used to present a phoneme was calculated in Hanna, Hanna, Hodges, and Rudorf (1966). For example, the word, *vain*, pronounced as /ven/, includes three phonemes, /v/, /e/, and /n/[2]. The percentage of using *v* to represents /v/ is 100%, and *v* is the most frequent letter that is used to represent /v/, so the phoneme-to-grapheme of /v/ in *vain* is 1 (100/100 = 1). The percentage of using *ai* to represent /e/ is 17.86%, and the most frequent letter, *a*, is 63.90%, so the phoneme-to-grapheme of /e/ in *vain* is 0.28. (17.86/63.90 = 0.28) The percentage of using n to represent /n/ is 97.51%, and the most frequent letter, *n* is 97.51%, so the phoneme-to-grapheme of /n/ in *vain* is 1 (97.51 / 97.51 =1). Therefore, the phoneme-to-grapheme consistency of *vain* is 0.76 {(1 + 0.28 + 1) / 3 = 0.76}.

Procedure

This study consisted of four phases: a pilot study for orthographic processing, a pilot study for word selection, a pretest, and a main study.

Pilot studies for the self-designed orthographic processing assessment. Two pilot studies were conducted to test the reliability and validity of the orthographic assessment in Fall 2014 and Summer 2015.

Pilot study of word selection. The goal of the pilot study was to finalize the selection of words. Schoolteachers circled the words that they thought second grade students should know and crossed out the words that they believed they did not know.

Pretest. Based on the information obtained in the pilot study of word selection, I designed a multiple-choice task, where the participants selected the correct spelling among four options. For example, the participants saw a picture of pouch, and they selected a spelling among four options, *powch*, *pouct*, *pouch*, *poack*. The students completed the pretest two weeks before Session 1 of the experiment.

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[2] The Kenyon and Knott phonetic symbols are used here. In the Kenyon and Knott's system, they considered the "ay", /e/, in *day* as one sound or phoneme. The entire phonetic symbols can be found in Kenyon, J. S. & Knott, T. A. (1953). A pronouncing Dictionary of American English (2nd ed.). Springfield, MA: Merriam-Webster.

Main study. 71 second grade students completed the individual difference assessments within a month. After the assessments, each session of the experiment was conducted within one week. The second session did not begin until the first session was completed. The outcome assessments for each session were administered immediately and two days after the session.

Data Analysis

Before using three-level hierarchical logistic modeling to analyze the data, I examined outliers and patterns of missing data. I used the rule of interquartile range, third quartile ± 1.5*(third quartile – first quartile), to identify outliers. If a participant had more than 3 variables that were considered as outliers, he/she would be excluded from data-analyses.

Three-level logistic modeling with random effects for sessions and participants was used to analyze the data. The model allows between-participants variation in orthographic learning outcomes due to the individual differences in participants. The model also allowed for between-session, within participant variation due to contextual effects at the session level. The outcome variable is the participants' performance on the orthographic choice and spelling tasks, both dichotomous variables. Level 1 includes the characteristics of the words, Level 2 those of the sessions, and Level 3 those of the participants. Let the outcome variable for word i in session j learned by student k be denoted by Y_{ijk}. The model in its reduced form is written as:

$$\begin{aligned}\text{logit}\{\Pr\left(Y_{ijk} = 1 \middle| X_{\text{ijk}}, X_{\text{jk}}, X_{\text{k}}, \zeta_{0\text{jk}}^{(2)}, \zeta_{00\text{k}}^{(3)}\right)\} \\ = \beta_0 + \beta_1 \text{Pretest}_{\text{ijk}} + \beta_2 \text{BaseWord}_{\text{ijk}} + \beta_3 \text{LetterN}_{\text{ijk}} \\ + \beta_4 \text{Frequency}_{\text{ijk}} + \beta_5 \text{PGC}_{\text{ijk}} + \beta_6 \text{Rime}_{\text{ijk}} + \beta_7 \text{Sub}_{\text{ijk}} \\ + \beta_8 \text{Trans}_{\text{ijk}} + \beta_9 \text{Session}_{\text{jk}} + \beta_{10} \text{PhonP}_{\text{k}} + \beta_{11} \text{OralLan}_{\text{k}} + \beta_{12} \text{Decoding}_{\text{k}} \\ + \beta_{13} \text{PrintK}_{\text{k}} + \beta_{14} \text{OrthP}_{\text{k}} + \beta_{15} \text{Rime}_{\text{ijk}} \times \text{OrthP}_{\text{k}} + \beta_{16} \text{Sub}_{\text{ijk}} \times \text{OrthP}_{\text{k}} \\ + \beta_{17} \text{Trans}_{\text{ijk}} \times \text{OrthP}_{\text{k}} + \zeta_{00\text{k}}^{(3)} + \zeta_{0\text{jk}}^{(2)}\end{aligned}$$

where

- β_0 is the grand-mean intercept,
- $\text{Pretest}_{\text{ijk}}$, represents the participants' performance on pretest (1: correct answer and 0: incorrect answer),
- $\text{BaseWord}_{\text{ijk}}$, represents the participants' ability to recognize base words (1: correctly recognize base word and 0 incorrectly recognize base word),
- $\text{LetterN}_{\text{ijk}}$ is the number of letters,
- $\text{Frequency}_{\text{ijk}}$ represents the log of word frequency,
- PGC_{ijk} represents the strength of phoneme to grapheme correspondence,
- Rime_{ijk}, Sub_{ijk}, $\text{Trans}_{\text{ijk}}$ are the dummy variables that represent the conditions of rime, substitution, and transposition neighbors (with the control words as the reference group),
- $\text{Session}_{\text{jk}}$ is the session number,
- PhonP_{k} is phonological processing ability,
- $\text{OralLan}_{\text{k}}$is oral language ability,
- $\text{Decoding}_{\text{k}}$ is decoding ability,
- PrintK_{k} is print knowledge,
- OrthP_{k} is orthographic processing ability,

- $\mathrm{Rime_{ijk}}\times\mathrm{OrthP_k}$, $\mathrm{Sub_{ijk}}\times\mathrm{OrthP_k}$, and $\mathrm{Trans_{ijk}}\times\mathrm{OrthP_k}$ are the cross-level interactions between rime, substitution, and transposition neighbors and orthographic processing ability,
- $\zeta_{0jk}^{(2)}$ is the session-level residual (assumed to be normally distributed with zero mean, and given the covariates, the random intercept has variance $\psi_{00}^{(2)}$)
- $\zeta_{00k}^{(3)}$ is the random intercept or the participant-level residual (assumed to be normally distributed with zero mean and given the covariates, the random intercept has variance $\psi_{00}^{(3)}$),
- and β_1 to β_{17} are the corresponding coefficients.

Research Question 1

To test the effect of orthographic neighbors on spelling acquisition, the coefficients of interest are $\beta_6, \beta_7, \beta_8$. Each coefficient represents the effect of a given neighbor on the participants' spelling acquisition, compared to the words without neighbors (control words). The coefficient of the $\mathrm{BaseWord_{ijk}}$, β_2, provides additional evidence by demonstrating the influence of knowing the base words on spelling acquisition.

Research Question 2

To examine the effect of orthographic consistency, β_5 is the coefficient of interest. It represents the influence of phoneme-to-grapheme consistency (feedback consistency) on spelling acquisition.

Research Question 3

To address whether there is an effect of delay on the participants' performance on the orthographic choice task and the spelling task, a one-sample t-test was performed to test the difference in mean between the immediate and delayed orthographic choice task, as well as the difference in mean between the immediate and delayed spelling task.

Research Question 4

To examine the effect of sessions, the coefficient of interest is β_9. Specifically, β_9 represents the change in the ability to learn spelling (the logit of probability to answer an item correctly each session) when the participants take one more session.

Research Question 5

To examine the interaction between orthographic processing ability and the types of neighbors, the coefficients of interest are $\beta_{15}, \beta_{16}, \beta_{17}$.

Unexplained heterogeneity

Unexplained heterogeneity can be expressed by the residual intraclass correlations of the latent response and the median odds ratio.

The median odds ratio, proposed by Larsen and colleagues (2000), represents the median of the odds ratios of pairs of randomly sampled units having the same covariate values, where the unit that has the larger random intercept is compared with the unit that has the smaller random intercept.

Chapter 4 Results

Beginning with descriptive statistics, this chapter first summarizes the participants' performance on a series of assessments—their pretest and posttests. Along with the descriptive statistics, the corresponding classical tests are presented. Then, the multiple three-level hierarchical linear models with random effects for sessions and participants are reported, the methods for identifying the final model are discussed, and the estimates are interpreted.

Performance on Cognitive, Language, and Literacy assessments

The participants' cognitive, language, and literacy ability, along with the corresponding age-comparable national norms, are summarized in Table 1. The age-comparable national averages or the 50 percentiles are reported. Compared to norms, the participants had higher performance on Word Attack, PPVT, and Letter Word Identification. These assessments measure the participants' decoding ability, oral receptive vocabulary, and word identification ability. In contrast, the participants' performances on Elision, Blending, RAN-Number, RAN-Letter were similar to the national average. These tests measured the participants' ability in phonological processing.

Two participants' performance on RAN-Number and one participant's performance on RAN-Letter were higher than $Q_3 + 1.5(Q_3 - Q_1)$, third quartile + 1.5(third quartile – first quartile). These observations were one measure of 64 seconds and one measure of 76.68 seconds on RAN-Number, and one measure of 76.14 seconds on RAN-Letter. The measures of 76.68 seconds on RAN-Number and 76.14 seconds on RAN-Letter belonged to the same participants. Four observations in orthographic knowledge fell beyond $Q_1 - 1.5(Q_3 - Q_1)$, first quartile – 1.5(third quartile – first quartile). These observations were four scores of 15 on the orthographic knowledge task. These responses are reasonable because the reaction time data are typically skewed to the right. The lower performance on the orthographic choice task reflected that some participants did not master American English patterns. Using the rule of interquartile range, no participants in this study had more than two observations that were potential outliers. Thus, all participants were included in the data analyses. One participant did not participate in Session 1 of the delayed posttests, so there was one missing observation in the delayed orthographic choice task and the delayed spelling task in Session 1. Both tasks include seven items, and thus the total amount of missing data was 0.56%.

Table 1. Raw Score on Each Assessment

Measures	n	Range			Age-comparative
		Mean (SD)	Sample	Possible	average or 50%iles*
Elision	7	12.76(4.29)	6–20	0–20	10-13
Blending	7	13.00 (2.57)	7–18	0–20	11-14
Word Attack	7	19.54(5.99)	7–30	0–32	12-14
RAN-Number	7	39.23 (9.26)	22.29–72.68	Time	37-45
RAN-Letter	7	42.75 (8.70)	23.96–76.14	Time	40-49
Letter & Word	7	49.24(7.45)	36–65	0–76	32-43
PPVT	7	142.85(15.31)	111–179	0–192	100.1 (14.7)
Orth. Knowledge	7	22.10 (2.04)	15–23	0-23	N.A.
Orth. Processing	7	36.30 (9.89)	13–54	0-60	N.A.

Note. RAN-Number: rapid automatic digit naming; RAN-Letter: rapid automatic letter naming; Orth. Knowledge: Orthographic knowledge; Orth. Processing: Orthographic processing; Letter & Word: Letter & Word Identification.
Elision, Blending, RAN-Number, and RAN-Letter are subtests of CTOPP; Word Attack and Letter & Word are the subtests of WJ-III. Orthographic Knowledge and Orthographic Processing are non-standardized assessments; *The age-related norm was reported by the research team of each standardized assessment.

Performance on the Pretest and Posttest

The proportion of the participants who answered each item correctly on the pretest test is summarized in the second column (Pretest) in Table 2. Depending on the words, the proportion of the participants who selected correct spelling on the pretest ranged from 23% to 86%. It is critical to note that the pretest is a spelling-picture matching test, where the participants choose a corresponding spelling for a given picture. The task difficulty is much lower than for the spelling tasks. A correct response on the pretest does not necessarily imply that the participants have solid knowledge of the orthographic representation of a word. A correct response might also be due to the effect of guessing. There was significant variation between words, $F(34, 2450) = 13.12$, $p < .001$, reflecting the need to conduct item-by-item analyses of orthographic learning. To account for this variation of the pretest performance and to partial out the influence of the effect of pretest accuracy on spelling acquisition, pretest accuracy was included as word-level covariate in the three-level logistic models. The participants' performance on the orthographic choice tasks and spelling tasks across target words is reported in the third to sixth columns in Table 2.

Table 2. Proportion of Participants with Correct Responses by Target Words

Target word	Pretest	Choice Immediate	Choice Delayed	Spell Immediate	Spell Delayed
albe	pseudoword	0.86	0.85	0.48	0.28
axle	0.48	0.85	0.79	0.49	0.41
calm	0.77	0.93	0.94	0.85	0.69
champ	0.79	0.9	1	0.89	0.8
clamp	0.56	0.86	0.87	0.8	0.68
conch	0.37	0.8	0.67	0.37	0.31
cramp	0.86	0.89	0.87	0.85	0.85
crouch	0.61	0.85	0.73	0.76	0.64
envy	0.41	0.7	0.76	0.52	0.41
estate	0.59	0.9	0.83	0.61	0.37
hitch	0.52	0.79	0.7	0.55	0.42
ibex	0.28	0.56	0.61	0.58	0.42
itch	0.38	0.82	0.61	0.7	0.54
loin	0.27	0.86	0.89	0.54	0.44
musket	0.44	0.66	0.59	0.51	0.45
okra	0.27	0.8	0.61	0.48	0.38
pouch	0.79	0.9	0.87	0.85	0.83
rein	0.46	0.86	0.8	0.69	0.51
ruin	0.42	0.87	0.75	0.69	0.56
satin	0.45	0.85	0.79	0.39	0.28
skate	0.75	0.86	0.92	0.83	0.82
slam	0.79	0.92	0.99	0.96	0.92
statue	0.72	0.77	0.75	0.54	0.54
stein	0.48	0.86	0.56	0.41	0.21
stew	0.73	0.9	0.86	0.86	0.72
strep	0.39	0.79	0.82	0.59	0.44
switch	0.37	0.77	0.65	0.56	0.45
theft	0.37	0.86	0.73	0.63	0.44
tulip	0.61	0.8	0.44	0.66	0.63
vain	0.49	0.86	0.77	0.80	0.58
vicar	0.23	0.87	0.62	0.62	0.30
vomit	0.46	0.87	0.96	0.80	0.72
whimsy	0.30	0.7	0.82	0.35	0.23
yeti	0.56	0.93	0.79	0.69	0.66
zion	0.24	0.76	0.81	0.63	0.63
Total	0.49	0.83	0.77	0.64	0.53

Table 3. Participants' Performance Across Sessions

Sessions	Choice IM	Choice DL	Spell IM	Spell DL
	Mean (*SD*)	*Mean* (*SD*)	*Mean* (*SD*)	*Mean* (*SD*)
Session 1	5.90 (1.43)	5.20 (1.61)	4.49 (1.94)	4.08 (2.03)
Session 2	5.62 (1.47)	5.62 (1.47)	4.99 (1.91)	4.04 (2.15)
Session 3	5.66 (1.29)	5.03 (1.96)	3.76 (2.31)	2.62 (2.38)
Session 4	5.77 (1.50)	5.99 (1.21)	5.37 (1.88)	4.62 (2.08)
Session 5	5.76 (1.57)	5.16 (2.03)	3.92 (2.45)	3.10 (2.23)
Average	5.81 (1.45)	5.40 (1.71)	4.50 (2.19)	3.70 (2.29)

Note. Choice = Orthographic choice task; Spell = Spelling task; IM = Immediately after the experiment; DL = Two days after the experiment

Performance on the orthographic choice tasks and the spelling tasks across sessions is summarized in Table 3. In each session, the participants spelled and chose seven words, thus the range for these four variables was 0 – 7. Session 3 had the lowest scores for all these four tasks. The effect of the two-day delay was significant for the orthographic choice task, $t(353) = 5.67$ $p < .001$, *Cohen's d*= 0.30; and for the spelling task, $t(353) = 10.87$, $p < .001$, *Cohen's d* = 0.58. The participants performed better on the orthographic choice task than on the spelling task across five sessions, both on the immediately posttests, $t(354) = 14.11$, $p < .001$, *Cohen's d* = 0.75; and the two-day delayed posttests, $t(353) = 20.70$, $p <.001$, *Cohen's d* = 1.10.

Participants' performance on the pretest, the orthographic choice tasks, and the spelling tasks by word types is summarized in Table 5. The results of the two-sample tests of proportions are summarized in Table 6. For the control and rime words, the participants' performance on the four posttests was higher than on the pretest. For the substitution words, the participants' performance on the immediate orthographic choice task, the delayed orthographic choice task, and the immediate spelling task was higher than on the pretest, but their performance on the delayed spelling task was not higher than on the pretest. The same pattern was found in the transposition words: all posttests were higher than the pretest except for the delayed spelling task.

Among the four types of posttests, the average percentage of participants who provided correct responses was lowest for the control words in the immediate and delayed orthographic choice tasks. For the immediate and delayed spelling tasks, the transposition words had the lowest average percentage of participants who spelled the words correctly. The rime words had the highest average percentage of participants who spelled the words correctly at both the immediate and the delayed spelling tasks. In short, no conclusive pattern could be found based on the average effect of word types, for the primary reason that the influences of other word-features had not been partialled. These word features include word frequency, the number of letters, and orthographic consistency. In three-level logistic analyses, these word features were statistically controlled.

Table 4. Participants' Performance Across Word Types

Word types	Number of words	Pretest	Choice IM	Choice DL	Spell IM	Spell DL
Control	10	39.15%	77.74%	69.21%	58.45%	46.19%
Rime	14	58.05%	84.71%	81.74%	74.14%	63.87%
Substitution	7	52.31%	84.51%	73.99%	57.74%	46.57%
Transposition	4	37.23%	87.32%	86.57%	56.33%	42.40%

Note. The pretest is in an orthographic choice format, where participants selected the correct spelling among four options.

Correlations Between Tasks

The Pearson's correlations between tasks are summarized in Table 7[3]. *Elision* was significantly correlated with all the other tasks, $.25 \leq |r| \leq .57$, except for *Choice IM*, *Choice DL* and *Pretest*. *Blending* moderately correlated with *Word Attack*, *Letter & Word*, *PPVT*, *Orth. Proces*sing, *Spell IM* , *Spell DL*, and *Pretest*, $.34 \leq |r| \leq .46$. However, *Blending* did not significantly correlate with *Orth. Knowledge*, *RAN-Number*, *RAN-Letter*, and the two orthographic choice posttests. *RAN-Letter* and *RAN-Number* strongly correlated with each other, $r = .82$, and moderately correlated with *Elision*, *Word Attack*, *Letter & Word*, *Orth. Processing*, and *Spell IM*, $-.30 \leq r \leq -.38$.

Word Attack significantly correlated with all the other tasks $.30 \leq |r| \leq .73$; among these correlation coefficients, the correlation coefficient between *Word Attack* and *Letter & Word* was highest. *Letter & Word* significantly correlated with all other tasks. Of these significant correlation coefficients, the correlations with *RAN-Number* and with *RAN-Letter* were the weakest, both $r = -.30$.

PPVT did not correlate with *RAN-Number*, *RAN-Letter*, *Orth. Knowledge*, and *Pretes*t at the 5% significance level. Among the significant correlations with *PPVT*, the degree of correlation was strongest between *PPVT* and *Letter & Word*.

Orth. Knowledge significantly correlated with most tasks, except for *Blending*, *RAN-Number*, *RAN-Letter*, and *PPVT*. Among the significant correlations with *Orth. Knowledge*, the correlation between *Elision* and *Orth. Knowledge* was the weakest, $r = .25$ and the correlations with *Choice IM* was the strongest, $r = .65$.

[3] In this dissertation, all numbers are rounded to the two decimal places except for the p-values, which are rounded to three decimal places. Due to the limited space, unlike the other parts of results in this chapter, p-values were reported to two decimal places instead of three decimal places in the correlation table.

Orth. Processing significantly correlated with all the other tasks, $.33 \leq |r| \leq .73$. The strongest correlation of *Orth. Processing* was with *Spell IM* and the two weakest correlations were with *RAN-Number* and *RAN-Letter*.

For *Pretest* and all the posttest tasks (*Choice IM*, *Choice DL*, *Spell IM*, *Spell DL*), they significantly correlated with one another. The correlations between *Pretest* and each posttest task ranged from .29 to .48 and the degree of correlations between each posttest ranged from .55 to .71.

