Winter 12-2019

Double Trouble: How Children and Adults Decide When to Use Double Consonants

Ruth Caputo
Washington University in St. Louis

WASHINGTON UNIVERSITY IN ST. LOUIS
Department of Psychological and Brain Sciences

Double Trouble: How Children and Adults Decide When to use Double Consonants

by

Ruth Marie Caputo

A Thesis presented to
The Graduate School
of Washington University in
partial fulfillment of the
requirements for the degree
of Master of Arts

December 2019
St. Louis, Missouri

Table of Contents

List of Tables

Acknowledgments

First and foremost, I would like to express my gratitude for my advisor, Dr. Rebecca Treiman, for her constant support. This project would not exist without your immeasurable input. I am especially grateful for your willingness to read draft after draft, providing fresh feedback each time. Additionally, I thank my committee members, Dr. Kristin Van Engen and Dr. Lori Markson, for their time and encouragement throughout this process.

I must also extend a special thanks to Dr. Brett Kessler, for his valuable input into the corpus and statistical work of this project, as well as for always having his door open in the lab to answer my endless questions.

Finally, my heartfelt gratitude to my spouse, Michael Caputo, for his boundless moral support and encouragement to follow my dreams.

Ruth Caputo

Washington University in St. Louis

December 2019

ABSTRACT OF THE THESIS

Double Trouble: Double trouble: How Children and Adults Decide when to use Double Consonants

by

Ruth Caputo

Master of Arts in Psychological and Brain Sciences

Washington University in St. Louis, 2019

Dr. Rebecca Treiman, Chair

Consonant doubling in English is difficult to master because it is inconsistent. In two-syllable words, consonants are usually doubled after short vowels (phonological context) spelled with a single letter (graphotactic context). Knowledge about context may help children learn when use double consonants. In the present study, second, fourth, and sixth grade elementary schoolers, as well as undergraduates, spell disyllabic nonwords to dictation in order to investigate if they consider phonological and graphotactic context when making decisions about doubling. We compare participants' doubling patterns to those of a grade leveled corpus of English vocabulary. The results indicate that all groups drew upon knowledge of phonological and graphotactic context when deciding when to use a consonant doublet, but that only undergraduates' doubling patterns resembled those of the English vocabulary. These results add to the literature because they indicate use of context early in learning how to spell. However, if doubling is learned through statistical learning, it takes places over a number of years, as use of phonological context increased with grade level.

Chapter 1: Literature Review

1.1 Introduction

Learning to spell in English is long process, and even the most competent spellers still make mistakes. In early elementary school, teachers devote a large portion of time and energy to teaching students how to write. Children spend hours learning the names and sounds of letters and memorizing how to spell lists of words. In short, learning to spell is a difficult and protracted process. One reason that learning to spell in English is particularly challenging is that one can spell the same speech sound, or phoneme, with a variety of letters or combinations of letters. This is not true in other writing systems such as Navajo, in which most phonemes are always spelled the same way. To illustrate, the sound /p/[1] may appropriately be represented as ‹p› or ‹pp› in English, whereas in Navajo /p/ may only be represented by ‹p›. When spelling the sound /p/ and most other English sounds, spellers have multiple options of which letter(s) to use. Consonant doubling, the use of two successive identical letters representing one phoneme (e.g. ‹bb› in *bubble*), is one of the most difficult English spelling patterns to master. This study investigates the development of consonant doubling into adulthood. Because it seems that even experienced spellers struggle to decide when to use consonant doublets, children's development of consonant doubling into adult-like spelling can help us understand what strategies and knowledge children and adults bring to the spelling process.

Spelling is not simply knowing what string of characters matches a word. Children who are learning to read and write in English must learn not only which letters represent which sounds but also how to choose between several alternative options of spellings. To decide

[1] A note on conventions: to distinguish between forms, phonological forms are transcribed in the International Phonetic Alphabet and written in /slashes/, written forms are put in ‹angled brackets›, and general words are in *italics*.

between the options, a speller must consider both what *function* the grapheme must serve and whether it will be an appropriate *form* according to the rules of the writing system (Fereirro & Teberosky, 1982). Function refers to writing's relationship to spoken language—the idea that letters and sequences of letters represent the phonemes of the spoken language. Form, on the other hand, refers to rules and patterns that govern the written language itself. The form of written language tells us that some letters and combinations of letters can only appear in certain contexts. The patterns of letters that may appear together are call graphotactics. For instance, while ‹ff› functions to represent /f/, it never occurs at the beginning of a word (a rule of written form). Put simply, a speller must first identify which letters or combinations of letters function to represent a particular phoneme. Next, the speller must consider, according to the rules of the language's written form, which of those options will create a legal string of letters in the larger phonological and graphic context of the word.