Table 5. Correlation Between Tasks

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.
1.Elision	1													
2.Blending	.4	1												
	(<.01)													
3.WordAttack	.55	.46	1											
	(<.01)	(<.01)												
4.RAN-Number	–.3	–.12	–.36	1										
	(.01)	(.31)	(<.01)											
5.RAN-Letter	–.3	–.15	–.38	.82	1									
	(.01)	(.22)	(<.01)	(<.01)										
6.Letter & Word	.51	.41	.73	–.30	–.30	1								
	(<.01)	(<.01)	(<.01)	(.01)	(<.01)									
7.PPVT	.31	.39	.36	–.06	<0.01	.46	1							
	(.01)	(<.01)	(<.01)	(.63)	(.98)	(<.01)								
8.Orth.Knowedge	.25	.02	.46	–.17	–.21	.55	.13	1						
	(.04)	(.84)	(<.01)	(.15)	(.09)	(<.01)	(.29)							
9.Orth.Processing	.57	.45	.61	–.37	–.33	.59	.39	.46	1					
	(<.01)	(<.01)	(<.01)	(<.01)	(.01)	(<.01)	(<.01)	(<.01)						
10.Pretest	.01	.15	.30	–.23	–.12	.49	.20	.35	.28	1				
	(.92)	(.22)	(.01)	(.06)	(.33)	(<.01)	(.09)	(<.01)	(.02)					
11. Choice IM	0.11	0.13	.41	–.23	–.17	.49	.29	.65	.49	.43	1			
	(.38)	(.28)	(<.01)	(.06)	(.16)	(<.01)	(.01)	(<.01)	(<.01)	(<.01)				
12. Choice DL	0.18	0.19	.40	–.12	–.13	.51	.29	.51	.49	.29	.68	1		
	(.13)	(.12)	(<.01)	(.31)	(.27)	(<.01)	(.01)	(<.01)	(<.01)	(<.01)	(<.01)			
13. Spell IM	.42	.34	.60	–.38	–.31	.64	.40	.50	.73	.37	.55	.58	1	
	(<.01)	(<.01)	(<.01)	(<.01)	(.01)	(<.01)	(<.01)	(<.01)	(<.01)	(<.01)	(<.01)	(<.01)		
14. Spell DL	.33	.38	.57	–.19	–.22	.71	.44	.59	.63	.48	.60	.71	.71	1
	(<.01)	(<.01)	(<.01)	(.11)	(.06)	(<.01)	(<.01)	(<.01)	(<.01)	(<.01)	(<.01)	(<.01)	(<.01)	

Note. p-values are in the parentheses

Three-Level Logistic Models

The probability of correctly spelling a target word or choosing a target word was estimated by using three-level logistic regression with random effects for sessions and participants. The three-level logistic regression is similar to latent regression linear logistic test models (De Boeck, Wilson, 2004; Fischer, 1973; Zwinderman, 1997), except that the three-level logistic regression additionally includes the random effects at the session level.

The *melogit* function in Stata was used to estimate parameters. It assumes the conditional distribution of the response given the random effects to be Bernoulli, with success probability determined by the logistic cumulative distribution function. When estimate parameters were less than 1×10^{-5}, the *meqrlogit* function in Stata was used (Version14). Both functions were designed to fit mixed-effects models for dichotomous responses. The difference between *melogit* and *meqrlogit* is that *meqrlogit* uses the QR decomposition of the variance-components matrix. This method may aid convergence when variance components are near the boundary of the parameter space.

The outcome variables are the participants' responses on both immediate and delayed orthographic choice and spelling tasks: Correct responses were coded as 1 and incorrect responses as 0. The Level 1 (word level) variables include the log frequency of each target word, phoneme-to-grapheme consistency of each target word, the pretest performance of each target word, the performance on each base word, and the types of orthographic neighbors of the target words. The Level 2 (session level) variable is the session number. The Level 3 (participant level) variables include the participants' phonological processing ability, decoding ability, print knowledge, and orthographic processing.

To make sure that the estimation is adequate, multiple integration points were used until the estimation stabilized. The odds ratios are reported in tables. The intercept is not an odds ratio, as the column heading implies, but the odds when all covariates are zero. Before presenting models for each outcome variable, unconditional intraclass correlations were reported.

Model constructions and comparisons

Each outcome variable was analyzed individually. First, a model without covariates was fitted. Second, random intercept models with various fixed effects of word level covariates, the session level covariate, and participant level covariates were considered. Then, random coefficients for orthographic neighbors (Rime, Substitution, Transposition) and phoneme-to-grapheme, word frequency, and word length were considered. Last, cross-level interactions between types of orthographic neighbors and the participants' orthographic processing were tested.

Likelihood ratio tests, Bayesian Information Criterion (BIC), were used to compare models. Likelihood ratio tests were used to compare nested models and BICs were used to compare models with different random parts. Snijders and Bosker's (2012) R^2 was also provided. Snijder and Bosker's (2012) R^2 is extended from McKelvery and Zavoina's (1975) R^2. In logistic regression models, the level-1 residual variance for the latent response is fixed to 3.29. Thus, unlike the typical interpretation R^2 in linear regression (i.e. the proportion of variance explained by the covariates in a model), the R^2 in this dissertation was only used for model comparisons.

Intraclass correlations

The performance on orthographic learning of each word correlated within participants and within session, so the participants' performance on the spelling acquisition of each word was clustered within sessions that were nested in participants. Based on a three-level logistic regression model without covariates, the highest estimated intraclass correlation was for SpellIM, $ICC_{participant \mid session} = .50$, $p < .01$, 95% CI[.41, .59]; $ICC_{participant} = .40$, p < .001, 95% CI [.31, .51]. The lowest correlation was for ChoiceIM, $ICC_{participant \mid session} = .32$, $p < .001$, 95% CI[.23, .42]; $ICC_{participant} = .30$, $p < .001$, 95% CI [.22, .41]. The intraclass correlation under the column of "within the same participant" can be interpreted as the amount of variation in participants' performance on a given posttest that is explained by the individual differences between the participants. For example, 30% of variance in participants' performance on immediate choice task is explained by the individual differences between participants. Similarly, the intraclass correlation under the column of "Within the same Session of the same participant" can be interpreted as the amount of variation in participants' performance on a given posttest that is explained by the individual differences between the participants and variations in sessions

Table 6. Unconditional Intraclass Correlations

	Within the same participant		Within the same Session of the same participant	
	Est.	95% C.I.	Est.	95% C.I.
ChoiceIM	.30	[.22,.41]	.32	[.23,.42]
ChoiceDL	.30	[.22,.41]	.38	[.29, .47]
SpellIM	.40	[.31,.51]	.50	[.41,.59]
SpellDL	.35	[.26, .45]	.47	[.38, .55]

Choice = Orthographic choice task; Spell = Spelling task; IM = Immediately after the experiment; DL = Two days after the experiment.

Immediate Orthographic Choice Task

The models for the immediate orthographic choice (Choice IM) are summarized in Table 7. To make the table concise, except for Model 0 (Variance Components Model), Model 1, Model 1a, Model 2, and Model 3, only the models that fit better than Model 3 are presented in Table 7. Likelihood ratio tests were used to compare cross-level interaction models to Model 3. BICs were used to compare models with various random parts to Model 3. None of the random slope models was better-fitting than Model 3, and the cross-interaction models were not significant at the 5% level. Thus, Table 7 includes only the model without the covariates (Model 0) and the random intercept models (Model 1 to Model 3). Appendix C provides the detailed results for other models. Although the model that included cross-level interaction between the strength of the phoneme-to-grapheme correspondence and orthographic processing ability was better fitting than Model 3, Therefore, for the sake of parsimony, Model 3 was chosen for interpretations. Model 3, had a pseudo- R-squared of 29.47%. All covariates significantly predicted the participants' performance at the 5% significance level, except *Session* and *Decoding*.

Fixed effects

The estimated odds of choosing the correct answer in the immediate orthographic choice task were higher when the target words were rime, substitution, or transposition neighbors of the base words than for the control words. Holding other covariates constant, the odds ratio of rime neighbor words to control words was estimated to be 1.52; the odds ratio of substitution neighbor words to control words was estimated to be 1.74; the odds ratio of transposition neighbor words to control words was estimated to be 2.62. Comparing the estimates of the neighbor words, there were statistically significant differences between rime words, substitution words, and transposition words at the 5% level. The estimated odds ratios between Rime to Substitution was 0.88, $z = 2.63$, $p = .009$; the odds ratios between Rime to Transposition was 0.57, $z = 2.58$, $p = .010$; and the odds ratios between Substitution to Transposition was 0.66, $z = 2.58$, $p = .010$

For every one-letter increase in word length, the odds of choosing the correct answer were estimated to decrease by 20%, holding other covariates constant. For every unit increase in the log word frequency (i.e., for every 2.7-fold increase in word frequency), the odds of choosing the correct answer were estimated to increase by 9%, holding other covariates constant. For every 10 percent increase in phoneme-to-grapheme consistency, the estimated odds of choosing the correct answer were estimated to increase by 10%. Figure 1, Figure 2, and Figure 3 show the predicted marginal probability as a function of the number of the letters, a function of word frequency, and a function of phoneme-to-grapheme consistency.

The estimated odds of choosing the correct answer were higher when the participants correctly selected the spelling for a target word in the pretest. For the participants who selected the correct spelling for a target word in the pretest, the odds of choosing the correct spelling for that target word were estimated to be 1.84 times as high as for participants who did not select the correct spelling for the target word in the pretest, holding other covariates constant. Similarly, for participants who selected the correct picture for a base word, the odds of choosing the correct answer were estimated to be 2.02 times as high as for participants who did not select the correct picture for the base words, holding other covariates constant.

The estimated odds of choosing the correct answer in the immediate orthographic choice task were higher when participants had higher scores for oral vocabulary, print knowledge, and orthographic processing. Controlling for other covariates, every one z-score increase in oral vocabulary, print knowledge, and orthographic processing the odds of correctly choosing the right answer were estimated to increase by 36%, 70%, and 48%, respectively. However, phonological processing showed an opposite effect; namely, the odds of choosing the correct answer were estimated to decrease by 28% for every one z-score increase for phonological processing.

Random effects

Based on Model 0, the estimated variance of the random intercept at the session level for a given participant was 0.06 and the estimated variance of the random intercept at the participant level was 1.46, suggesting that there was more residual variation between the participants than between sessions within the same participants. For Model 3, the estimated variance of the random intercept at the session level for a given participant was 0.09 and the estimated variance of the random intercept at the participant level was 0.33. The proportional reduction in variance at the participant level was 77.60%. After adding word-level, session-level, and participant-level covariates into the model, the proportion of variance at the session level increased from 0.06 to 0.09.

Empirical Bayes predictions showed that, depending on the participants, the predicted random effects of the participant-level intercept could be as high as 0.81 logits or as low as -1.37 logits in this sample. The predicted session-level random effects could be as high as 0.19 logits or as low as -0.28 logits in this sample. Figure 4 and Figure 5 show these random-effects predictions and approximate 95% confidence intervals versus the ranking of the predictions. Figure 4 summarizes the random-intercept prediction of each participant and Figure 5 summarizes the random-intercept prediction for each session of each participant.

Transforming into odds ratios, the odds ratio of correctly choosing a spelling in the immediate orthographic choice task between the top participant and the bottom participant while holding the effects of covariates constant was estimated to be 8.85. ($e^{0.81-(-1.37)}$=8.85). Adding Level 2 and Level 3 random effects ($\zeta_{00k}^{(3)}+\zeta_{0jk}^{(2)}$) per participant, the highest effect was 0.97 logits and the lowest effect was -1.61 logits in this sample. Transforming this into an odds ratio, the odds ratio of correctly choosing an option in the immediate orthographic choice task between the participant with the highest random effect and the participant with the lowest random effect in this sample was 13.20 ($e^{0.97-(-1.61)}$=13.20).

Unexplained heterogeneity

For the same participant *k* but different sessions *j* and *j'*, the residual intraclass correlation was estimated to be 0.09. For the same participant *k* and same session *j*, the residual intraclass correlation was estimated to be 0.11. Comparing responses from different sessions of different participants, the estimated median odds ratio of providing a correct response in the immediate orthographic choice task was 1.86. Comparing responses from different sessions of the same participant, the estimated median odds ratio was 1.34.

Table 7. Models for Immediate Orthographic Choice

	Variable	Model 0	Model 1	Model 1a	Model 2	Model 3
Fixed Effects						
Level 1 : Word characteristic	Intercept	7.48 (1.25)***	1.69 (1.05)	1.78 (1.10)	1.48 (0.93)	1.39 (0.85)
	Pretest Accuracy		2.00 (0.28)***		2.00 (0.27)***	1.84 (0.25)***
	Base Word Accuracy		2.03 (0.54)***	2.04 (0.54)**	1.93 (0.52)*	2.02 (0.53)***
	Number of Letters		0.77 (0.07)**	0.77 (0.07)**	0.80 (0.08)*	0.80 (0.08)*
	Log Frequency		1.06 (0.04)	1.08 (0.04)*	1.09 (0.04)*	1.09 (0.04)*
	PGC		1.01 (0.01)*	1.01 (0.01)*	1.01 (0.01)*	1.01 (0.01)*
	Rime		1.55 (0.23)***	1.69 (0.25)***	1.50 (0.22)**	1.52 (0.23)***
	Substitution		1.73 (0.32)***	1.84 (0.34)***	1.71 (0.32)***	1.74 (0.33)***
	Transposition		2.46 (0.61)***	2.49 (0.61)***	2.60 (0.66)***	2.62 (0.67)***
Level 2: Session	Session Number				0.92 (0.05)	0.92 (0.05)
Level 3: Participant	Phonological Processing					0.72 (0.12)*
	Oral vocabulary					1.36 (0.15)**
	Decoding					1.26 (0.19)
	Print Knowledge					1.70 (0.25)***
	Orthographic Processing					1.48 (0.21)**
Random Effects						
Session	var (Intercept)	1.46 (0.33)	1.30 (0.31)	1.45 (0.34)	1.31 (0.31)	0.33 (0.11)
SID	var (Intercept)	0.06 (0.10)	0.11 (0.11)	0.06 (0.10)	0.10 (0.11)	0.09 (0.11)
Statistics						
Log Likelihood		-998.14	-962.50	-975.97	-961.31	-929.31
BIC		2019.73	2011.01	2030.12	2016.45	1991.53
R^2			5.76%	3.15%	5.99%	27.02%

Note. Fixed Effect： Odd Ratio (Standard Error); * *p-value ≤ .05*; ** *p-value ≤ .01*; *** *p-value ≤ .005*

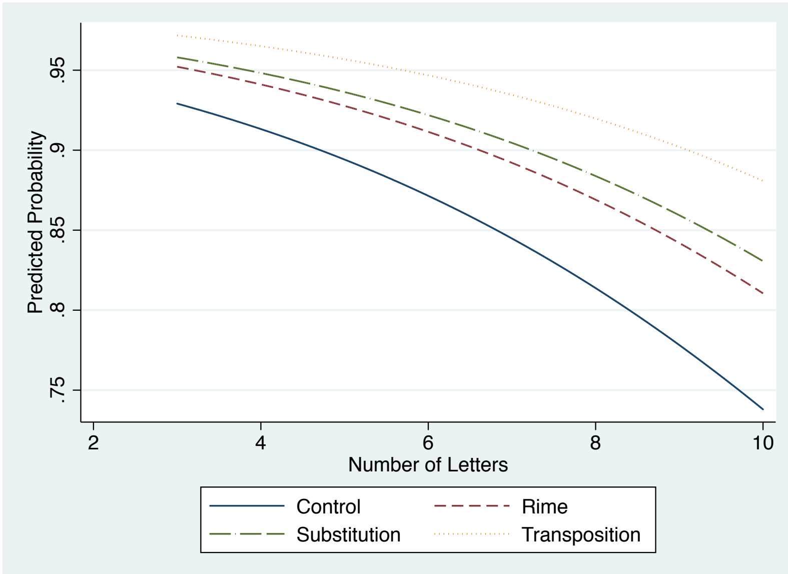

Figure 1. Marginal predicted probability of correct response versus the number of letters by word types. The predicted probability is conditional on Pretest ACC =1, Based Word=1, Word Frequency = 8, PGC= 80%, and all other covariates =0

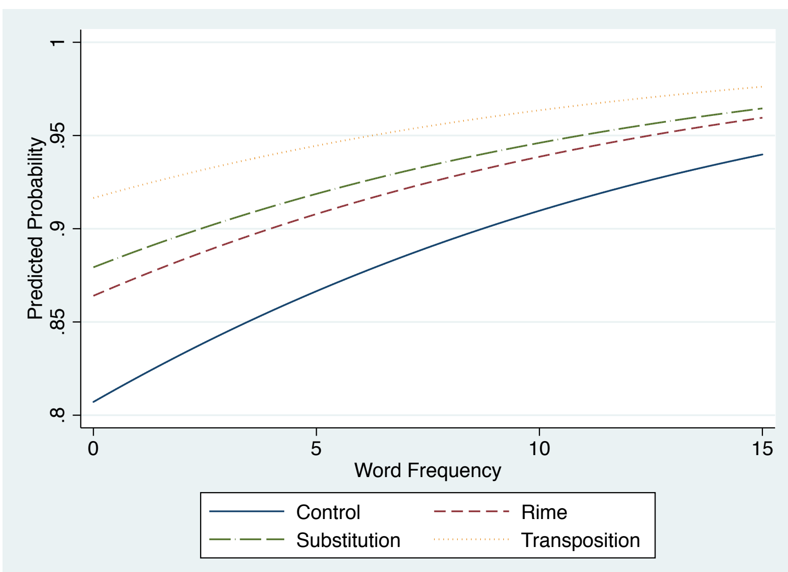

Figure 2. Marginal predicted probability of correct response versus word frequency by word types. The predicted probability is conditional on Pretest ACC =1, Based Word=1, Number of Letters = 5, PGC= 80%, and all other covariates = 0

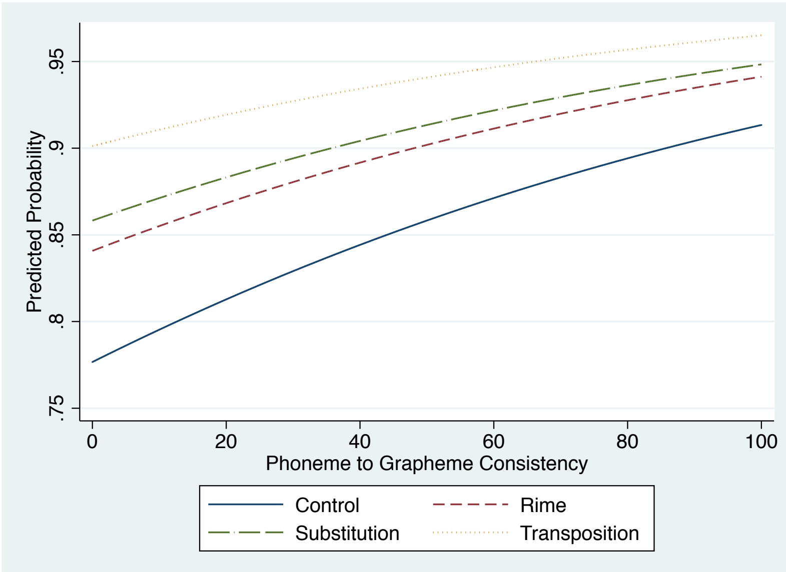

Figure 3. Marginal predicted probability of correct response versus word frequency by word types. The predicted probability is conditional on Pretest ACC =1, Based Word=1, Number of Letters = 5, Frequency = 8, and all other covariates = 0

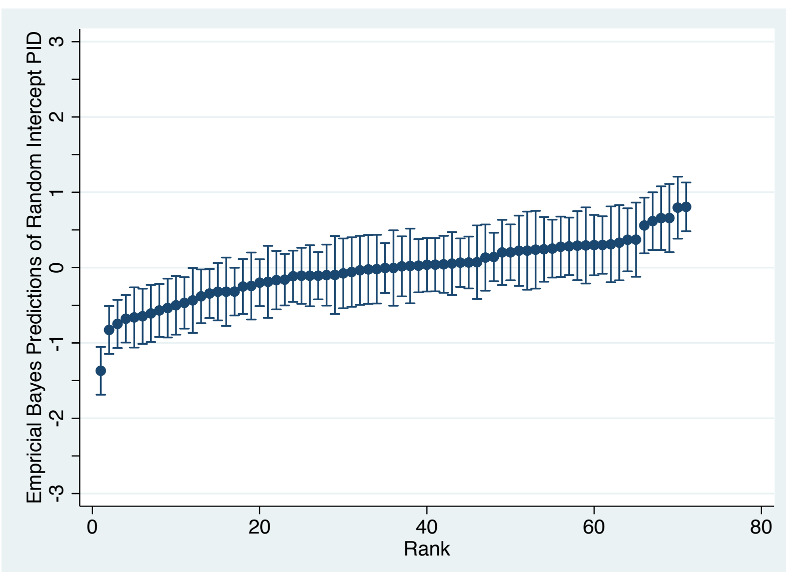

Figure 4. Caterpillar plot of participant-level random-intercept predictions and approximate 95% confidence intervals versus ranking

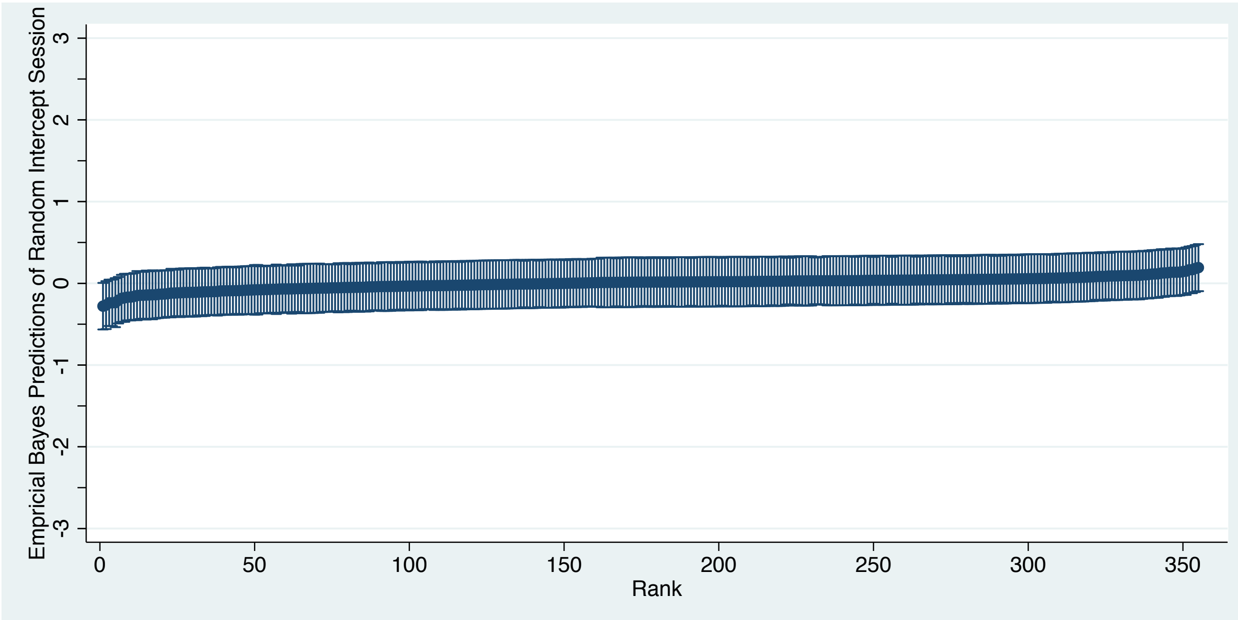

Figure 5. Caterpillar plot of session-level random-intercept predictions and approximate 95% confidence intervals versus ranking

Immediate Spelling Task

The models for the immediate spelling task (Spell IM) are summarized in Table 8 and Table 9. To make the table concise, except for Model 0 (Variance Components Model), Model 1, Model 1a, Model 2, and Model 3, only the models that fitted better than Model 3 are presented in Table 8 and Table 9. The model comparisons were based on likelihood ratio tests for comparing models with or without cross-level interaction models; and BICs for comparing models with various random parts. As indicated by BICs, none of the random slopes models provided a better fit to the data than Model 3. Deviance tests indicated that Model 10 was a better fitting model than Model 3, $\chi^2(1) = 5.93$, $p = .015$. Thus, Table 8 and Table 9 include the variance components model (Model 0) and the random intercept models (Model 1 to Model 3) and one cross-level interaction models (Model 10). Appendix D provides the detailed result for other models.

Model 10 was chosen to be interpreted. The Model 10, had a pseudo- R-squared of 40.47%. *Base Word*, *PGC*, *Substitution*, *Transposition*, *Sessions Number,* and *Phonological processing* were not significant predictors of the participants' performance on the immediate spelling task at the 5% significance level.

Fixed effects

The estimated odds of providing correct spelling in the immediate spelling task were higher when the target words were rime neighbors of the base words than for the control words. Holding other covariates constant, the odds ratio of rime neighbor words to control words was estimated to be 2.56 (main effect, Model 3). There were no significant differences between substitution words and control words as well as transposition words and control words.

Both the number of letters and word frequency significantly predicted the performance on the immediate spelling task at the 5% level. For every one-letter increase in word length, the odds of spelling the target word correctly in the immediate spelling task were estimated to decrease by 44%, holding other covariates constant. For every unit increase in the log word frequency (i.e., for every 2.7-fold increase in word frequency), the odds of spelling the target word correctly were estimated to increase by 14%, holding other covariates constant. Figure 6 and Figure 7 show the predicted marginal probability as a function of the number of the letters and a function of word frequency.

Pretest accuracy predicted the performance on the immediate spelling task. The estimated odds of providing correct spelling were higher when the participants correctly selected the corresponding spelling for a target word in the pretest. For the participants who selected the correct spelling for a target word in the pretest, the odds of providing correct spelling for that target word in the immediate spelling task were estimated to be 1.95 times as high as for participants who did not select the correct spelling for the target word in the pretest, holding other covariates constant.

The estimated odds of providing correct spelling in the immediate spelling task were higher when participants had higher scores for oral vocabulary, decoding, print knowledge, and orthographic processing. Controlling for other covariates, every one z-score increase in oral vocabulary, decoding, print knowledge, and orthographic processing, the odds of providing correct spelling were estimated to increase by 31%, 55%, 80% and 83%, respectively. Phonological processing showed a facilitative but non-significant effect.

The estimated interaction between *Rime* and *Orthographic processing* was 0.74 (Model 10), indicating that for every one z-score increase in orthographic processing, the facilitative effect of rime neighbors on spelling rime words in the immediate spelling task was estimated to decrease by 26%. This shrinkage in the facilitative effect of rime neighbors suggests that when participants had higher ability in orthographic processing, the advantage effect of rime neighbors was less evident, whereas when participants had lower ability in orthographic processing, the facilitative effect of the rime neighbors was more evident. Figure 8 presents the marginal predicted probability of providing correct spelling versus orthographic processing by word types. As shown in Figure 8, the gap in predicated probability between rime words to control words decreases as participants' orthographic processing ability increases. When the participants scored 3 z-scores on orthographic processing, there is no difference between their performance on rime neighbor words and control words. It appears that when the participants have superior orthographic processing ability, learning control words is not harder than learning rime neighbors. The interaction between *Substitution* and *Orthographic processing* and the interaction between *Transposition* and *Orthographic processing* were not significant (see Appendix D Models 11, 12, and 17).

Random effects

Based on Model 0, the estimated variance of the random intercept at the session level for a given participant was 0.62 and the estimated variance of the random intercept at the participant level was 2.64, suggesting that there was more residual variation between the participants than between sessions within the same participants. For Model 10, the estimated variance of the random intercept at the session level for a given participant was 0.47 and the estimated variance of the random intercept at the participant level was 0.40. After adding participant-level covariates, the proportional reduction in variance at the participant level was 84.85%. After adding word-level, session-level, and participant-level covariates into the model, the proportion of variance at the session level decreased from 0.62 to 0.47. The proportional reduction in variance at the session level was 24.19%, suggesting that a large amount of variance due to the learning context had not been sufficiently partialled out.

The estimated variance of the random intercepts at both the session and the participant level in the immediate spelling task were larger than those in the immediate orthographic choice task, suggesting that there was more variance in the spelling task than the orthographic choice task. Empirical Bayes predictions showed that, depending on the participants, the predicted random effects of the participant-level intercept could be as high as 1.04 logits or as low as -1.03 logits in this sample. The predicted session-level random effects could be as high as -1.10 logits or as low as -1.08 logits in this sample. Figure 9 and Figure 10 show these random-effects predictions and approximate 95% confidence intervals versus the ranking of the predictions. Figure 9 summarizes the random-intercept prediction of each participant and Figure 10 summarizes the random-intercept prediction for each session of each participant.

Transforming into odds ratios, the odds ratio of providing a correct spelling in the immediate spelling task between the top participant and the bottom participant while holding the effects of covariates constant was estimated to be 7.02. ($e^{1.04-(-1.03)}=7.02$). Adding Level 2 and Level 3 random effects ($\zeta^{(3)}_{00k}+\zeta^{(2)}_{0jk}$) per participant, the highest effect was 1.76 logits and the lowest effect was -1.81 logits in this sample. Transforming this estimate into an odds ratio, the odds ratio of providing a correct spelling in the immediate spelling task between the participant with the highest random effect and the participant with the lowest random effect while holding the effects of covariates constant in this sample was 35.52 ($e^{1.76-(-1.81)}=35.52$).

Unexplained heterogeneity

For the same participant *k* and same session *j*, the residual intraclass correlation was estimated to be 0.21. Comparing responses from different sessions of different participants, the estimated median odds ratio of providing a correct response in the immediate spelling task was 2.44. Comparing responses from different sessions of the same participant, the estimated median odds ratio was 1.92.

Table 8. Models for Immediate Spelling Task

	Variable	Model 0	Model 1	Model 1a	Model 2	Model 3
		Fixed Effects				
Level 1 : Word characteristic	Intercept	2.59 (0.54)***	5.08 (3.13)	5.33 (3.31)	4.93 (3.05)**	4.72 (2.79)**
	Pretest Accuracy		1.99 (0.23)***		1.98 (0.23)***	1.92 (0.23)***
	Base Word Accuracy		1.55 (0.43)	1.56 (0.44)	1.52 (0.43)	1.52 (0.42)
	Number of Letters		0.55 (0.05)***	0.56 (0.05)***	0.56 (0.05)***	0.56 (0.05)***
	Log Frequency		1.13 (0.04)***	1.15 (0.04)***	1.14 (0.04)***	1.14 (0.04)***
	PGC		1.00 (0.005)	1.00 (0.005)	1.00 (0.005)	1.00 (0.005)
	Rime		2.57 (0.36)***	2.84 (0.39)***	2.54 (0.35)***	2.56 (0.36)***
	Substitution		0.74 (0.12)	0.79 (0.13)	0.74 (0.12)	0.74 (0.12)
	Transposition		0.84 (0.17)	0.88 (0.17)	0.85 (0.17)	0.86 (0.17)
Level 2: Session	Session Number				0.96 (0.05)	0.96 (0.05)
Level 3: Participant	Phonological Processing					1.06 (0.18)
	Oral vocabulary					1.31 (0.16)*
	Decoding					1.55 (0.24)***
	Print Knowledge					1.79 (0.30)***
	Orthographic Processing					1.63 (0.25)***
		Random Effects				
SID	var (Intercept)	2.64 (0.58)	2.68 (0.59)	2.98 (0.64)	2.69 (0.59)	0.41 (0.14)
Session	var (Intercept)	0.62 (0.15)	0.46 (0.14)	0.49 (0.14)	0.46 (0.14)	0.46 (0.14)
		Statistics				
Log Likelihood		-1318.25	-1224.58	-1241.56	-1224.34	-1177.53
BIC		2659.95	2535.15	2561.30	2542.49	2487.97
R^2			8.52%	6.48%	8.54%	40.70%

Note. Fixed Effect：Odd Ratio (Standard Error); * *p-value* ≤ *.05*; ** *p-value* ≤ *.01*; *** *p-value* ≤ *.005*

Table 9. Models for Immediate Spelling Test

Variable		Model 10
		Fixed Effects
Level 1 : Word characteristic	Intercept	4.67 (2.76)**
	Pretest Accuracy	1.95 (0.23)***
	Base Word Accuracy	1.51 (0.42)
	Number of Letters	0.56 (0.05)***
	Log Frequency	1.14 (0.04)***
	PGC	1.00 (0.005)
	Rime	2.36 (0.34)***
	Substitution	0.73 (0.12)
	Transposition	0.86 (0.17)
Level 2: Session	Session Number	0.96 (0.05)
Level 3: Participant	Phonological Processing	1.05 (0.18)
	Oral vocabulary	1.31 (0.16)*
	Decoding	1.55 (0.24)***
	Print Knowledge	1.80 (0.30)***
	Orthographic Processing	1.83 (0.29)***
Cross-Level	Orthographic Processing × Rime	0.74 (0.09)*
		Random Effects
SID	var (Intercept)	0.40 (0.14)
Session	var (Intercept)	0.47 (0.14)
		Statistics
Log Likelihood		-1174.57
BIC		2489.86
R^2		40.47%

Note. Fixed Effect**:** Odd Ratio (Standard Error); * *p-value* ≤ *.05*; ** *p-value* ≤ *.01*; *** *p-value* ≤ *.005*

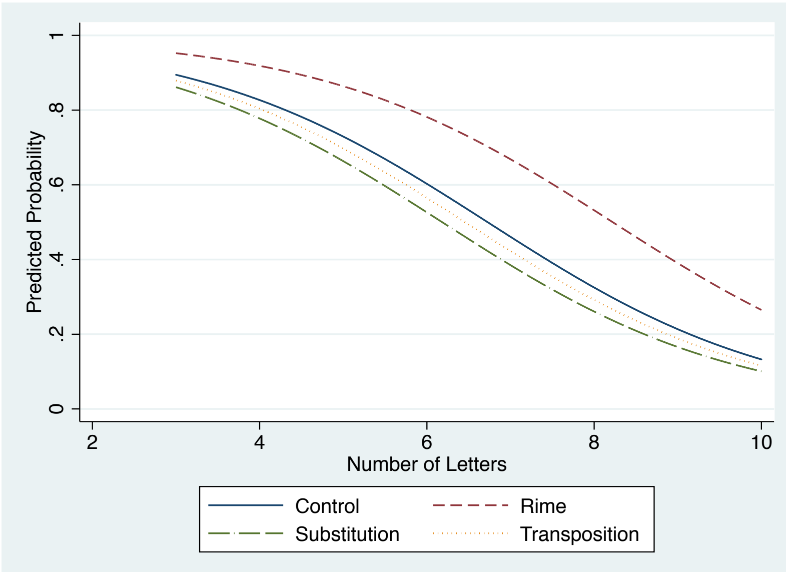

Figure 6. Marginal predicted probability of correct response versus the number of letters by word types. The predicted probability is conditional on Pretest ACC = 1, Based Word = 1, Word Frequency = 8, PGC = 80%, and all other covariates = 0

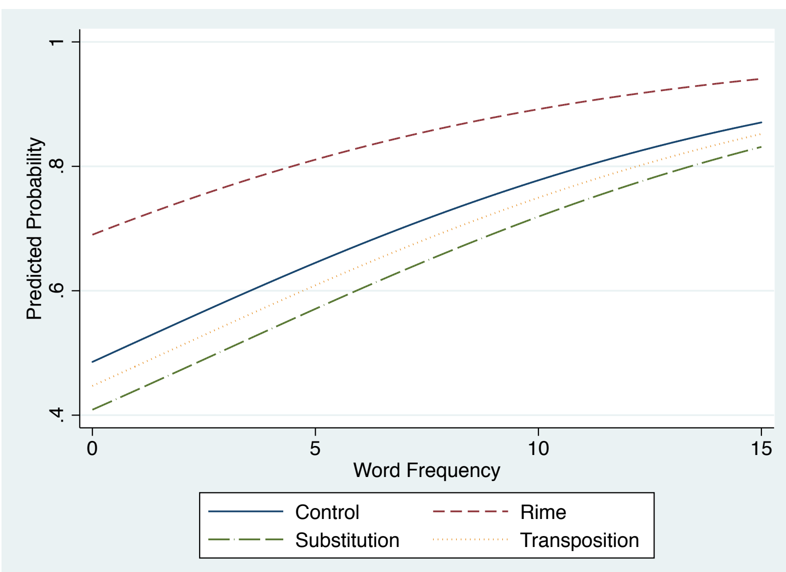

Figure 7. Marginal predicted probability of correct response versus word frequency by word types. The predicted probability is conditional on Pretest ACC = 1, Based Word= 1, Number of Letters = 5, PGC = 80%, and all other covariates = 0

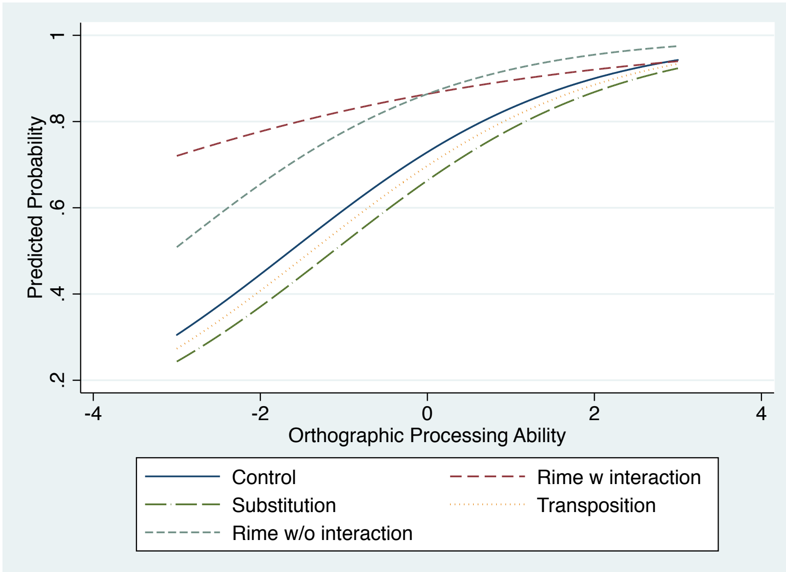

Figure 8. Marginal predicted probability of correct response versus orthographic processing by word types. The predicted probability is conditional on Pretest ACC =1, Based Word=1, Number of Letters = 5 Word Frequency=8, PGC =80%, and all other covariates = 0

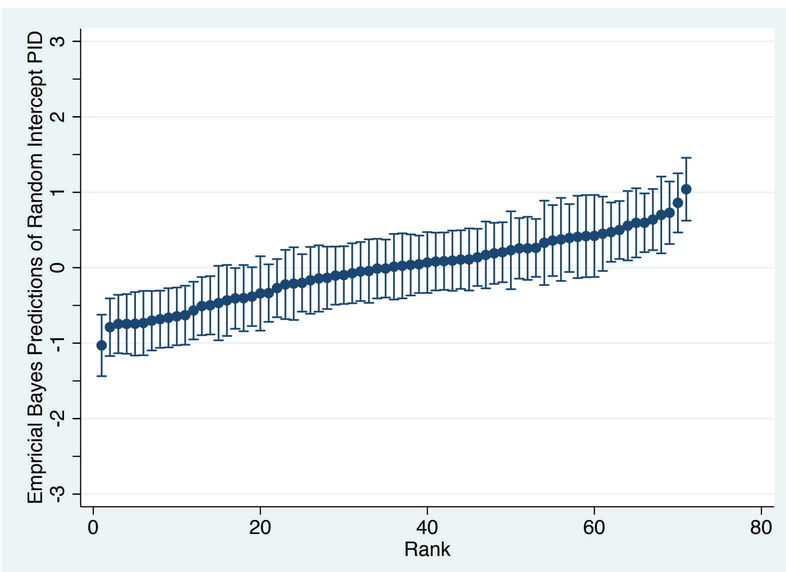

Figure 9. Caterpillar plot of participant-level random-intercept predictions and approximate 95% confidence intervals versus ranking

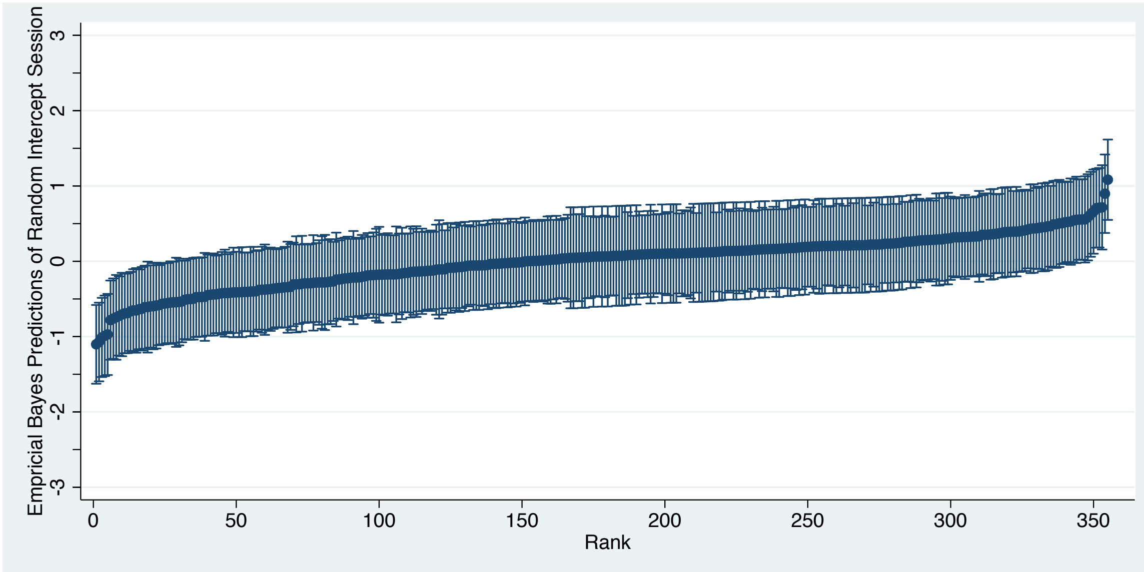

Figure 10. Caterpillar plot of session-level random-intercept predictions and approximate 95% confidence intervals versus ranking

Delayed Orthographic Choice

The models for the delayed orthographic choice (Choice DL) are summarized in Table 11, Table 12, and Table 13. To make the tables concise, except for Model 0 (Variance Components Model), Model 1, Model 1a, Model 2, and Model 3, only the models that fitted better than Model 3 are presented in Table 11 Table 12, and Table 13. Likelihood ratio tests were used for comparing cross-level interaction models to Model 3. BICs were used to compare models with various random parts. None of the random slope models was better-fitting than Model 3 and the six-cross-level interaction models are better-fitting than Model 3. Thus, Table 13 Table 14, and Table 15 include the variance components model (Model 0) and the random intercept models (Model 1 to Model 3) and three cross-level interaction models (Models 10, 11, 13). Appendix E provides detailed results for the other models.