Spellers can choose between alternative spellings in three different ways. First, they could simply choose a spelling at random from the options. Second, they could consider the overall frequency of each option, choosing the spelling that occurs most frequently in the language. If spellers were use overall frequency, they may choose ‹f› for /f/, rather than ‹ff›, ‹ph›, or even ‹gh› because it is the most common correspondence overall. Some research has suggested that English speaking adults do this when spelling vowel sounds (Barry & Seymour, 1988; Martin & Barry; 2012), but this research did not acknowledge that these spellings may have also arisen if the speller had used the third method of choosing a spelling—considering context. Rather than considering the most frequent spelling of a phoneme overall, spellers could consider the most frequent spelling in a specific context, such as position in the word, the surrounding phonemes, or the surrounding letters. For instance, if they are spelling ‹f› word

initially and consider how /f/ is spelled only at the beginning of words, they could choose ‹f› or ‹ph› for /f/, because the alternatives ‹ff› and ‹gh› do not appear word initially in the English vocabulary. By using context, the speller can make choices that are closer to the conventionally accepted spelling of a word.

If spellers use context when making decisions about spellings, it surely occurs in an implicit manner. We do not explicitly remember every time we have encountered the letter ‹f› and we do not explicitly do arithmetic each time we try to spell /f/. Treiman and Wolter (2018) used a questionnaire to assess their participants' explicit knowledge about the context of consonant doublets. They found that 26 of the 111 adult participants mentioned that the length[2] of the preceding vowel is related to consonant doubling. Even though almost a quarter of the adults had some explicit knowledge of doubling context, the context they described is not entirely accurate. While in general doublets occur following short vowels and not after long vowels, the pattern for consonant doubling in English is quite complex. The relationship between vowel length and consonant doubling is asymmetrical. The presence of a consonant doublet generally indicates that the preceding vowel is a short vowel, but the presence of a short vowel does not entail that the following consonant must be a doublet. Spellers who are familiar with English may use this context, either consciously if they have been taught a rule, or unconsciously, in order to make decisions about spelling.

Doubling is not influenced by the phonological length of the preceding vowel alone. Other doubling patterns in English depend on the structure of the word. Words can be categorized by multiple dimensions, two of which are by number of morphemes and number of syllables. A morpheme is the smallest unit of meaning in a language. Examples of morphemes

[2] We recognize that vowel length is not an accurate description of this phenomenon, but nonetheless use the term because of its ubiquity in the traditional pedagogical sense.

include *dog*, plural ‹-s›, and past tense ‹-ed›. The word *dog* is monomorphemic, whereas *dogs* and *dogged* are polymorphemic, having two morphemes each. A syllable is a unit of language that consists of a single vowel or diphthong with its surrounding consonants. Doubling patterns for single-morpheme words (e.g., *ball, bonnet*) are more complicated than the patterns for multimorphemic words (e.g., *bubbled, running*). In polymorphemic words, consonant doublets occur at morpheme boundaries when a suffix that begins with a vowel letter (e.g. *-ed,* but not *-s*) is added and the preceding vowel is spelled with a single letter. Note that this rule relies on the graphotactic context (the pattern of letters in the words) rather than the phonological context of the word (i.e. the sounds in the words). This rule explains why ‹g› is doubled in *dogged* but not *dogs*. In monomorphemic words, on the other hand, doubling does not follow a simple rule, but seems to require the speller to have some etymological knowledge of the word (Berg, 2016). For instance, Latinate words with prefixes frequently contain consonant doublets (e.g., *collect, illegal*). Additionally, it appears that the graphemic form of the word ending may predict whether the preceding consonant is a singlet or doublet, prescinding from morphological considerations. For example, doublets occur before final /ɪk/ when it is represented as ‹ick› (e.g. *gimmick),* but not if it is spelled ‹ic› (e.g., *panic).*