Comparing all cross-level interaction models, Model 13 was better fitting than all other cross-level interaction models. Thus, Model 13 was chosen for interpretation. Model 13, had a pseudo- R-squared of 34.04%. All covariates significantly predicted participants' performance at the 5% significance level, except for *Session*, *Phonological Processing*, and *Decoding*.

Table 10. Likelihood Ratio Tests for Comparing Cross-level Interaction Models

Complex Models	Basic Models	χ^2 statistics
10	3	$\chi^2(1) = 4.99$, $p = .026$
11	3	$\chi^2(1) = 4.26$, $p = .039$
12	3	$\chi^2(1) = 0.87$, $p = .352$
13	3	$\chi^2(3) = 14.66$, $p = .002$
13	10	$\chi^2(2) = 9.68$, $p = .008$
13	11	$\chi^2(2) = 10.41$, $p = .006$

Fixed effects

The estimated odds of choosing the correct answer in the delayed orthographic choice task were higher when the target words were rime, substitution, or transposition neighbors of the base words than for the control words. Holding other covariates constant, the odds ratio of rime neighbor words to control words was estimated to be 2.01 (main effect, Model 3); the odds ratio of substitution neighbor words to control words was estimated to be 1.52 (main effect, Model 3); the odds ratio of transposition neighbor words to control words was estimated to be 3.83 (main effect, Model 3). Comparing the estimates of the neighbor words, there were statistically significant differences between rime words, substitution words, and transposition words at the 5% level. The odds ratio between *Rime* to *Substitution* was 1.32, $z = 2.73$, $p = .006$; the odds ratio between *Rime* to *Transposition* was 0.52, $z = 4.12$, $p < .001$; the odds ratio between *Substitution* to *Transposition* was 0.40, $z = 2.46$, $p = .014$.

For every one letter-increase in word length, the odds of choosing the correct answer in the delayed orthographic choice task were estimated to decrease by 36%, holding other covariates constant. For every unit increase in the log word frequency (i.e., for every 2.7-fold increase in word frequency), the odds of choosing the correct answer were estimated to increase by 8%, holding other covariates constant. For every 10 percent increase in phoneme-to-grapheme consistency, the estimated odds of choosing the correct answer in the delayed orthographic choice task were estimated to increase by 30%. Figure 11, Figure 12, and Figure 13 show the predicted marginal probability as a function of the number of the letters, a function of word frequency, and a function of the phoneme-to-grapheme consistency.

The estimated odds of choosing the correct answer in the delayed orthographic choice task were higher when the participants correctly selected the corresponding spelling for a target word in the pretest. For the participants who selected the correct spelling for a target word in the pretest, the odds of choosing the correct spelling for that target word were estimated to be 2.00 times as high as for participants who did not select the correct spelling for the target word in the pretest, holding other covariates constant. Similarly, for participants who selected the correct picture for a base word, the odds of choosing the correct answer were estimated to be 2.57 times as high as for participants who did not select the correct picture for the base words, holding other covariates as constant.

The estimated odds of choosing the correct answer in the delayed orthographic choice task were higher when participants had higher scores for oral vocabulary, print knowledge, and orthographic processing. Controlling for other covariates, every one z-score increase in oral vocabulary and print knowledge, the odds of correctly choosing the right answer were estimated to increase by 28%, and 98% respectively. Phonological processing and decoding ability show a facilitative but non-significant effect.

Across word types, for every one z-score increase in orthographic processing, the odds of correctly choosing the right answer were estimated to increase by 39% [main effect, Model 3]. The interaction between orthographic processing transposition neighbor words was non-significant [Model 13]. The interaction between rime and orthographic processing was significant. For every one z-score increase in orthographic processing, the odds of correctly choosing the right answer were estimated to additionally increase by 58% for rime words. Similarly, the odds of correctly choosing the right answer for the substitution neighbors were estimated to additionally increase by 68% for every one z-score increase in orthographic processing.

Random effects

Based on Model 0, the estimated variance of the random intercept at the session level for a given participant was 0.39 and the estimated variance of the random intercept at the participant level was 1.61, suggesting that there was more residual variation between the participants than between sessions within the same participants. For Model 13, the estimated variance of the random intercept at the session level for a given participant was 0.46 and the estimated variance of the random intercept at the participant level was 0.23. The proportional reduction in variance at the participant level was 96.17%. Similar to the findings of the immediate orthographic choice task, in the delayed orthographic choice task, after adding word-level, session-level, participant-level covariates, and cross-level interaction into the model, the proportion of variance explained at the session level increased from 0.39 to 0.46.

Empirical Bayes predictions showed that, depending on the participants, the predicted random effects of the participant-level intercept could be as high as 0.58 logits or as low as -0.85 logits in this sample. The predicted session-level random effects could be as high as 0.81 logits or as low as -1.13 logits in this sample. Figure 14 and Figure 15 show these random-effects predictions and approximate 95% confidence intervals versus the ranking of the predictions. Figure 14 summarizes the random-intercept prediction of each participant and Figure 15 summarizes the random-intercept prediction for each session of each participant.

Transforming this into odds ratios, the odds ratio of correctly choosing a spelling in the delayed orthographic choice task between the top participant and the bottom participant while holding the effects of covariates constant was estimated to be 4.06. ($e^{0.58-(-0.85)} = 4.21$). Adding Level 2 and Level 3 random effects ($\zeta_{00k}^{(3)} + \zeta_{0jk}^{(2)}$) per participant, the highest effect was 1.17 logits and the lowest effect was -1.62 logits in this sample. Transforming this into an odds ratio, the odds ratio of correctly choosing an option in the delayed orthographic choice task between the participant with the highest random effect and the participant with the lowest random effect in this sample was 14.59 ($e^{1.17-(-1.62)} = 16.16$).

Unexplained heterogeneity

For the same participant *k* but different sessions *j* and *j'*, the residual intraclass correlation was estimated to be 0.06. For the same participant *k* and same session *j*, the residual intraclass correlation was estimated to be 0.17 Comparing responses from different sessions of different participants, the estimated median odds ratio of providing a correct response in the delayed orthographic choice task was 2.20. Comparing responses from different sessions of the same participant, the estimated median odds ratio was 1.90.

Table 11. Models for Delayed Orthographic Choice

	Variable	Model 0	Model 1	Model 1a	Model 2	Model 3
				Fixed Effects		
Level 1 : Word characteristic	Intercept	5.27 (0.91)***	0.25 (0.15)*	0.25 (0.15)*	0.26 (0.16)*	0.24 (0.14)*
	Pretest Accuracy		2.12 (0.28)***		2.12 (0.28)***	2.00 (0.26)***
	Base Word Accuracy		2.50 (0.70)***	2.50 (0.69)***	2.57 (0.72)***	2.57 (0.71)***
	Number of Letters		0.65 (0.06)***	0.66 (0.06)***	0.64 (0.06)***	0.64 (0.06)***
	Log Frequency		1.09 (0.04)*	1.11 (0.04)***	1.08 (0.04)	1.08 (0.04)*
	PGC		1.03 (0.01)***	1.03 (0.01)***	1.03 (0.01)***	1.03 (0.01)***
	Rime		1.96 (0.28)***	2.14 (0.30)***	1.99 (0.29)***	2.01 (0.29)***
	Substitution		1.51 (0.26)*	1.64 (0.28)***	1.51 (0.26)*	1.53 (0.26)*
	Transposition		3.88 (0.96)***	4.08 (1.00)***	3.77 (0.94)***	3.83 (0.95)***
Level 2: Session	Session Number				1.05 (0.06)	1.05 (0.06)
Level 3: Participant	Phonological Processing					1.06 (0.16)
	Oral vocabulary					1.28 (0.13)*
	Decoding					1.14 (0.16)
	Print Knowledge					1.98 (0.27)***
	Orthographic Processing					1.39 (0.18)*
				Random Effects		
SID	var (Intercept)	1.61 (0.37)	1.56 (0.36)	1.78 (0.40)	1.56 (0.36)	0.22 (0.10)
Session	var (Intercept)	0.39 (0.13)	0.42 (0.15)	0.39 (0.14)	0.42 (0.15)	0.42 (0.15)
				Statistics		
Log Likelihood		-1162.59	-1077.06	-1094.24	-1076.68	-1036.32
BIC		2348.63	2240.09	2266.64	2247.14	2205.51
R^2			10.34%	7.71%	10.37%	34.04%

Note. Fixed Effects: Odd Ratio (Standard Error); * *p-value* $\leq .05$; ** *p-value* $\leq .01$; *** *p-value* $\leq .005$

Table 12. Models for Delayed Orthographic Choice

Variable		Model 10	Model 11
Fixed Effects			
Level 1 : Word characteristic	Intercept	0.23(0.14)*	0.25 (0.15)*
	Pretest Accuracy	1.99 (0.26)***	2.02 (0.26)***
	Base Word Accuracy	2.62 (0.72)***	2.45 (0.68)***
	Number of Letters	0.64 (0.06)***	0.63 (0.06)***
	Log Frequency	1.08 (0.04)	1.08 (0.04)*
	PGC	1.03 (0.01)***	1.03 (0.01)***
	Rime	2.26 (0.35)***	1.97 (0.28)***
	Substitution	1.53 (0.26)*	1.67 (0.30)***
	Transposition	3.76 (0.93)***	3.70 (0.92)***
Level 2: Session	Session Number	1.06 (0.06)	1.05 (0.06)
Level 3: Participant	Phonological Processing	1.07 (0.16)	1.06 (0.16)
	Oral vocabulary	1.28 (0.13)*	1.28 (0.13)*
	Decoding	1.14 (0.16)	1.14 (0.16)
	Print Knowledge	1.98 (0.28)***	1.99 (0.28)***
	Orthographic Processing	1.27 (0.18)	1.31 (0.18)*
Cross-Level	Orthographic Processing ×	Rime 1.34 (0.18)*	Substitution 1.37 (0.21)
Random Effects			
SID	var (Intercept)	0.22 (0.10)	0.22 (0.10)
Session	var (Intercept)	0.44 (0.15)	0.43 (0.15)
Statistics			
Log Likelihood		-1033.83	-1034.20
BIC		2208.33	2209.07
R^2		35.05%	34.12%

Note. Fixed Effects：Odd Ratio (Standard Error); * *p-value* ≤ *.05*; ** *p-value* ≤ *.01*; *** *p-value* ≤ *.005*

Table 13. Models for Delayed Orthographic Choice

Variable			Model 13
			Fixed Effects
Level 1 : Word characteristic	Intercept		0.24 (0.14)*
	Pretest Accuracy		2.01 (0.26)***
	Base Word Accuracy		2.42 (0.68)***
	Number of Letters		0.64 (0.06)***
	Log Frequency		1.08 (0.04)*
	PGC		1.03 (0.01)***
	Rime		2.33 (0.37)***
	Substitution		1.75 (0.32)***
	Transposition		3.67 (0.97)***
Level 2: Session	Session Number		1.06 (0.06)
Cross-Level Level 3: Participant	Phonological Processing		1.06 (0.16)
	Oral vocabulary		1.29 (0.14)*
	Decoding		1.14 (0.16)
	Print Knowledge		1.99 (0.28)***
	Orthographic Processing		1.07 (0.17)
	Orthographic Processing ×	Rime	1.58 (0.23)***
		Substitution	1.68 (0.29)***
		Transposition	1.09 (0.25)
			Random Effects
SID	var (Intercept)		0.23 (0.11)
Session	var (Intercept)		0.46 (0.15)
			Statistics
Log Likelihood			-1028.99
BIC			2214.29
R^2			35.93%

Note. Fixed Effects：Odd Ratio (Standard Error); * *p-value ≤ .05*; ** *p-value ≤ .01*; *** *p-value ≤ .005*

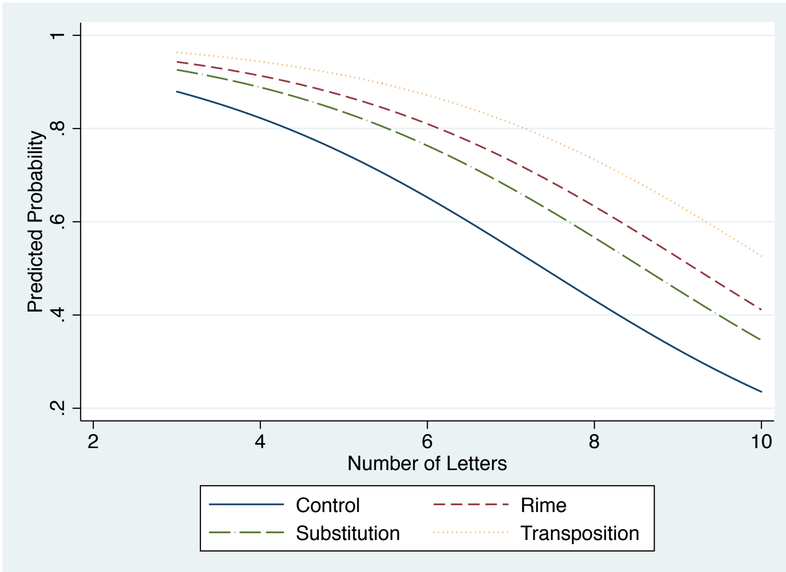

Figure 11. Marginal predicted probability of correct response versus the number of letters by word types. The predicted probability is conditional on Pretest ACC =1, Based Word=1, Word Frequency = 8, PGC=80%, and all other covariates =0

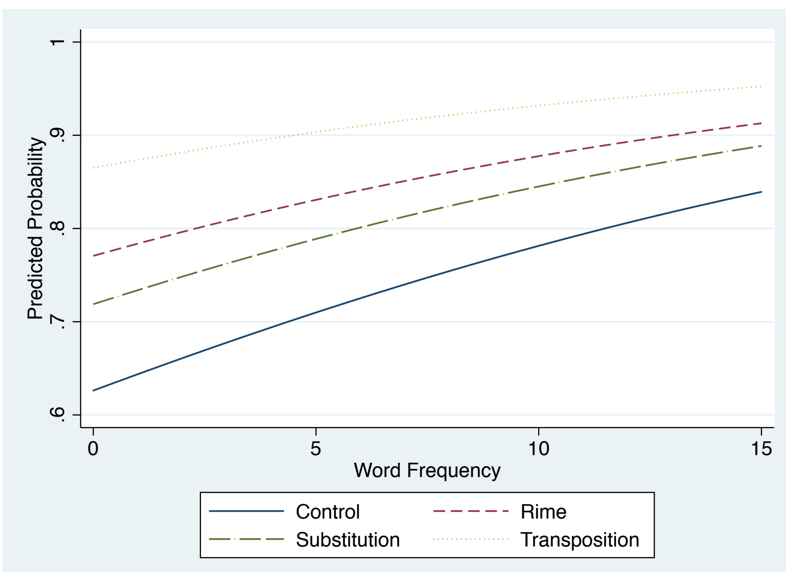

Figure 12. Marginal predicted probability of correct response versus word frequency by word types. The predicted probability is conditional on Pretest ACC =1, Based Word=1, Number of Letters = 5, PGC=80%, and all other covariates = 0

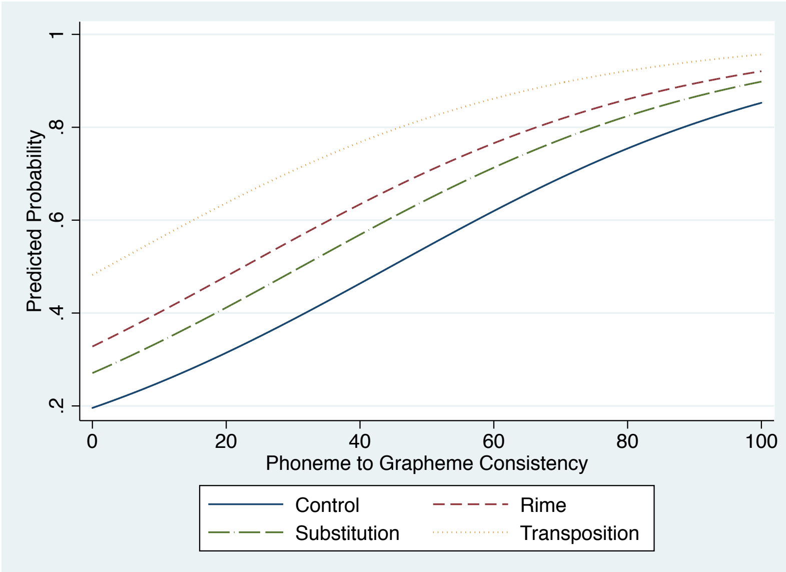

Figure 13. Marginal predicted probability of correct response versus phoneme to grapheme consistency by word types. The predicted probability is conditional on Pretest ACC =1, Based Word=1, Number of Letters = 5 Word Frequency=8, and all other covariates = 0

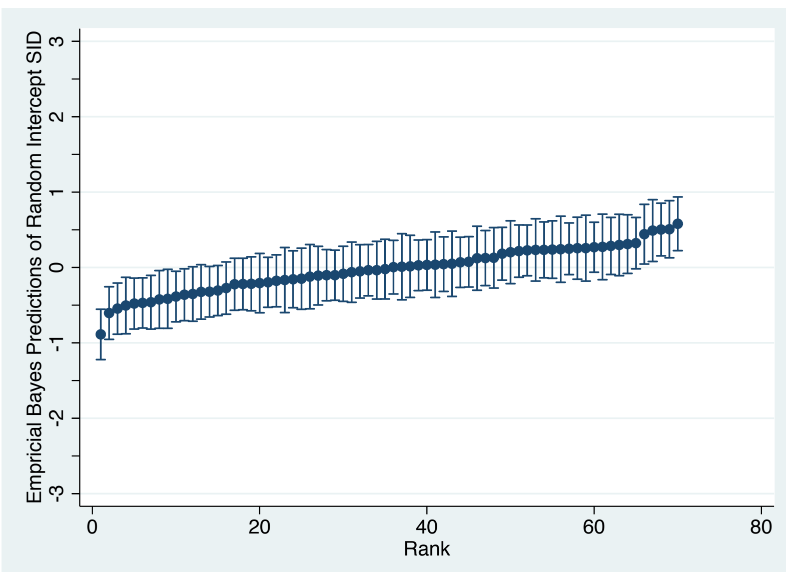

Figure 14. Caterpillar plot of participant-level random-intercept predictions and approximate 95% confidence intervals versus ranking

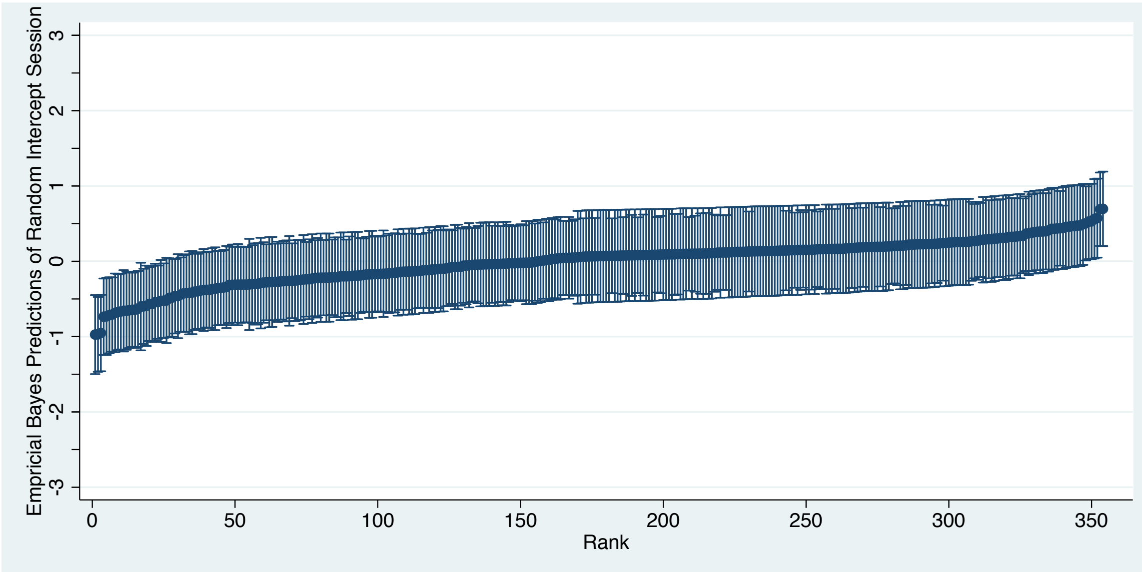

Figure 15. Caterpillar plot of session-level random-intercept predictions and approximate 95% confidence intervals versus ranking

Delayed Spelling Task

The models for the delayed spelling task (Spell DL) are summarized in Table 16 and Table 17. To make the tables concise, except for Model 0 (Variance Components Model), Model 1, Model 1a, Model 2, and Model 3, only the models that fitted better than Model 3 are presented in Table 16 and Table 17. The model comparisons were based on the likelihood ratio tests for comparing models with or without cross-level interaction models and BICs for comparing models with various random parts. As indicated by BICs, none of the random slope models provided a better fit to the data than Model 3. Deviance tests indicated that one cross-level interaction models were better-fitting than Model 3: Models 10, $\chi^2(1)= 5.93$, $p = .015$. Thus, Table 16 and Table 17 include the variance components model (Model 0) and the random intercept models (Model 1 to Model 3) and one cross-level interaction models (Model 10). Appendix F provides the detailed result for other models. Model 10 was chosen to interpret.

The Model 10, had a pseudo- R-squared of 39.90%. *Base Word*, *PGC*, *Substitution*, *Transposition*, *Phonological processing,* and *Decoding* did not significantly predict the participants' performance on the delayed spelling task at the 5% significance level.

Fixed effects

The estimated odds of providing the correct spelling in the delayed spelling task were higher when the target words were the rime neighbor words than for the control words. Holding other covariates constant, the odds ratio of rime neighbor words to control words was estimated to be 2.51(main effect, Model 3).

Both word frequency and the number of letters significantly predicted the performance on the delayed spelling task at the 5% level. For every one letter increase in word length, the odds of correctly spelling the target word in the immediate spelling task were estimated to decrease by 36%, holding other covariates constant. For every unit increase in the log word frequency (i.e., for every 2.7-fold increase in word frequency), the odds of correctly spelling the target word in the delayed spelling task were estimated to increase by 9%, holding other covariates constant. Figure 16 and Figure 17 show the predicted marginal probability as a function of the number of letters and a function the word frequency.

Pretest accuracy predicted the performance on the delayed spelling task. The estimated odds of providing correct spelling were higher when the participants correctly selected the corresponding spelling for a target word in the pretest. For the participants who selected the correct spelling for a target word in the pretest, the odds of providing correct spelling for that target word in the delayed spelling task were estimated to be 2.49 times as high as for participants who did not select the correct spelling for the target word in the pretest, holding other covariates constant. This relation was not found in the participants' performance on base words.

The estimated odds of providing correct spelling in the delayed spelling task were higher when participants had higher scores for oral vocabulary, print knowledge, and orthographic processing. Controlling for other covariates, every one z-score increase in oral vocabulary, print knowledge, and orthographic processing, the odds of providing correct spelling were estimated to increase by 38%, 113%, and 73%, respectively. Phonological processing and decoding ability show a facilitative but non-significant effect.

The estimated interaction between *Rime* and *Orthographic processing* was .76, indicating that for every one z-score increase in orthographic processing, the facilitative effect of rime neighbors on spelling rime words in the delayed spelling task was estimated to decrease by 24%. This shrinkage in the facilitative effect of rime neighbors indicated that when participants had higher ability in orthographic processing, the advantage effect of rime neighbors was less evident, whereas when participants had lower ability in orthographic processing, the facilitative effect of the rime neighbors was more evident. Figure 18 presents the marginal predicted probability of providing correct spelling versus orthographic processing by word types. As shown in Figure 18, the gap in predicated probability between rime words to control words decreases as the participants' orthographic processing ability increases. When the participants scored 3 z-scores on orthographic processing, there was no difference between their performance on rime neighbor words and control words. It appears that when the participants have superior orthographic processing ability, learning control words is not harder than learning rime neighbors. The interaction between *Substitution* and *Orthographic processing* and the interaction between *Transposition* and *Orthographic processing* were not significant (see Appendix E Models 11, 12, and 13).

Random effects

Based on Model 0, the estimated variance of the random intercept at the session level for a given participant was 0.71 and the estimated variance of the random intercept at the participant level was 2.18, suggesting that there was more residual variation between the participants than between sessions within the same participants. For Model 10, the estimated variance of the random intercept at the session level for a given participant was 0.56 and the estimated variance of the random intercept at the participant level was 0.31. After adding participant-level covariates, the proportional reduction in variance at the participant level was 85.78%. After adding word-level, session-level, and participant-level covariates into the model, the proportion of variance at the session level decreased from 0.71 to 0.56. The proportional reduction in variance at the session level was 21.13%, suggesting that other variations due to the learning context had not been sufficiently partialled out.

The estimated variance of the random intercepts at both the session and participant level in the delayed spelling task was larger than the variance in the delayed orthographic choice task, suggesting that there was more variance in the spelling tasks than in the orthographic choice tasks. Empirical Bayes predictions showed that, depending on the participants, the predicted random effects of the participant-level intercept could be as high as 1.04 logits or as low as -0.82 logits in this sample. The predicted session-level random effects could be as high as -1.16 logits or as low as -1.27 logits in this sample. Figure 19 and Figure 20 show these random-effects predictions and approximate 95% confidence intervals versus the ranking of the predictions.

Figure 19 summarizes the random-intercept prediction of each participant and Figure 20 summarizes the random-intercept prediction for each session of each participant.

Transforming into odds ratios, the odds ratio of providing a correct spelling in the delayed spelling task between the top participant and the bottom participant while holding the effects of covariates constant was estimated to be 6.42. ($e^{1.04-(-0.82)} = 6.42$). Adding Level 2 and Level 3 random effects ($\zeta_{00k}^{(3)} + \zeta_{0jk}^{(2)}$) per participant, the highest effect was 2.05 logits and the lowest effect was -2.02 logits in this sample. Transforming this estimate into odds ratios, the odds ratio of providing a correct spelling on the delayed spelling task between the participant with highest random effect and the participant with the lowest random effect while holding the effects of covariates constant in this sample was 58.56 ($e^{2.05-(-2.02)} = 58.56$).

Unexplained heterogeneity

For the same participant *k* but different sessions *j* and *j'*, the residual intraclass correlation was estimated to be 0.10. For the same participant *k* and same session *j*, the residual intraclass correlation was estimated to be 0.21. Comparing responses from different sessions of different participants, the estimated median odds ratio of providing a correct response in the delayed spelling task was 2.44. Comparing responses from different sessions of the same participant, the estimated median odds ratio was 1.92.

Table 14. Models for Delayed Spelling Task

	Variable	Model 0	Model 1	Model 1a	Model 2	Model 3
Fixed Effects						
Level 1 : Word characteristic	Intercept	1.21 (0.23)	1.99 (1.20)	2.00 (1.21)	1.85 (1.12)	1.82 (1.05)
	Pretest Accuracy		2.57 (0.29)***		2.55 (0.29)***	2.46 (0.28)***
	Base Word Accuracy		1.54 (0.46)	1.56 (0.47)	1.48 (0.44)	1.46 (0.44)
	Number of Letters		0.61 (0.05)***	0.62 (0.06)***	0.64 (0.06)***	0.64 (0.06)***
	Log Frequency		1.06 (0.03)	1.10 (0.03)***	1.08 (0.04)*	1.08 (0.04)*
	PGC		1.00 (0.004)	1.00 (0.004)	1.00 (0.004)	1.00 (0.004)
	Rime		2.56 (0.34)***	2.96 (0.39)***	2.49 (0.33)***	2.51 (0.34)***
	Substitution		0.81 (0.13)	0.92 (0.14)	0.81 (0.13)	0.82 (0.13)
	Transposition		0.71 (0.14)	0.76 (0.14)	0.73 (0.14)	0.74 (0.14)
Level 2: Session	Session Number				0.89 (0.05)*	0.90 (0.05)*
Level 3: Participant	Phonological Processing					1.06 (0.17)
	Oral vocabulary					1.38 (0.15)***
	Decoding					1.22 (0.18)
	Print Knowledge					2.10 (0.34)***
	Orthographic Processing					1.55 (0.22)***
Random Effects						
SID	var (Intercept)	2.18 (0.46)	2.14 (0.46)	2.46 (0.51)	2.15 (0.46)	0.32 (0.11)
Session	var (Intercept)	0.71 (0.15)	0.56 (0.15)	0.64 (0.15)	0.55 (0.14)	0.56 (0.14)
Statistics						
Log Likelihood		-1413.81	-1305.29	-1340.18	-1303.17	-1256.76
BIC		2851.06	2696.55	2758.52	2700.11	2646.38
R^2			9.76%	6.12%	10.06%	39.62%

Note: Fixed effects: Odd Ratio (Standard Error); * *p-value* ≤ *.05*; ** *p-value* ≤ *.01*; *** *p-value* ≤ *.005*

Table 15. Models for Delayed Spelling Task

Variable		Model 10
Fixed Effects		
Level 1 : Word characteristic	Intercept	1.79 (1.04)
	Pretest Accuracy	2.49 (0.28)***
	Base Word Accuracy	1.46 (0.44)
	Number of Letters	0.64 (0.06)***
	Log Frequency	1.09 (0.04)*
	PGC	1.00 (0.004)
	Rime	2.46 (0.33)***
	Substitution	0.81 (0.13)
	Transposition	0.73 (0.14)
Level 2: Session	Session Number	0.89 (0.05)*
Level 3: Participant	Phonological Processing	1.06 (0.17)
	Oral vocabulary	1.38 (0.15)***
	Decoding	1.21 (0.18)
	Print Knowledge	2.13 (0.35)***
	Orthographic Processing	1.73 (0.26)***
Cross-Level	Orthographic Processing× Rime	0.76 (0.26)*
Random Effects		
SID	var (Intercept)	0.31 (0.11)
Session	var (Intercept)	0.56 (0.15)
Statistics		
Log Likelihood		-1254.10
BIC		2648.88
R^2		39.90%

Note: Fixed effects: Odd Ratio (Standard Error); * *p-value* ≤ *.05*; ** *p-value* ≤ *.01*; *** *p-value* ≤ *.005*

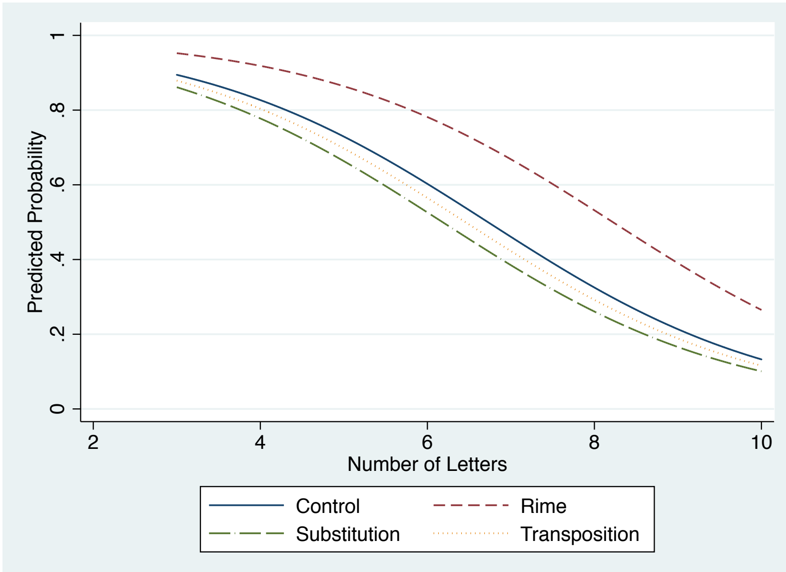

Figure 16.Marginal predicted probability of correct response versus number of letters by word types. The predicted probability is conditional on Pretest ACC =1, Based Word=1, Word Frequency = 8, PGC=80%, and all other covariates = 0

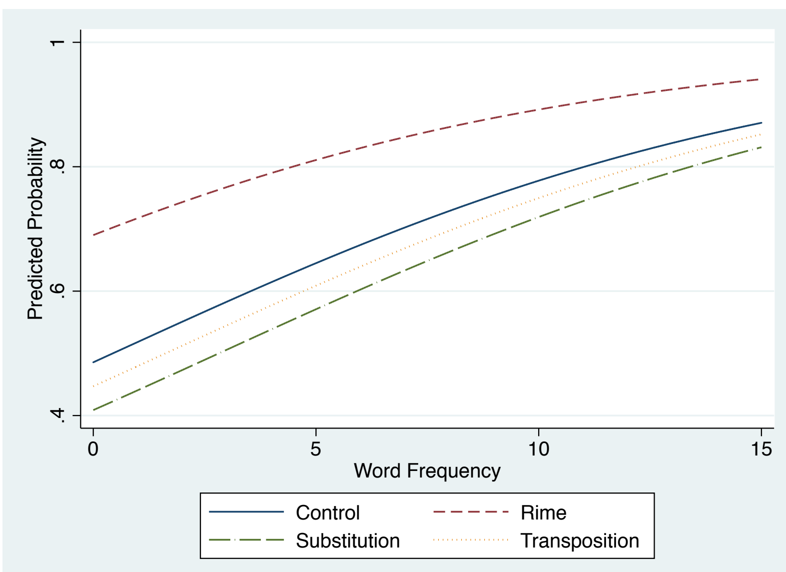

Figure 17. Marginal predicted probability of correct response versus the word frequency by word types. The predicted probability is conditional on Pretest ACC =1, Based Word=1, Number of Letters = 5, PGC=80%, and all other covariates =0

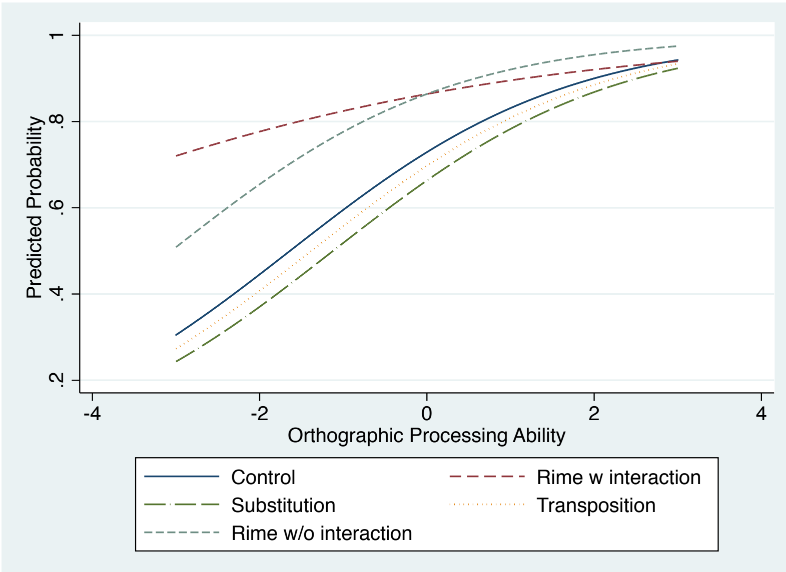

Figure 18. Marginal predicted probability of correct response versus orthographic processing by word types. The predicted probability is conditional on Pretest ACC =1, Based Word=1, Number of Letter = 5 Word Frequency=8, PGC =80%, and all other covariates = 0

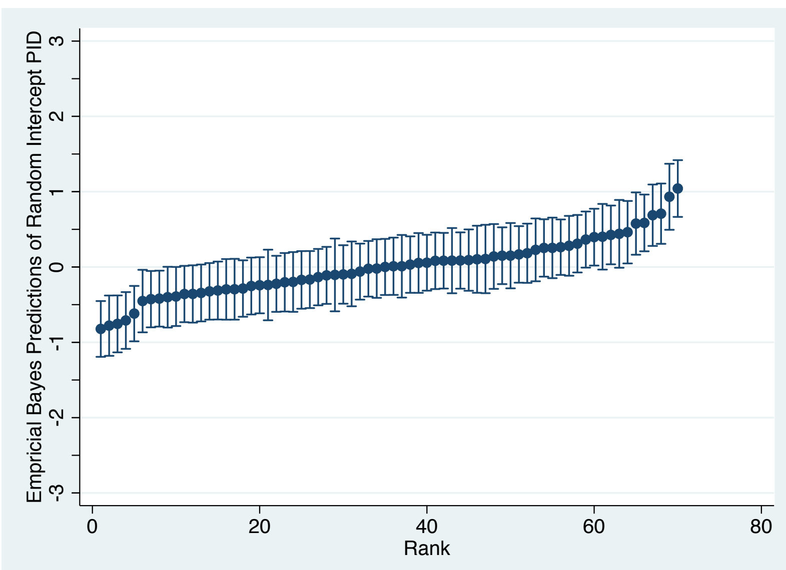

Figure 19. Caterpillar plot of participant-level random-intercept predictions and approximate 95% confidence intervals versus ranking

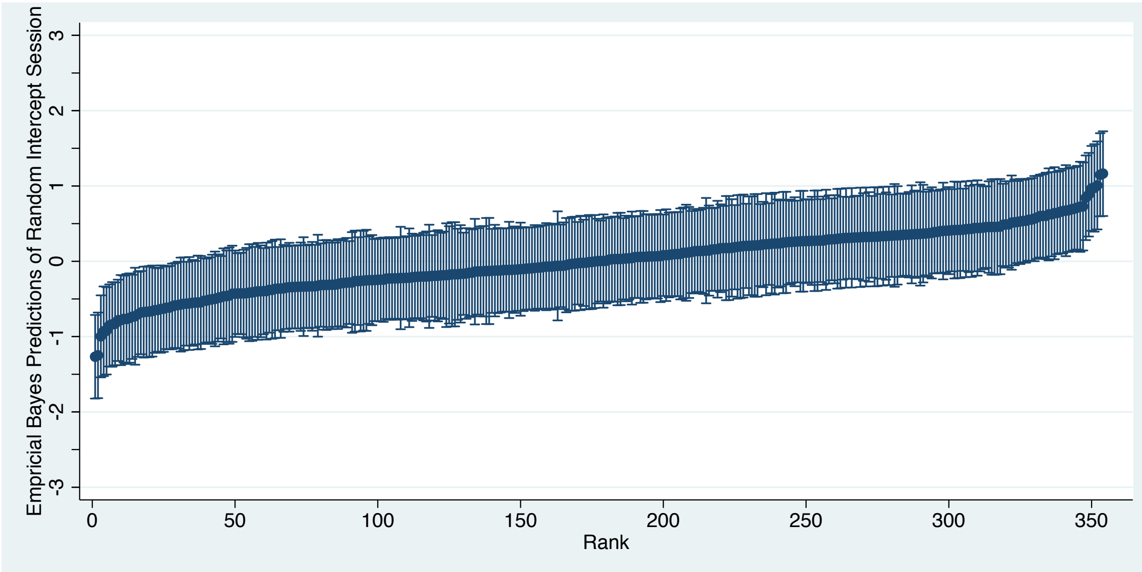

Figure 20. Caterpillar plot of session-level random-intercept predictions and approximate 95% confidence intervals versus ranking

Chapter 5 Discussion

The goal of this dissertation study was to explore factors beyond phonological decoding that may affect or contribute to orthographic learning. Five questions were addressed in this study. (1) Is there an effect of orthographic neighbors on spelling acquisition? (2) Is there a contribution of phoneme-to-grapheme consistency on spelling acquisition? (3) Is there an effect of delay on participants' performance on the assessments of orthographic learning? (4) Can participants' ability to learn to spell improve without specific instruction? (5) Are there interactions between orthographic processing ability and the effects of orthographic neighbors? Word characteristics, individual differences, and learning context (i.e., variations in sessions, variation in immediate or delayed posttest) were examined. Among the array of variables used in three-level logistic regressions, the effects of orthographic neighbors on spelling acquisition were of particular interest. Thus, the discussion begins with the effects of orthographic neighbors.

The Effects of Orthographic Neighbors on Spelling Acquisition

Four posttests were used to assess participants' orthographic learning: immediate and delayed orthographic choice tasks as well as immediate and delayed spelling tasks. The effect of rime neighbors consistently showed a facilitative effect on the performance of these four types of assessments. The estimated odds ratios between rime words and control words range from 1.52 to 2.56, indicating that rime words are easier to learn than control words. This finding is consistent with Goswami's (1988, 1990a, 1990b, 1992) findings, suggesting that beginning readers might use orthographic analogies to learn new words with the same rhyme.

The findings of substitution and transposition neighbors are less straightforward. The models show two different patterns in orthographic learning. When orthographic learning was assessed by the orthographic choice tasks, both substitution and transposition neighbors facilitated the orthographic learning. The estimated odds ratio between substitution words or transposition words to control words range from 1.53 to 3.83. However, when orthographic learning was assessed by the spelling tasks, the facilitative effect of substitution and transposition neighbors disappeared. It appears that beginning readers can take advantage of the substitution and transposition neighbors only on recognition tasks but not production tasks.