However, children do not learn about both the phonological and graphotactic context when learning to spell. Elementary school teachers often encourage students to use the phonological context, or the sounds surrounding the one in question. This may explain why some adults in Treiman and Wolter's (2018) study knew about the relationship between vowel length and doubling. The "Rabbit Rule" is frequently taught to children to help them remember when to use consonant doublets. This rule is similar to, but not the same as, the doubling rules outlined by Berg (2016). The Rabbit Rule states that when a word has two syllables, a short vowel in the first

syllable, and only one consonant sound between the first and second vowels, one should double the middle consonant. The typical words used as examples for this rule are all monomorphemic, although we speculate that children are not taught about the morphological structure of words. This rule works for most two-syllable, monomorphemic English words, including *rabbit, tennis, butter, supper, banner, kitten,* and *ladder*, but fails to explain the single consonants in words such as *panic, double,* and *vapid*. Despite some children learning about the phonological context of doublets, it does not help them spell a large number of words accurately. To our knowledge, children are not taught about the relationship between the number of vowel letters and doubling the following consonant. Because even adults struggle with consonant doubling, it can be assumed that whatever explicit instruction they have received is not sufficient. Therefore, we must consider what children and adults know through experience with text. Studying how spellers make use of context, both phonological and graphotactic, may help explain how children learn the spellings of words that are not explained by the rules they learn explicitly in school.

Children's presumed lack of explicit instruction on graphotactic context of consonant doubling may reflect theories on children's spelling development, some of which have neglected the issue. Historically, theories of spelling development (e.g., Ehri, 1985; Gentry, 1982; Henderson, 1985) have argued that children learn about writing's function before its form. That is, children learn about the relationships between letters and phonemes (e.g., ‹ff› corresponds to /f/) before they learn about the relationships between letters (e.g., ‹ff› does not occur at the beginning of a word). Other models of spelling, such as Houghton and Zorzi's (2003) dual-route model, simplify the process of spelling into either spelling directly from stored orthographic representations in memory or translating phonemes to graphemes sound by sound, assigning no role for the patterns of the writing system itself. However, more recent studies have found that

even young children have some knowledge of the formal properties of writing (Cassar & Treiman, 1997; Treiman & Kessler, 2006). This calls into question past theories on spelling development. Rather than learning function prior to form, newer studies indicate that children might learn the two aspects of spelling simultaneously.

Before delving into how spellers use context specifically to spell doublets, we must consider what previous research has found regarding the use of context to spell more generally. In the past, studies focused on the role of the *rime* (i.e. vowel + coda) in using context to spell, arguing that rimes were a unique constituent of a word, or that people naturally separate words into onset + rime (Kessler & Treiman, 1997; Taraban & McClelland, 1987; Treiman, 1983; Treiman, Mullennix, Bijeljac-Babic, & Richmond-Welty, 1995; Treiman & Zukowski, 1988). In separate experiments, Treiman et al. (2002) found that in addition to using the following consonant to help spell the vowel in a monosyllabic word, adults also use the preceding consonant to decide on a vowel spelling. This indicates no special role for rimes, rather a general use of context to spell vowels. This study, however, did not differentiate between phonological and orthographic context, considering only the identity of the preceding or following phoneme where phonemes were consistently spelled the same way.

Hayes, Kessler, and Treiman (2006) investigated children's use of context both within and across rime boundaries in one-syllable words. They used two tasks, a nonword spelling to dictation task, and a forced choice task. In the spelling to dictation task, participants produced a spelling after listening to the experimenter say a nonword. This is a more difficult task than the forced choice task, in which two alternative spellings of the same nonword are presented, and children simply pick which spelling looks more like a real word, without hearing the pronunciation. The forced choice task is useful because it may show that children have learned

that some spelling patterns are illegal in their writing system. For instance, when presented with ‹saef› and ‹saeff›, choosing ‹saef› would indicate knowledge that doublets may not appear after a two-letter vowel.