Comparing the facilitative effect between transposition and substitution neighbor words on the orthographic choices tasks, transposition neighbors have the stronger effect. This result echoes the findings of Castles and colleagues (2007), who examined the effect of substitution and transposition neighbors on a lexical decision task, a recognition task. They found that Grade 3 children demonstrated a priming effect for both substitution and transposition neighbors. When they conducted a follow-up testing session with the same group of children in Grade 5, the priming effect of the substitution neighbors disappeared, but the priming effect of the transposition neighbors remained statistically significant.

The difference between rime, substitution, and transposition neighbors on spelling tasks might reflect that *producing* spelling of words requires more similarity or more support than *recognizing* the spelling of words. Rime neighbors implicitly inform the participants that the difference between base words and rime neighbor words is either before the vowel or the first letter of a word (e.g., rain and vain). Moreover, rime neighbors provide an additional benefit of the rhymes. In contrast, transposition and substitution neighbors do not provide such information, thus providing less support to learners.

The negligible effects of substitution and transposition neighbors on spelling tasks, but their facilitative effects on orthographic choice tasks, might suggest cognitive variations in performing orthographic choice tasks and spelling tasks. In the orthographic choice tasks, the similarity and difference between substitution and transposition neighbors might be easier to recognize, related to the fact that the words are visually presented as options. On the other hand, when words are not presented but must be produced, as in the spelling tasks, it is harder for beginning learners to recall the difference and similarity between base words and substitution and transposition neighbors, which further inhibits making orthographic analogies. It may well be that making orthographic analogies for transposition neighbors and substitution neighbors is cognitively more complex than making orthographic analogies for rime neighbors.

The Effects of Sessions and Two-day Delay

There were significant variations of orthographic learning between sessions, suggesting that the learning context plays a crucial role in spelling acquisition. The random effects of sessions were larger in the delayed posttests than in the immediate posttests, perhaps related to the fact that participants' learning is not only influenced by the current learning context but also by the context outside the learning events, such as their home literacy environment or their daily interactions with others.

A significant effect of sessions on orthographic learning was found only in the delayed spelling task. This negative effect on the delayed spelling task, along with three other non-significant effects in the other three posttests, indicated that the participants' learning skills did not improve while participating in one more session. It seems that without explicit instructional support from the teachers, beginning readers are less likely to improve their word learning skills. Given a variety of spelling patterns, without instructional support, beginning readers might be overwhelmed by multiple rules and exceptions of English spelling.

The participants' performance on the delayed posttests was significantly lower than the immediate posttests, suggesting that the forgetting effect occurs within two days. Even so, participants' performance in the delayed orthographic choice task and delayed spelling task were significantly higher than in the pretest. It seems that three five-second exposures to printed words might be sufficient for some learners to acquire spelling. Nevertheless, additional exposures after the initial learning might minimize the forgetting effect.

The Contribution of Phoneme-to-Grapheme Consistency

The facilitative effect of phoneme-to-grapheme consistency was found in both immediate and delayed orthographic choice tasks, but not in the spelling tasks. The lack of the latter effects may be linked to the fact that the scoring of spelling tasks is based on a dichotomous system (i.e., correct spelling or incorrect spelling). Such a rudimentary scoring system does not document the accuracy of spelling each individual letter. This methodology may explain why the relation between phoneme-to-grapheme consistency on spelling performance was not observed.

In contrast, the facilitative effect when employing the orthographic choice tasks might be due to the design of the orthographic choices. Specifically, in the orthographic choice tasks, the options are different in one letter or the sequence of letters, except for the unrelated control word: for example, a target (e.g., *veal*), its alternative homophone (*veel*), its visually similar stimulus (*vael*), and another unrelated word (*vite*). Because the design of the orthographic choices elicits the letter difference, the orthographic choice tasks appear to be more sensitive to the effect of phoneme-to-grapheme consistency

The Contribution of Word Length and Word Frequency

The effects of word length and word frequency are consistent across the four posttests. As the word length increases, the probability of providing a correct answer decreases, indicating that the number of letters is one of key indicators of the difficulty in spelling acquisition.

Currently, there is no available tool to measure the quantity of an individual's exposure to a printed word. Hence, the word frequency in text is used in this study as a proxy for a participant's print exposures to words. Consistent with Cunningham and Stanovich (1990) and Stanovich and West (1989), as the frequency of a word increases, the probability of providing or recognizing the correct spelling of that word increases, suggesting that the amount of exposure to print contributes to spelling acquisition.

The Contribution of Phonological Processing and Decoding

Phonological processing was not found to be a significant predictor of participants' performance on spelling tasks and delayed orthographic choice tasks. However, the effect of phonological processing on the immediate orthographic task was significant and inhibitive. Although the result is not consistent across the four posttests, three out of four outcome assessments show that the effect of phonological processing was non-significant but facilitative. It appears that phonological processing, as measured by the Elision and Blending subtests of CTOPP, does not contribute to orthographic learning after accounting for participants' ability in orthographic processing, decoding, print knowledge, and oral vocabulary.

Similar to phonological processing, phonological decoding was not a significant predictor on three posttests. The effect of phonological decoding was significant only in the immediate spelling task. Unlike the findings of phonological processing, decoding always demonstrates facilitate effects on spelling acquisition, with estimated odds ratios that range from 1.14 to 1.55. Given the sample size of 71, one must conclude that the current findings on the contribution of phonological processing and decoding to spelling acquisition are inconclusive.

The Contribution of Oral Vocabulary and Print Knowledge

Both oral vocabulary and print knowledge were significant predictors of participants' performance on all four posttests. The probability of providing or recognizing the correct spelling of a word is higher when the participants had higher scores on oral vocabulary and print knowledge. This finding indicates that participants' background, previous orthographic knowledge, or previous receptive oral vocabulary promote their spelling acquisition. Moreover, this facilitative effect was more evident in the delayed posttests than in immediate posttests; and more evident in the spelling tasks than in the orthographic choice tasks.

The Contribution of Orthographic Processing

Orthographic processing was a significant predictor of participants' performance on all four posttests, indicating that the learners' ability to perceive, access, and manipulate orthographic representations and patterns play an important role in their spelling acquisition. Given the current findings, orthographic processing might be more important than phonological processing and decoding in spelling acquisition. The estimated odds ratios of orthographic processing were larger in the spelling tasks (Spell IM: 1.83 and Spell DL: 1.73) than in the orthographic choices tasks (Choice IM: 1.48 and Choice DL: 1.39), suggesting that spelling production required more orthographic processing skills then spelling recognition.

The Interaction Between Neighbors and Orthographic Processing

A non-significant interaction between orthographic processing and rime neighbors was found for the immediate orthographic choice task, but a significant interaction between rime and orthographic processing and substitution and orthographic processing was found in the delayed orthographic choice task. Given the current results, the interactive effects between neighbors and orthographic processing are inconclusive.

Nevertheless, a significant interaction between orthographic processing and rime neighbors was found in analyzing both the immediate and the delayed spelling tasks. The estimated interaction is 0.74 in the immediate spelling task and 0.76 in the delayed spelling task, suggesting that every one z-score increase in orthographic processing, the facilitative effect of rime neighbors on spelling rime words in the immediate and delayed spelling task was estimated to decrease by 26% and 24%, respectively. This slight reduction in the facilitative effect of rime neighbors suggests that when the participants have a higher ability in orthographic processing, the advantage effect of rime neighbors is less evident, whereas when the participants have a lower ability in orthographic processing, the facilitative effect of the rime neighbors is more evident. It seems that when learners have superior orthographic processing skills (i.e., scored a 3 on orthographic processing), the difficulty in learning rime neighbors and control words is equivalent.

Limitations

Several limitations exist in this study. The major challenge pertains to the selection of the words. Ideally, the target words and control words should not be recognized by the participants in the pretest. However, this ideal selection was constrained because finding words with various types of neighbor words and without neighbors limited the options. There remained little flexibility after selecting the neighbors. As mentioned at the beginning of Chapter 3, orthographic neighbors were the primary factor when considering the design of the experiment and the selection of words. A statistical method was applied to overcome this limitation: Use pretest accuracy as a word-level covariate in three-level logistic models. This method, used by Elleman, Steacy, Olinghouse, and Compton (2017), can partial the influence of the pretest accuracy of each individual word on spelling acquisition, conditional on each participant.

Another limitation is using a dichotomous scoring system for the spelling posttests. The primary focus was to examine the effect of orthographic neighbors on spelling acquisition, which is a word-level effect, and thus the current dichotomous scoring system was chosen to analyzing the data. Nevertheless, Caravolas, Kessler, Hulme, and Snowling (2005) indicated the degree of orthographic consistency of vowels in words significantly predicts children's vowel spelling accuracy. It seems that the relation between orthographic consistency and spelling production should be examined at a syllable level or at a letter level. However, the dichotomous scoring system reflected only the word level. A more fine-grained coding system is needed for future studies.

Moreover, as discussed in Chapter 2, morphological knowledge plays a role in orthographic learning or spelling acquisition. However, the words used in this dissertation study are not morphologically complex. Thus, examining and testing the relation between morphological complexity and orthographic learning was not feasible. Nevertheless, this limitation cannot be easily overcome due to the limited freedom of word selection after manipulating orthographic neighbors. The field still lacks the empirical evidence of the role of morphemes in orthographic learning, meaning that it is of particular interest to design innovative approaches to tackle this challenge.

Implications

This dissertation has several implications for literacy research and instruction. First, because this study assesses students' cognitive and language ability comprehensively, the findings contribute to our understanding of the fundamental cognitive abilities and literacy skills that predict students' acquisition of spelling, which is known to influence the development of reading and writing (Reed, Petscher, & Foorman, 2016; Weiser & Mathes, 2011; Ferroil & Shanahan, 1987).

Second, evidence that supports the facilitative effect of orthographic neighbors on reading and spelling acquisition is limited to rime and substitution neighbors (Goswami, 1988; 1990a; 1990b; 1992). This study extends previous findings by examining the effect of transposition neighbors on spelling acquisition, while covarying word length, word frequency, and phoneme-to-grapheme consistency as well as individual differences.

Third, previous researchers have used the breadth of orthographic knowledge to assess orthographic processing, due to the lack of tools for measuring orthographic processing. Although researchers can make inferences regarding an individual's orthographic processing skill based on his/her performance on an assessment of orthographic knowledge, this method does not provide explicit and accurate information about orthographic processing (Burt, 2006). This study introduces a computer-based assessment to evaluate individuals' ability to form, store, and access orthographic representations, called orthographic processing, in an attempt to overcome the limitation of previous orthographic processing assessments and distinguish orthographic processing from word recognition and spelling ability.

Moreover, this study employs the three-level model, developed in other areas of early literacy research, in which Leve 1 includes the words' characteristics, Level 2 includes session variation, and Level 3 includes the participants' characteristics. This comprehensive and powerful model has the advantage of accounting for the variation between sessions, participants, and word stimuli—thus allowing for examination of between-participant variation in learning outcomes due to the individual differences among participants, as well as contextual effects at the session level. This model is a powerful tool for literacy researchers for examining variability in context (e.g., learning condition), student backgrounds, and learning materials (e.g., words) in the literacy acquisition.

The results have multiple implications for teaching practices. First, because the findings specify the role of fundamental cognitive abilities and essential literacy skills in learning to spell, educators can use these findings to understand the challenges that beginning readers encounter while learning to spell, such as difficulty in phonological decoding or orthographic processing. Findings offers explanations and answers to the question: Why do some students learn to spell with relative ease whereas others experience inordinate difficulty?

Second, because the goal of this study was to examine the effects of orthographic neighbors on spelling acquisition, results also contribute to our understanding of effective spelling instruction. The findings show that when the participants scored a 3 z-score on orthographic processing, there was no difference between their performance on rime neighbor words and control words. The suggestion is that using rhyme to teach students with advanced orthographic processing skills to acquire new words is not necessary and not beneficial. When students have advanced orthographic processing skills, the focus on the instruction should not be rime neighbors. Because participants were second-grade students, it seems evident that fourth or higher-grade students might not benefit from rhyme instruction for their spelling acquisition. In contrast, based on the participants' performance on spelling tasks, it appears that without explicit instruction, students cannot make orthographic analogies for the substitution and transposition neighbors. Thus, the implications are that teachers need to highlight the difference between the substitution neighbors and the difference between transposition neighbors in their teaching.

The acquisition of orthographic knowledge, both of specific representations and patterns, is important because in addition to phonological awareness, orthographic knowledge has a significant role in word recognition, which in turn, supports reading comprehension. This dissertation comprehensively examined the role of word characteristic and individual differences on the development of orthographic knowledge. Findings provide the scientific foundation for considering the orthographic neighbors in spelling instruction and highlight the importance of facilitating orthographic processing, in addition to phonics, in literacy instruction in elementary schools.

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Appendices

Appendix A. Word List

Session	Base words	Effect	Target	Log frequency	PGC %	Number of letters
1	couch	rime	pouch	7.54	100	5
		rime	crouch	7.10	100	6
		substitution	conch	6.31	75.94	5
		control	tulip	6.799	76.03	5
	lion	rime	Zion	7.26	70.28	4
		transposition	loin	6.49	100	4
		control	yeti	5.28	86.47	4
2	rain	rime	vain	8.00	75.94	4
		substitution	rein	7.45	73.38	4
		substitution	ruin	8.53	100	4
		control	okra	6.88	65.48	4
	clam	transposition	calm	9.78	67.00	4
		rime	slam	8.34	100	4
		control	envy	8.24	100	4
3	witch	rime	hitch	7.37	100	5
		rime	switch	9.543	100	6
		rime	itch	8.46	67.53	4
		control	vicar	8.79	82.76	5
		control	whimsy	7.82	100	6
	able	transposition	albe	0	100	4
		substitution	axle	8.48	100	4
4	camp	rime	champ	9.72	100	5
		rime	clamp	8.95	100	5
		rime	cramp	7.71	100	5
		control	vomit	8.83	100	5
	step	substitution	stew	8.99	67.79	4
		rime	strep	7.16	100	4
		control	ibex	6.89	75.96	4
5	state	deletion	estate	12.68	100	6
		deletion	statue	10.94	75.02	6
		substitution	skate	9.86	79.11	5
		control	musket	6.78	86.07	6
	stain	transposition	satin	8.47	100	5
		substitution	stein	9.55	75.25	5
		control	theft	11.48	100	5

Appendix B. Orthographic Processing Assessment

Instructions

This assessment is computer-based. Please read the following instructions carefully. The goal of this instrument is to identify an individual's orthographic processing ability. This instrument is not suitable for assessing an individual's spelling and word recognition ability. The instrument is designed for English users who use the American English spelling system. There are six different cognitive processing tasks in this instrument. Each task has 1 to 4 practice trials and 9-12 actual items. In total, there are 60 actual items and 10 practice trials. Only actual items are scored.Before starting this assessment, it is critical to use the *Baseline* task to help the respondents familiarize themselves with the keyboard.

Each task has its own brief description page, which provide instructions for the task. After the description page, 1 to 4 practice trials are presented. For respondents who are not able to read independently, the test administrator should read these aloud. Level 1 items have a four second time limit to answer; Level 2 items have a four second time limit to memorize the stimulus. It is important to make sure that respondents concentrate on the task and keep their eyes on the computer screen.Level 6 items require respondents to type their answer. The respondents can press keys up to 80 times. Respondents are not able to answer an item after pressing keys more than 80 times.This assessment cannot not be considered an assessment of English ability.

Items

Correct answers appear in bold. The correct answers were randomized in the multiple-choice items.

Baseline list

Numbers 0 to 9 and letters A to Z are presented on the screen in a random sequence. Respondents are required to press the key based on the stimulus they saw.

Level 1: Perception

Hello! Count how many LETTERS you see and press that number. For example, see "**vk7i**", press "3", and see "**GHV!b**", press "4"

Careful: Some of them may not be letters. You have four seconds to answer. Press SPACEBAR to continue.

How many letters do you see? Press SPACEBAR to GO!

Trial items: gkj3 TIKL& sjby ERT7GSX

Item 1-10

1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
vqu#ap	rh!nv	g4cykh	QK&G	CBT?SI	L3VHJ	vPrQwy	RigJMW	BGCQER	imnqte

Level 2&3: Storing and retrieval

You are going to memorize some letters! After the letters disappear, you will see a question "*Which letter combination did you see*?" Then you will see four options. Pick the one you just saw. Press SPACEBAR to Go.

Which letter combination did you see?

Item 11-20

Trial		**11.**	**12.**	**13.**	**14.**	**15.**	**16.**	**17.**	**18.**
byt	YTD	vuio	wyiho	tplkmn	GHRT	VKSZA	XMWNGI	academy	CALIBRATE
byu	YTO	viuo	whiyo	tpiknm	GRHT	VHZSA	XWMNCI	acabemy	CAILBRATE
dyt	YTB	uvio	wylho	tplhmn	GHRY	VRSZA	XMWNBI	aacdemy	CALIRBATE
byk	YDT	viuo	wyioh	tplkwn	GHRI	VKZSA	XMNWGI	acadeny	CAILBRTAE

19.	20.
RWEQ	birct
RQWE	bcirt
RWQE	dcirt
RWOE	bcitr

Level 4: Differentiation list

Hello! Choose the word that looks like it could be a real word! You can only choose one.

Ready? Press SPACEBAR to Go!

Which word looks like a real word?

Item 21-31

Trial	21.	22.	23.	24.	25.	26.	27.	28.	29.	30.	31.
tought	jeocle	gop	beff	filk	heniss	feeb	celf	swen	phow	vop	ceeb
tiught	eoccje	gzp	ffeb	vayj	hhenis	fiip	lfer	cwen	phiw	vhp	caab
cuught	jeceo	gwp	ssof	voqh	qqenis	gaad	lfec	bwen	phyw	vzp	cehh
cyught	joeoce	gcp	foww	filv	qenijj	devv	lfce	hwen	phuw	vhe	ciib

Level 5-1: Addition list

Hello! Fix the spelling by adding a letter!

Ready? Press SPACEBAR to Go!

Which letter needs to be added to make a real word in English?

Item 32-41

Trial	32.	33.	34.	35.	36.	37.	38.	39.	40.	41.
hapy	bok	yelow	detals	clasroom	cotact	natioal	pecial	betwen	reort	buter
p	o	l	i	s	n	n	s	e	p	t
v	p	o	l	n	o	a	v	a	v	b
y	e	m	o	l	k	b	h	i	h	d
a	h	e	h	p	w	l	l	n	m	p

Level 5-2: Removal list

Hello! Fix the spelling by removing a letter!

Ready? Press SPACEBAR to Go!

Which letter needs to be removed to make a real word in English?

Item 42-51

Trial	42.	43.	44.	45.	46.	47.	48.	49.	50.	51.
bbelly	lauyout	writting	positivie	inhsert	wamter	locatione	bottomm	titvle	studenit	revfiew
b	u	t	i	h	m	e	m	v	i	f
e	y	i	e	n	a	o	t	e	t	v
l	o	r	t	s	t	c	o	i	s	i
y	a	g	v	r	w	n	b	t	u	e

Level 6: Arrangement list

Hello! Use ALL the letters to spell a word!

Ready? Press SPACEBAR to Go!

Every letter must be used! You can use BACKSPACE to fix your spelling.

Press ENTER after you finish. Ready? Press ENTER to Go!