To examine use of context across the onset-rime boundary, Hayes et al. (2006) looked at how the quality of the vowel in a monosyllabic word influenced the spelling of the onset. The sound /k/ is most often represented as ‹c› in English. However, /k/ is represented with ‹k› at the beginning of a word when the following vowel is a front vowel, such as /ɛ/ or /ɪ/. Hayes et al. (2006) found that as early as second grade, children used the identity of the following vowel phoneme to determine how to spell /k/ in the onset position. This indicates that children use phonological context when deciding how to spell word initial /k/. Because Hayes et al. only looked at the identity of the vowel following /k/, this aspect of the study, like Treiman et al. (2002), did not distinguish between the phonological and graphotactic influence that the vowel might have on the consonant spelling. It does, however, demonstrate that children use some type of context when making spelling decisions over the onset-rime boundary. To distinguish between phonological and graphotactic context, the researchers looked at children's use of context within the rime.

Within the rime, Hayes et al. (2006) wanted to know whether children use both the phonological and graphotactic forms of the vowel when deciding how to spell the consonant coda. They looked at when children decide to use extended spellings of consonants (e.g. ‹-ff› as opposed to unextended ‹-f›). They found that, similarly to the patterns of English orthography, children in second, fourth, and fifth grades, as well as university students used extended spellings more often following short vowels than following long vowels. This finding supports the idea that children use phonological context for coda spellings. In order to evaluate whether children

also use the graphic form of vowel spellings to decide on a coda spelling, the researchers looked post-hoc at those second-grade spellers who produced both single and multiple-letter vowel spellings for both long and short vowels. Through a simultaneous regression, the authors found that the graphotactic context, but not the phonological context, predicted extended coda spellings for this subset of second grade students. Nonetheless, only a small number of students were included in this analysis, and there was substantial variance in the graphotactic effect among the different codas. Further research with a larger number of students would help illuminate the nature of the graphotactic effect. Still, the findings from Hayes et al. (2006) indicate that as early as second grade, children use both phonological and graphotactic information when making decisions about spelling.

Now we consider previous research on the use of context specifically to decide between single and double consonants. A number of studies have examined this issue (Cassar & Treiman, 1997; Lehtonen & Bryant, 2015; Pacton, Sobaco, Fayol, & Treiman, 2013; Sobaco, Treiman, Peereman, Borchardt, & Pacton, 2015; Treiman & Wolter, 2018). Several of these studies come from non-English languages, such as French. There are three graphotactic aspects of doubling that have been studied in French, which are slightly different than the patterns in English. As in English, doubling may not occur in the word initial position, and some consonants may not double in any position. In French, doubling also may not occur following a different single consonant. For example, the nonword ‹gupprane› follows French spelling conventions whereas ‹guprrane› does not. Pacton et al. (2013) asked whether graphotactic patterns influenced how French third-grade children learned to spell. The children in this study performed two tasks, which were similar across both experiments. In the first task, children spelled nonwords after seeing the nonwords in a story. Across the two experiments, children were generally more likely

to correctly spell nonwords that did not contain a doublet (e.g. ‹mupile›) than words that did contain a doublet (e.g. ‹muppile›). However, children did not consistently remember spellings with legal doublets better than spellings with illegal doublets. When the illegal doublet was in the word initial position, children correctly spelled those words correctly more often than words with a medial doublet (e.g. ‹mmupile› and ‹muppile›). The authors suggested that children's strong memory for words with initial doublets was due to the saliency of the word initial position, and not a reflection of how children thought the words should be spelled. When the doublets were presented word medially, either illegally ‹aprrulir› or legally ‹apprulir›, children recalled the legal doublet spelling more accurately, and produced more legal transpositional errors (incorrectly doubling the first medial consonant) than illegal transpositional errors (incorrectly doubling the second medial consonant). The most common error, however, was simply omitting the medial doublet. The authors argued that their error patterns demonstrated relatively weak knowledge that doublets may not occur following a single consonant. It appeared that children may remember the presence of a word medial doublet, but not exactly which letter was doubled.