Items 52-60

Trial	52.	53.	54.	55.	56.	57.	58.	59.	60.
e, n, p	e, i, l, k	a, l, l, t	a, e, p, p l,	c, h, l, o, o, s	d, e, g, i, u	a, b, i, n, o, r, w,	a, c, e, e, r ,t	a, a, b, e, h, l p, t	e, e, l, l, v
pen	like	tall	apple	school	guide	rainbow	create	alphabet	level

Appendix C. All Immediate Orthographic Choice Models

	Variable	Model 0	Model 1	Model 1a	Model 2	Model 3
Fixed Effects						
Level 1 : Word characteristic	Intercept	7.48 (1.25)***	1.69 (1.05)	1.78 (1.10)	1.48 (0.93)	1.39 (0.85)
	Pretest Accuracy		2.00 (0.28)***		2.00 (0.27)***	1.84 (0.25)***
	Base Word Accuracy		2.03 (0.54)***	2.04 (0.54)**	1.93 (0.52)*	2.02 (0.53)***
	Number of Letters		0.77 (0.07)**	0.77 (0.07)**	0.80 (0.08)*	0.80 (0.08)*
	Log Frequency		1.06 (0.04)	1.08 (0.04)*	1.09 (0.04)*	1.09 (0.04)*
	PGC		1.01 (0.01)*	1.01 (0.01)*	1.01 (0.01)*	1.01 (0.01)*
	Rime		1.55 (0.23)***	1.69 (0.25)***	1.50 (0.22)**	1.52 (0.23)***
	Substitution		1.73 (0.32)***	1.84 (0.34)***	1.71 (0.32)***	1.74 (0.33)***
	Transposition		2.46 (0.61)***	2.49 (0.61)***	2.60 (0.66)***	2.62 (0.67)***
Level 2: Session	Session Number				0.92 (0.05)	0.92 (0.05)
Level 3: Participant	Phonological Processing					0.72 (0.12)*
	Oral vocabulary					1.36 (0.15)**
	Decoding					1.26 (0.19)
	Print Knowledge					1.70 (0.25)***
	Orthographic Processing					1.48 (0.21)**
Random Effects						
SID	var (Intercept)	1.46 (0.33)	1.30 (0.31)	1.45 (0.34)	1.31 (0.31)	0.33 (0.11)
Session	var (Intercept)	0.06 (0.10)	0.11 (0.11)	0.06 (0.10)	0.10 (0.11)	0.09 (0.11)
Statistics						
χ^2			66.04	43.26	67.88	154.86
Log Likelihood		-998.14	-962.50	-975.97	-961.31	-929.31
AIC		2002.28	1947.01	1971.94	1946.63	1892.62
BIC		2019.73	2011.01	2030.12	2016.45	1991.53

Note: Odd Ratio (Standard Error); * *p-value* $\leq .05$; ** *p-value* $\leq .01$; *** *p-value* $\leq .005$

Variable		Model 4	Model 5	Model 6
Fixed Effects				
Level 1 : Word characteristic	Intercept	1.40 (0.86)	1.36 (0.83)	1.39 (0.86)
	Pretest Accuracy	1.85 (0.25)***	1.85 (0.25)***	1.84 (0.25)***
	Base Word Accuracy	2.04 (0.54)**	2.04 (0.54)**	2.02 (0.53)**
	Number of Letters	0.80 (0.08)*	0.80 (0.08)*	0.80 (0.08)*
	Log Frequency	1.09 (0.04)*	1.09 (0.04)*	1.09 (0.04)*
	PGC	1.01 (0.01)*	1.01 (0.01)*	1.01 (0.01)*
	Rime	1.48 (0.24)*	1.51 (0.23)**	1.52 (0.23)***
	Substitution	1.75 (0.33)***	2.08 (0.48)***	1.74 (0.33)***
	Transposition	2.64 (0.67)***	2.61 (0.66)***	2.58 (0.69)***
Level 2: Session	Session Number	0.92 (0.05)	0.92 (0.05)	0.92 (0.05)
Level 3: Participant	Phonological Processing	0.71 (0.12)*	0.66 (0.11)*	0.72 (0.12)*
	Oral vocabulary	1.37 (0.15)**	1.38 (0.15)***	1.36 (0.15)**
	Decoding	1.26 (0.19)	1.27 (0.19)	1.26 (0.19)
	Print Knowledge	1.70 (0.25)***	1.67 (0.23)***	1.70 (0.25)***
	Orthographic Processing	1.50 (0.22)***	1.53 (0.21)***	1.48 (0.21)**
Random Effects				
SID	var (Intercept)	0.39 (0.15)	0.25 (0.10)	0.33 (0.12)
	var (x)	Rime 0.09 (0.19)	Substitution 0.22 (0.23)	Transposition 0.002 (0.03)
	cov (x,intercept)	-0.09 (0.14)	0.24 (0.12)	-0.03 (0.16)
Session	var (Intercept)	0.10 (0.11)	0.10 (0.11)	0.09 (0.11)
Statistics				
χ^2		153.50	162.31	153.47
Log Likelihood		-929.07	-927.21	-929.29
AIC		1896.15	1892.42	1896.59
BIC		2006.69	2002.96	2007.13

Note: Odd Ratio (Standard Error); * *p-value* ≤ *.05*; ** *p-value* ≤ *.01*; *** *p-value* ≤ *.005*

Variable		Model 7	Model 8	Model 9
Fixed Effects				
	Intercept	1.38 (0.87)	1.30 (0.82)	1.33 (0.82)
Level 1 : Word characteristic	Pretest Accuracy	1.84 (0.25)***	1.83 (0.25)***	1.83 (0.25)***
	Base Word Accuracy	2.02 (0.054)**	2.01 (0.54)**	2.02 (0.53)**
	Number of Letters	0.80 (0.08)*	0.82 (0.09)	0.80 (0.08)*
	Log Frequency	1.09 (0.04)*	1.09 (0.04)*	1.10 (0.04)*
	PGC	1.01 (0.01)*	1.01 (0.01)*	1.01 (0.01)*
	Rime	1.52 (0.23)***	1.52 (0.23)***	1.52 (0.23)***
	Substitution	1.74 (0.33)***	1.74 (0.33)***	1.74 (0.33)***
	Transposition	2.62 (0.67)***	2.62 (0.67)***	2.62 (0.67)***
Level 2: Session	Session Number	0.92 (0.05)	0.92 (0.05)	0.92 (0.05)
Level 3: Participant	Phonological Processing	0.72 (0.12)*	0.72 (0.12)*	0.71 (0.12)*
	Oral vocabulary	1.35 (0.16)**	1.36 (0.15)**	1.36 (0.15)**
	Decoding	1.26 (0.19)	1.25 (0.19)	1.26 (0.19)
	Print Knowledge	1.70 (0.25)***	1.71 (0.25)***	1.71 (0.25)***
	Orthographic Processing	1.48 (0.21)**	1.49 (0.21)***	1.49 (0.21)**
Random Effects				
SID	var (Intercept)	0.38 (1.74)	0.28 (1.76)	0.17 (0.24)
	var (x)	PGC 0.11 (2.06)	Number of Letters 0.01 (0.07)	Log Frequency 0.0004 (0.001)
	cov (x,intercept)	-0.08 (1.86)	-0.02 (0.35)	0.01 (0.01)
Session	var (Intercept)	0.09 (0.11)	0.09 (0.11)	0.09 (0.11)
Statistics				
χ^2		150.62	154.15	155.94
Log Likelihood		-929.31	-929.19	-929.14
AIC		1896.62	1896.38	1896.29
BIC		2007.16	2006.92	2006.83

Note: Odd Ratio (Standard Error); * *p-value ≤ .05*; ** *p-value ≤ .01*; *** *p-value ≤ .005*

Variable		Model 10	Model 11	Model 12
Fixed Effects				
Level 1 : Word characteristic	Intercept	1.39 (0.86)	1.40 (0.86)	1.38 (0.85)
	Pretest Accuracy	1.84 (0.25)***	1.84 (0.25)***	1.84 (0.25)***
	Base Word Accuracy	2.02 (0.53)**	2.01 (0.53)**	2.02 (0.53)**
	Number of Letters	0.80 (0.08)*	0.80 (0.08)*	0.80 (0.08)*
	Log Frequency	1.09 (0.04)*	1.09 (0.04)*	1.09 (0.04)*
	PGC	1.01 (0.01)*	1.01 (0.01)*	1.01 (0.01)*
	Rime	1.51 (0.24)**	1.52 (0.23)***	1.51 (0.23)**
	Substitution	1.74 (0.33)***	1.77 (0.35)***	1.73 (0.33)***
	Transposition	2.63 (0.67)***	2.62 (0.67)***	2.89 (0.83)***
Level 2: Session	Session Number	0.92 (0.05)	0.92 (0.05)	0.92 (0.05)
Level 3: Participant	Phonological Processing	0.72 (0.12)*	0.72 (0.12)*	0.72 (0.12)*
	Oral vocabulary	1.36 (0.15)**	1.36 (0.15)**	1.36 (0.15)**
	Decoding	1.26 (0.19)	1.26 (0.19)	1.26 (0.19)
	Print Knowledge	1.70 (0.25)***	1.70 (0.25)***	1.70 (0.25)***
	Orthographic Processing	1.50 (0.23)**	1.47 (0.22)**	1.46 (0.21)**
Cross - Level	Orthographic Processing ×	Rime 0.98 (0.13)	Substitution 1.04 (0.17)	Transposition 1.20 (0.27)
Random Effects				
SID	var (Intercept)	0.33 (0.11)	0.33 (0.11)	0.33 (0.11)
Session	var (Intercept)	0.09 (0.11)	0.09 (0.11)	0.09 (0.11)
Statistics				
χ^2		154.94	154.82	154.42
Log Likelihood		-929.30	-929.28	-928.99
AIC		1894.60	1894.56	1893.98
BIC		1999.32	1999.28	1998.71

Note: Odd Ratio (Standard Error); * *p-value* $\leq .05$; ** *p-value* $\leq .01$; *** *p-value* $\leq .005$

Variable		Model 13
Fixed Effects		
Level 1 : Word characteristic	Intercept	1.38 (0.85)
	Pretest Accuracy	1.84 (0.25)***
	Base Word Accuracy	2.00 (0.53)**
	Number of Letters	0.80 (0.08)*
	Log Frequency	1.09 (0.04)*
	PGC	1.01 (0.01)*
	Rime	1.53 (0.24)**
	Substitution	1.78 (0.36)***
	Transposition	2.91 (0.84)***
Level 2: Session	Session Number	0.92 (0.05)
Level 3: Participant	Phonological Processing	0.72 (0.12)*
	Oral vocabulary	1.36 (0.15)**
	Decoding	1.26 (0.19)
	Print Knowledge	1.69 (0.25)***
	Orthographic Processing	1.42 (0.24)*
Cross-Level	Orthographic Processing ×	Rime 1.03 (0.15) Substitution 1.08 (0.20) Transposition 1.23 (0.30)
Random Effects		
SID	var (Intercept)	0.33 (0.11)
Session	var (Intercept)	0.09 (0.11)
Statistics		
χ^2		154.17
Log Likelihood		-928.90
AIC		1897.79
BIC		2014.15

Note: Odd Ratio (Standard Error); * *p-value* $\leq$ *.05*; ** *p-value* $\leq$ *.01*; *** *p-value* $\leq$ *.005*

Appendix D. All Immediate Spelling Models

	Variable	Model 0	Model 1	Model 1a	Model 2	Model 3
Fixed Effects						
Level 1 : Word characteristic	Intercept	2.59 (0.54)***	5.08 (3.13)	5.33 (3.31)	4.93 (3.05)**	4.72 (2.79)**
	Pretest Accuracy		1.99 (0.23)***		1.98 (0.23)***	1.92 (0.23)***
	Base Word Accuracy		1.55 (0.43)	1.56 (0.44)	1.52 (0.43)	1.52 (0.42)
	Number of Letters		0.55 (0.05)***	0.56 (0.05)***	0.56 (0.05)***	0.56 (0.05)***
	Log Frequency		1.13 (0.04)***	1.15 (0.04)***	1.14 (0.04)***	1.14 (0.04)***
	PGC		1.00 (0.005)	1.00 (0.005)	1.00 (0.005)	1.00 (0.005)
	Rime		2.57 (0.36)***	2.84 (0.39)***	2.54 (0.35)***	2.56 (0.36)***
	Substitution		0.74 (0.12)	0.79 (0.13)	0.74 (0.12)	0.74 (0.12)
	Transposition		0.84 (0.17)	0.88 (0.17)	0.85 (0.17)	0.86 (0.17)
Level 2: Session	Session Number				0.96 (0.05)	0.96 (0.05)
Level 3: Participant	Phonological Processing					1.06 (0.18)
	Oral vocabulary					1.31 (0.16)*
	Decoding					1.55 (0.24)***
	Print Knowledge					1.79 (0.30)***
	Orthographic Processing					1.63 (0.25)***
Random Effects						
SID	var (Intercept)	2.64 (0.58)	2.68 (0.59)	2.98 (0.64)	2.69 (0.59)	0.41 (0.14)
Session	var (Intercept)	0.62 (0.15)	0.46 (0.14)	0.49 (0.14)	0.46 (0.14)	0.46 (0.14)
Statistics						
χ^2			166.68	138.42	166.99	284.64
Log Likelihood		-1318.25	-1224.58	-1241.56	-1224.34	-1177.53
AIC		2642.49	2471.15	2503.12	2472.68	2389.07
BIC		2659.95	2535.15	2561.30	2542.49	2487.97

Note: Odd Ratio (Standard Error); * *p-value* ≤ *.05*; ** *p-value* ≤ *.01*; *** *p-value* ≤ *.005*

Variable		Model 4	Model 5	Model 6
Fixed Effects				
Level 1 : Word characteristic	Intercept	4.76 (2.82)**	4.86 (2.88)**	4.74 (2.80)**
	Pretest Accuracy	1.94 (0.23)***	1.93 (0.23)***	1.92 (0.23)***
	Base Word Accuracy	1.52 (0.43)	1.49 (0.41)	1.53 (0.42)
	Number of Letters	0.56 (0.05)***	0.56 (0.05)***	0.56 (0.05)***
	Log Frequency	1.14 (0.04)	1.14 (0.04)	1.13 (0.04)
	PGC	1.00 (0.005)	1.00 (0.005)	1.00 (0.005)
	Rime	2.67 (0.41)***	2.57 (0.36)***	2.57 (0.36)***
	Substitution	0.74 (0.12)	0.72 (0.12)*	0.74 (0.12)
	Transposition	0.86 (0.17)	0.86 (0.17)	0.84 (0.17)
Level 2: Session	Session Number	0.97 (0.05)	0.96 (0.05)	0.97 (0.05)
Level 3: Participant	Phonological Processing	1.04 (0.18)	1.07 (0.18)	1.06 (0.18)
	Oral vocabulary	1.28 (0.15)*	1.32 (0.16)*	1.30 (0.16)*
	Decoding	1.61 (0.26)***	1.53 (0.24)**	1.56 (0.24)***
	Print Knowledge	1.79 (0.30)***	1.84 (0.31)***	1.80 (0.30)***
	Orthographic Processing	1.70 (0.26)***	1.63 (0.24)***	1.65 (0.25)***
Random Effects				
SID	var (Intercept)	0.33 (0.14)	0.49 (0.16)	0.45 (0.15)
	var (x)	Rime 0.15 (0.19)	Substitution 0.05 (0.08)	Transposition 0.04 (0.08)
	cov (x,intercept)	0.12 (0.12)	-0.16 (0.13)	-0.13 (0.15)
Session	var (Intercept)	0.47 (0.14)	0.46 (0.14)	0.46 (0.14)
Statistics				
χ^2		270.87	287.38	283.62
Log Likelihood		-1176.21	-1176.55	-1177.11
AIC		2390.42	2391.10	2392.23
BIC		2500.97	2501.65	2502.77

Note: Odd Ratio (Standard Error); * *p-value ≤ .05*; ** *p-value ≤ .01*; *** *p-value ≤ .005*

	Variable	Model 7	Model 8	Model 9
		Fixed Effects		
Level 1 : Word characteristic	Intercept	4.61 (2.74)**	4.99 (3.00)**	4.91 (2.98)*
	Pretest Accuracy	1.92 (0.23)***	1.92 (0.23)***	1.93 (0.23)***
	Base Word Accuracy	1.52 (0.42)	1.52 (0.42)	1.53 (0.43)
	Number of Letters	0.56 (0.05)***	0.56 (0.05)***	0.56 (0.05)***
	Log Frequency	1.14 (0.04)	1.14 (0.04)	1.14 (0.04)
	PGC	1.00 (0.005)	1.00 (0.005)	1.00 (0.005)
	Rime	2.56 (0.36)***	2.56 (0.36)***	2.55 (0.36)***
	Substitution	0.74 (0.12)	0.74 (0.12)	0.73 (0.12)
	Transposition	0.86 (0.17)	0.86 (0.17)	0.85 (0.17)
Level 2: Session	Session Number	0.96 (0.05)	0.96 (0.05)	0.96 (0.05)
Level 3: Participant	Phonological Processing	1.06 (0.18)	1.06 (0.18)	1.05 (0.18)
	Oral vocabulary	1.30 (0.16)*	1.31 (0.16)*	1.28 (0.15)*
	Decoding	1.56 (0.24)***	1.56 (0.24)***	1.63 (0.25)***
	Print Knowledge	1.79 (0.30)***	1.80 (0.30)***	1.78 (0.29)***
	Orthographic Processing	1.63 (0.25)***	1.64 (0.25)***	1.58 (0.23)***
		Random Effects		
SID	var (Intercept)	0.24 (0.51)	1.02 (1.06)	1.46 (0.84)
	var (x)	PGC 0.03 (0.20)	Number of Letters 0.01 (0.02)	Log Frequency 0.005 (0.006)
	cov (x,intercept)	0.08 (0.20)	-0.08 (0.15)	-0.09 (0.07)
Session	var (Intercept)	0.46 (0.14)	0.47 (0.14)	0.47 (0.14)
		Statistics		
χ^2		284.11	283.13	287.95
Log Likelihood		-1177.49	-1177.28	-1175.90
AIC		2392.98	2392.56	2398.81
BIC		2503.53	2503.10	2500.35

	Variable	Model 10	Model 11	Model 12
		Fixed Effects		
Level 1 : Word characteristic	Intercept	4.67 (2.76)**	4.76 (2.81)**	4.60 (2.72)**
	Pretest Accuracy	1.95 (0.23)***	1.93 (0.23)***	1.93 (0.23)***
	Base Word Accuracy	1.51 (0.42)	1.49 (0.42)	1.52 (0.42)
	Number of Letters	0.56 (0.05)***	0.56 (0.05)***	0.57 (0.05)***
	Log Frequency	1.14 (0.04)***	1.14 (0.04)***	1.14 (0.04)***
	PGC	1.00 (0.005)	1.00 (0.005)	1.00 (0.005)
	Rime	2.36 (0.34)***	2.54 (0.36)***	2.53 (0.35)***
	Substitution	0.73 (0.12)	0.74 (0.12)	0.73 (0.12)
	Transposition	0.86 (0.17)	0.86 (0.17)	0.89 (0.18)
Level 2: Session	Session Number	0.96 (0.05)	0.96 (0.05)	0.96 (0.05)
Level 3: Participant	Phonological Processing	1.05 (0.18)	1.06 (0.18)	1.06 (0.18)
	Oral vocabulary	1.31 (0.16)*	1.31 (0.16)*	1.31 (0.16)*
	Decoding	1.55 (0.24)***	1.55 (0.24)***	1.55 (0.24)***
	Print Knowledge	1.80 (0.30)***	1.80 (0.30)***	1.79 (0.30)***
	Orthographic Processing	1.83 (0.29)***	1.60 (0.25)***	1.59 (0.24)***
Cross-Level	Orthographic Processing ×	Rime 0.74 (0.09)*	Substitution 1.11 (0.17)	Transposition 1.25 (0.24)
		Random Effects		
SID	var (Intercept)	0.40 (0.14)	0.41 (0.14)	0.41 (0.14)
Session	var (Intercept)	0.47 (0.14)	0.46 (0.14)	0.46 (0.14)
		Statistics		
χ^2		290.74	285.34	285.62
Log Likelihood		-1174.57	-1177.28	-1176.85
AIC		2395.14	2390.55	2389.71
BIC		2489.86	2495.28	2494.43

Note: Odd Ratio (Standard Error); * *p-value* ≤ *.05*; ** *p-value* ≤ *.01*; *** *p-value* ≤ *.005*

Variable		Model 13
Fixed Effects		
Level 1 : Word characteristic	Intercept	4.61 (2.73)**
	Pretest Accuracy	1.95 (0.23)***
	Base Word Accuracy	1.51 (0.42)
	Number of Letters	0.56 (0.05)***
	Log Frequency	1.14 (0.04)***
	PGC	1.00 (0.005)
	Rime	2.36 (0.34)***
	Substitution	0.73 (0.12)
	Transposition	0.87 (0.18)
Level 2: Session	Session Number	0.96 (0.05)
Level 3: Participant	Phonological Processing	1.05 (0.18)
	Oral vocabulary	1.31 (0.16)*
	Decoding	1.55 (0.24)***
	Print Knowledge	1.80 (0.30)***
	Orthographic Processing	1.81 (0.32)***
Cross-Level	Orthographic Processing ×	Rime 0.75 (0.11)
		Substitution 0.99 (0.17)
		Transposition 1.11 (0.24)
Random Effects		
SID	var (Intercept)	0.40 (0.14)
Session	var (Intercept)	0.47 (0.14)
Statistics		
χ^2		290.75
Log Likelihood		-1174.42
AIC		2388.84
BIC		2505.20

Note: Odd Ratio (Standard Error); * *p-value* ≤ *.05*; ** *p-value* ≤ *.01*; *** *p-value* ≤ *.005*

Appendix E. All Delayed Orthographic Choice Models

Variable		Model 0	Model 1	Model 1a	Model 2	Model 3
Fixed Effects						
Level 1 : Word characteristic	Intercept	5.27 (0.91)***	0.25 (0.15)*	0.25 (0.15)*	0.26 (0.16)*	0.24 (0.14)*
	Pretest Accuracy		2.12 (0.28)***		2.12 (0.28)***	2.00 (0.26)***
	Base Word Accuracy		2.50 (0.70)***	2.50 (0.69)***	2.57 (0.72)***	2.57 (0.71)***
	Number of Letters		0.65 (0.06)***	0.66 (0.06)***	0.64 (0.06)***	0.64 (0.06)***
	Log Frequency		1.09 (0.04)*	1.11 (0.04)***	1.08 (0.04)	1.08 (0.04)*
	PGC		1.03 (0.01)***	1.03 (0.01)***	1.03 (0.01)***	1.03 (0.01)***
	Rime		1.96 (0.28)***	2.14 (0.30)***	1.99 (0.29)***	2.01 (0.29)***
	Substitution		1.51 (0.26)*	1.64 (0.28)***	1.51 (0.26)*	1.53 (0.26)*
	Transpositio n		3.88 (0.96)***	4.08 (1.00)***	3.77 (0.94)***	3.83 (0.95)***
Level 2: Session	Session Number				1.05 (0.06)	1.05 (0.06)
Level 3: Participant	Phonological Processing					1.06 (0.16)
	Oral vocabulary					1.28 (0.13)*
	Decoding					1.14 (0.16)
	Print Knowledge					1.98 (0.27)***
	Orthographic Processing					1.39 (0.18)*
Random Effects						
SID	var (Intercept)	1.61 (0.37)	1.56 (0.36)	1.78 (0.40)	1.56 (0.36)	0.22 (0.10)
Session	var (Intercept)	0.39 (0.13)	0.42 (0.15)	0.39 (0.14)	0.42 (0.15)	0.42 (0.15)
Statistics						
χ^2			148.70	122.31	149.61	251.56
Log Likelihood		-1162.59	-1077.06	-1094.24	-1076.68	-1036.32
AIC		2331.19	2176.12	2208.49	2177.35	2106.65
BIC		2348.63	2240.09	2266.64	2247.14	2205.51

Note: Odd Ratio (Standard Error); * *p-value ≤ .05*; ** *p-value ≤ .01*; *** *p-value ≤ .005*

	Variable	Model 4	Model 5	Model 6
Fixed Effects				
Level 1 : Word characteristic	Intercept	0.24 (0.14)*	0.24 (0.15)*	0.24 (0.14)*
	Pretest Accuracy	2.01 (0.26)***	2.00 (0.26)***	2.01 (0.26)***
	Base Word Accuracy	2.64 (0.73)***	2.57 (0.71)***	2.58 (0.72)***
	Number of Letters	0.64 (0.06)***	0.64 (0.06)***	0.64 (0.06)***
	Log Frequency	1.08 (0.04)*	1.08 (0.04)*	1.08 (0.04)*
	PGC	1.03 (0.01)***	1.03 (0.01)***	1.03 (0.01)***
	Rime	1.94 (0.29)***	2.01 (0.29)***	2.01 (0.29)***
	Substitution	1.53 (0.26)*	1.51 (0.26)*	1.53 (0.26)*
	Transposition	3.86 (0.96)***	3.83 (0.96)***	3.76 (1.03)***
Level 2: Session	Session Number	1.05 (0.06)	1.05 (0.06)	1.05 (0.06)
Level 3: Participant	Phonological Processing	1.07 (0.16)	1.07 (0.16)	1.07 (0.16)
	Oral vocabulary	1.30 (0.14)*	1.28 (0.13)*	1.27 (0.13)*
	Decoding	1.13 (0.15)	1.15 (0.16)	1.13 (0.16)
	Print Knowledge	1.96 (0.27)***	2.00 (0.28)***	1.97 (0.28)***
	Orthographic Processing	1.43 (0.19)**	1.39 (0.18)*	1.40 (0.19)*
Random Effects				
SID	var (Intercept)	0.30 (0.14)	0.24 (0.12)	0.22 (0.11)
	var (x)	Rime 0.04 (0.07)	Substitution 0.01 (0.03)	Transposition 0.07 (0.44)
	cov (x,intercept)	-0.11 (0.11)	-0.04 (0.10)	-0.06 (0.18)
Session	var (Intercept)	0.42 (0.15)	0.42 (0.15)	0.43 (0.15)
Statistics				
χ^2		248.93	243.27	227.97
Log Likelihood		-1035.57	-1036.24	-1036.26
AIC		2109.14	2110.48	2110.52
BIC		2219.63	2220.97	2221.01

Note: Odd Ratio (Standard Error); * *p-value ≤ .05*; ** *p-value ≤ .01*; *** *p-value ≤ .005*

	Variable	Model 7	Model 8	Model 9
Fixed Effects				
Level 1 : Word characteristic	Intercept	0.26 (0.16)*	0.26 (0.16)*	0.26 (0.16)*
	Pretest Accuracy	2.00 (0.26)***	2.01 (0.26)***	2.00 (0.26)***
	Base Word Accuracy	2.60 (0.72)***	2.63 (0.06)***	2.65 (0.07)***
	Number of Letters	0.64 (0.06)***	0.63 (0.06)***	0.64 (0.06)***
	Log Frequency	1.08 (0.04)*	1.08 (0.04)*	1.06 (0.04)*
	PGC	1.03 (0.01)***	1.03 (0.01)***	1.03 (0.01)***
	Rime	2.01 (0.29)***	2.00 (0.29)***	2.02 (0.29)***
	Substitution	1.53 (0.26)*	1.53 (0.26)*	1.54 (0.26)*
	Transposition	3.84 (0.96)***	3.85 (0.96)***	3.87 (0.97)***
Level 2: Session	Session Number	1.05 (0.06)	1.05 (0.06)	1.06 (0.06)
Level 3: Participant	Phonological Processing	1.09 (0.17)	1.04 (0.16)	1.04 (0.16)
	Oral vocabulary	1.29 (0.13)*	1.28 (0.13)*	1.25 (0.13)*
	Decoding	1.13 (0.15)	1.16 (0.16)	1.16 (0.16)
	Print Knowledge	1.95 (0.27)***	1.99 (0.28)***	2.02 (0.27)***
	Orthographic Processing	1.41 (0.19)**	1.41 (0.19)**	1.46 (0.20)***
Random Effects				
SID	var (Intercept)	0.88 (1.15)	1.09 (1.27)	1.14 (0.85)
	var (x)	PGC 0.29 (0.75)	Number of Letters 0.01 (0.03)	Log Frequency 0.01 (0.01)
	cov (x,intercept)	-0.51 (0.97)	-0.13 (0.20)	-0.08 (0.08)
Session	var (Intercept)	0.42 (0.15)	0.42 (0.15)	0.41 (0.14)
Statistics				
χ^2		247.88	246.72	250.16
Log Likelihood		-1036.02	-1035.88	-1035.24
AIC		2110.04	2109.77	2108.48
BIC		2220.53	2220.25	2218.97

	Variable	Model 10	Model 11	Model 12
		Fixed Effects		
Level 1 : Word characteristic	Intercept	0.23 (0.14)*	0.25 (0.15)*	0.24 (0.14)*
	Pretest Accuracy	1.99 (0.26)***	2.02 (0.26)***	2.00 (0.26)***
	Base Word Accuracy	2.62 (0.72)***	2.45 (0.68)***	2.59 (0.71)***
	Number of Letters	0.64 (0.06)***	0.63 (0.06)***	0.64 (0.06)***
	Log Frequency	1.08 (0.04)	1.08 (0.04)*	1.08 (0.04)*
	PGC	1.03 (0.01)***	1.03 (0.01)***	1.03 (0.01)***
	Rime	2.26 (0.35)***	1.97 (0.28)***	2.02 (0.29)***
	Substitution	1.53 (0.26)*	1.67 (0.30)***	1.53 (0.26)*
	Transposition	3.76 (0.93)***	3.70 (0.92)***	3.46 (0.92)***
Level 2: Session	Session Number	1.06 (0.06)	1.05 (0.06)	1.05 (0.06)
Level 3: Participant	Phonological Processing	1.07 (0.16)	1.06 (0.16)	1.06 (0.16)
	Oral vocabulary	1.28 (0.13)*	1.28 (0.13)*	1.28 (0.13)*
	Decoding	1.14 (0.16)	1.14 (0.16)	1.14 (0.16)
	Print Knowledge	1.98 (0.28)***	1.99 (0.28)***	1.99 (0.27)***
	Orthographic Processing	1.27 (0.18)	1.31 (0.18)*	1.42 (0.19)**
Cross-Level	Orthographic Processing ×	Rime 1.34 (0.18)*	Substitution 1.37 (0.21)	Transposition 0.82 (0.18)
		Random Effects		
SID	var (Intercept)	0.22 (0.10)	0.22 (0.10)	0.22 (0.10)
Session	var (Intercept)	0.44 (0.15)	0.43 (0.15)	0.43 (0.15)
		Statistics		
χ^2		248.91	254.01	253.05
Log Likelihood		-1033.83	-1034.20	-1035.89
AIC		2103.66	2104.39	2107.78
BIC		2208.33	2209.07	2212.45

Note: Odd Ratio (Standard Error); * *p-value ≤ .05*; ** *p-value ≤ .01*; *** *p-value ≤ .005*

Variable			Model 13
Fixed Effects			
Level 1 : Word characteristic	Intercept		0.24 (0.14)*
	Pretest Accuracy		2.01 (0.26)***
	Base Word Accuracy		2.42 (0.68)***
	Number of Letters		0.64 (0.06)***
	Log Frequency		1.08 (0.04)*
	PGC		1.03 (0.01)***
	Rime		2.33 (0.37)***
	Substitution		1.75 (0.32)***
	Transposition		3.67 (0.97)***
Level 2: Session	Session Number		1.06 (0.06)
Level 3: Participant	Phonological Processing		1.06 (0.16)
	Oral vocabulary		1.29 (0.14)*
	Decoding		1.14 (0.16)
	Print Knowledge		1.99 (0.28)***
	Orthographic Processing		1.07 (0.17)
Cross-Level	Orthographic Processing ×	Rime	1.58 (0.23)***
		Substitution	1.68 (0.29)***
		Transposition	1.09 (0.25)
		Number of Letters	
		Log Frequency	
		PGC	
Random Effects			
SID	var (Intercept)		0.23 (0.11)
Session	var (Intercept)		0.46 (0.15)
Statistics			
χ^2			251.41
Log Likelihood			-1028.99
AIC			2097.98
BIC			2214.29

Note: Odd Ratio (Standard Error); * *p-value* $\leq .05$; ** *p-value* $\leq .01$; *** *p-value* $\leq .005$

Appendix F. All Delayed Spelling Models

	Variable	Model 0	Model 1	Model 1a	Model 2	Model 3
Fixed Effects						
Level 1 : Word characteristic	Intercept	1.21 (0.23)	1.99 (1.20)	2.00 (1.21)	1.85 (1.12)	1.82 (1.05)
	Pretest Accuracy		2.57 (0.29)***		2.55 (0.29)***	2.46 (0.28)***
	Base Word Accuracy		1.54 (0.46)	1.56 (0.47)	1.48 (0.44)	1.46 (0.44)
	Number of Letters		0.61 (0.05)***	0.62 (0.06)***	0.64 (0.06)***	0.64 (0.06)***
	Log Frequency		1.06 (0.03)	1.10 (0.03)***	1.08 (0.04)*	1.08 (0.04)*
	PGC		1.00 (0.004)	1.00 (0.004)	1.00 (0.004)	1.00 (0.004)
	Rime		2.56 (0.34)***	2.96 (0.39)***	2.49 (0.33)***	2.51 (0.34)***
	Substitution		0.81 (0.13)	0.92 (0.14)	0.81 (0.13)	0.82 (0.13)
	Transpositio n		0.71 (0.14)	0.76 (0.14)	0.73 (0.14)	0.74 (0.14)
Level 2: Session	Session Number				0.89 (0.05)*	0.90 (0.05)*
Level 3: Participant	Phonological Processing					1.06 (0.17)
	Oral vocabulary					1.38 (0.15)***
	Decoding					1.22 (0.18)
	Print Knowledge					2.10 (0.34)***
	Orthographic Processing					1.55 (0.22)***
Random Effects						
SID	var (Intercept)	2.18 (0.46)	2.14 (0.46)	2.46 (0.51)	2.15 (0.46)	0.32 (0.11)
Session	var (Intercept)	0.71 (0.15)	0.56 (0.15)	0.64 (0.15)	0.55 (0.14)	0.56 (0.14)
Statistics						
χ^2			192.09	133.83	194.86	313.41
Log Likelihood		-1413.81	-1305.29	-1340.18	-1303.17	-1256.76
AIC		2833.61	2632.58	2700.37	2630.33	2547.52
BIC		2851.06	2696.55	2758.52	2700.11	2646.38

Note: Odd Ratio (Standard Error); * *p-value ≤ .05*; ** *p-value ≤ .01*; *** *p-value ≤ .005*

Variable		Model 4	Model 5	Model 6
Fixed Effects				
Level 1 : Word characteristic	Intercept	1.85 (1.08)	1.83 (1.06)	1.82 (1.06)
	Pretest Accuracy	2.50 (0.29)***	2.47 (0.28)***	2.45 (0.28)***
	Base Word Accuracy	1.46 (0.44)	1.46 (0.43)	1.47 (0.44)
	Number of Letters	0.64 (0.06)***	0.64 (0.06)***	0.64 (0.06)***
	Log Frequency	1.08 (0.04)*	1.08 (0.04)*	1.08 (0.04)*
	PGC	1.00 (0.004)	1.00 (0.004)	1.00 (0.004)
	Rime	2.59 (0.39)***	2.52 (0.34)***	2.52 (0.34)***
	Substitution	0.81 (0.13)	0.81 (0.13)	0.82 (0.13)
	Transposition	0.73 (0.14)	0.73 (0.14)	0.73 (0.14)
Level 2: Session	Session Number	0.89 (0.05)*	0.89 (0.05)*	0.90 (0.05)*
Level 3: Participant	Phonological Processing	1.06 (0.17)	1.06 (0.17)	1.06 (0.17)
	Oral vocabulary	1.41 (0.16)***	1.39 (0.15)***	1.39 (0.16)***
	Decoding	1.18 (0.17)	1.16 (0.18)	1.21 (0.18)
	Print Knowledge	2.29 (0.41)***	2.21 (0.38)***	2.11 (0.35)***
	Orthographic Processing	1.57 (0.22)***	1.57 (0.22)***	1.55 (0.22)***
Random Effects				
SID	var (Intercept)	0.26 (0.12)	0.38 (0.14)	0.34 (0.13)
	var (x)	Rime 0.27 (0.19)	Substitution 0.04 (0.08)	Transposition 0.11 (0.35)
	cov (x,intercept)	0.06 (0.13)	-0.13 (0.13)	-0.08 (0.15)
Session	var (Intercept)	0.56 (0.15)	0.56 (0.15)	0.56 (0.15)
Statistics				
χ^2		282.86	311.84	305.00
Log Likelihood		-1254.14	-1256.20	-1256.58
AIC		2546.28	2550.40	2551.16
BIC		2656.77	2660.89	2661.65

Note: Odd Ratio (Standard Error); * *p-value* $\leq .05$; ** *p-value* $\leq .01$; *** *p-value* $\leq .005$

Variable		Model 7	Model 8	Model 9
Fixed Effects				
Level 1 : Word characteristic	Intercept	1.71 (0.99)	1.81 (1.05)	1.79 (1.05)
	Pretest Accuracy	2.47 (0.28)***	2.46 (0.28)***	2.46 (0.28)***
	Base Word Accuracy	1.47 (0.44)	1.46 (0.44)	1.48 (0.44)
	Number of Letters	0.64 (0.06)***	0.64 (0.06)***	0.64 (0.06)***
	Log Frequency	1.08 (0.04)*	1.08 (0.04)*	1.08 (0.04)*
	PGC	1.00 (0.004)	1.00 (0.004)	1.00 (0.004)
	Rime	2.52 (0.34)***	2.52 (0.34)***	2.51 (0.34)***
	Substitution	0.82 (0.13)	0.82 (0.13)	0.82 (0.13)
	Transposition	0.73 (0.14)	0.74 (0.14)	0.73 (0.14)
Level 2: Session	Session Number	0.89 (0.05)*	0.90 (0.05)*	0.89 (0.05)*
Level 3: Participant	Phonological Processing	1.05 (0.17)	1.06 (0.17)	1.06 (0.17)
	Oral vocabulary	1.35 (0.15)**	1.38 (0.15)***	1.37 (0.15)***
	Decoding	1.19 (0.17)	1.21 (0.18)	1.23 (0.18)
	Print Knowledge	2.18 (0.36)***	2.11 (0.34)***	2.10 (0.35)***
	Orthographic Processing	1.58 (0.22)***	1.55 (0.22)***	1.56 (0.22)***
Random Effects				
SID	var (Intercept)	0.00005 (0.01)	0.42 (1.67)	0.65 (0.80)
	var (x)	PGC 0.43 (0.75)	Number of Letters 0.01 (0.07)	Log Frequency 0.003 (0.01)
	cov (x,intercept)	-0.005 (0.33)	-0.04 (0.34)	-0.03 (0.01)
Session	var (Intercept)	0.55 (0.14)	0.56 (0.15)	0.56 (0.15)
Statistics				
χ^2		315.64	302.36	309.13
Log Likelihood		-1256.11	-1256.72	-1256.66
AIC		2550.22	2551.44	2551.32
BIC		2660.71	2661.93	2661.81

Note: Odd Ratio (Standard Error); * *p-value* $\leq .05$; ** *p-value* $\leq .01$; *** *p-value* $\leq .005$

Level	Variable	Model 10	Model 11	Model 12
	Fixed Effects			
Level 1 : Word characteristic	Intercept	1.79 (1.04)	1.85 (1.07)	1.79 (1.04)
	Pretest Accuracy	2.49 (0.28)***	2.46 (0.28)***	2.46 (0.28)***
	Base Word Accuracy	1.46 (0.44)	1.44 (0.43)	1.47 (0.44)
	Number of Letters	0.64 (0.06)***	0.64 (0.06)***	0.64 (0.06)***
	Log Frequency	1.09 (0.04)*	1.08 (0.04)*	1.09 (0.04)*
	PGC	1.00 (0.004)	1.00 (0.004)	1.00 (0.004)
	Rime	2.46 (0.33)***	2.50 (0.34)***	2.50 (0.34)***
	Substitution	0.81 (0.13)	0.81 (0.13)	0.82 (0.13)
	Transposition	0.73 (0.14)	0.73 (0.14)	0.72 (0.14)
Level 2: Session	Session Number	0.89 (0.05)*	0.90 (0.05)*	0.89 (0.05)*
Level 3: Participant	Phonological Processing	1.06 (0.17)	1.06 (0.17)	1.06 (0.17)
	Oral vocabulary	1.38 (0.15)***	1.38 (0.15)***	1.38 (0.15)***
	Decoding	1.21 (0.18)	1.22 (0.18)	1.22 (0.18)
	Print Knowledge	2.13 (0.35)***	2.11 (0.35)***	2.11 (0.34)***
	Orthographic Processing	1.73 (0.26)***	1.51 (0.22)***	1.52 (0.21)***
Cross-Level	Orthographic Processing ×	Rime 0.76 (0.26)*	Substitution 1.13 (0.22)	Transposition 1.17 (0.22)
	Random Effects			
SID	var (Intercept)	0.31 (0.11)	0.32 (0.11)	0.32 (0.11)
Session	var (Intercept)	0.56 (0.15)	0.56 (0.14)	0.56 (0.14)
	Statistics			
χ^2		318.25	314.36	314.01
Log Likelihood		-1254.10	-1256.38	-1256.39
AIC		2544.20	2548.76	2548.79
BIC		2648.88	2653.43	2653.46

Note: Odd Ratio (Standard Error); * *p-value* $\leq .05$; ** *p-value* $\leq .01$; *** *p-value* $\leq .005$

Variable			Model 13
Fixed Effects			
Level 1 : Word characteristic	Intercept		1.79 (1.04)
	Pretest Accuracy		2.49 (0.28)***
	Base Word Accuracy		1.46 (0.44)
	Number of Letters		0.64 (0.06)***
	Log Frequency		1.09 (0.04)*
	PGC		1.00 (0.004)
	Rime		2.45 (0.33)***
	Substitution		0.81 (0.13)
	Transposition		0.73 (0.14)
Level 2: Session	Session Number		0.89 (0.005)*
Level 3: Participant	Phonological Processing		1.06 (0.17)
	Oral vocabulary		1.38 (0.15)***
	Decoding		1.21 (0.18)
	Print Knowledge		2.13 (0.35)***
	Orthographic Processing		1.71 (0.28)***
Cross-Level	Orthographic Processing ×	Rime	0.77 (0.11)
		Substitution	1.01 (0.17)
		Transposition	1.05 (0.22)
Random Effects			
SID	var (Intercept)		0.31 (0.11)
Session	var (Intercept)		0.56 (0.15)
Statistics			
χ^2			318.23
Log Likelihood			-1254.07
AIC			2548.14
BIC			2664.44

Note: Odd Ratio (Standard Error); * *p-value* $\leq$ *.05*; ** *p-value* $\leq$ *.01*; *** *p-value* $\leq$ *.005*