In Pacton et al. (2013)'s second task, a nonword judgment task, children decided between two spellings of a nonword, one with an illegal doublet, and one with a legal doublet, and chose which one could be a real word. The judgment task tested knowledge of the three graphotactic doubling rules in French. For all three graphotactic doubling rules, the third graders chose legal spellings more often than illegal spellings (i.e. *muppile* > *mmupile*, *apprulir* > *aprrulir*, *onnave* > *ojjave*). Given these results and the results of the nonword learning task, the authors concluded that third grade children had unequal knowledge about the three graphotactic rules. That is, the third graders seemed to have more established knowledge that some letter may never double, and that doublets may not occur word initially, but only emerging knowledge that doublets may not

appear following a single consonant. This suggests that children learn about some aspects of graphotactic patterns before others, or that some are more salient.

Following up on Pacton et al. (2013), Sobaco et al. (2015) investigated how the graphotactic legitimacy of medial consonants affects adults' memory for spellings. The authors asked French speaking adults to spell nonwords in two conditions. First, they asked participants to spell the nonwords after seeing the nonwords in a story, as in Pacton et al. The adults were more likely to correctly spell the words that followed the French orthographic convention of consonant doubling than words that did not follow the orthographic convention, demonstrating the use of orthographic knowledge in reconstructing the spellings. This did not differ by which graphotactic rule was being violated, unlike the third graders in Pacton et al. This suggests that the adults had equal knowledge about the different aspects of graphotactic context. Second, Sobaco et al. asked a different group of adults to spell the words nonwords after hearing the word. Again, the participants showed a preference for using the orthographic pattern that is conventional to French, showing that adults use orthographic knowledge when spelling. Although the research is still developing, these initial studies indicate that whereas children use graphotactic rules to different degrees in their own spellings, adults use their knowledge of graphotactic patterns consistently to spell.

Context of medial consonants has also been studied in Finnish. Lehtonen and Bryant (2005) examined children's knowledge of word medial doublets in Finnish, where the context in which consonants may double is more consistent than in English. In Finnish, consonant doublets only occur word medially, a formal rule, and function to represent a long consonant sound. Long consonants may occur word initially, but are not spelled with a double consonant when in that position. Lehtonen and Bryant found that Finnish children in their first year of schooling

(equivalent to first grade in the United States) had learned where in a word consonant doublets may occur but not the phonological function that they signaled (i.e. that they represent long consonants). That is, they demonstrated knowledge of one aspect of the graphotactic context earlier than the phonological function. This directly contradicts early theories of spelling, which predict functional knowledge to emerge before formal knowledge (e.g. Ehri, 1985; Frith, 1985). While this study is important in showing that children attain graphotactic knowledge early in spelling development, it did not address phonological context, which is important in English consonant doubling.

In English-speaking adults, Treiman and Wolter (2018) found similar results to those of Sobaco et al. (2015)'s French-speaking adults in regards to graphotactic as well as phonological context. As a reminder, consonant doublets in English occur following short vowels, but not long vowels. There are several graphotactic rules involving doublets in English, including that they may not appear word initially or following a vowel spelled with multiple letters. Treiman and Wolter had adults spell nonwords such as /zæmɪd/ to dictation. They found that adults used consonant doublets more often following short vowels than long vowels, indicating use of phonological context when spelling word medial consonants. Additionally, the adults used double consonants more often following a single letter vowel (e.g. ‹e›) than a multi-letter vowel (e.g. ‹ea›). Finally, Treiman and Wolter (2018) also found a graphotactic effect of the word ending on doubling. For example, doubling was more common before /ɪk/ when spelled as ‹ick› than ‹ic›. These findings demonstrate that adults use consonant doublets in contexts similar to what Berg (2016) described. Taken together, the findings of Sobaco et al. (2015) and Treiman and Wolter (2018) demonstrate that adults use similar doubling patterns in nonwords to the

statistical patterns they have seen in their own writing system, suggesting that experience with the writing system influences spelling.

In an influential study of children's knowledge about the context of doublets, Cassar and Treiman (1997) examined children's knowledge of the preceding phonological vowel length on doublets as well as several aspects of the graphotactic context of doublets. To assess children's knowledge of vowel length on doubling, the authors used a forced choice task with two conditions – audiovisual and visual only. In the visual only condition, children were simply shown two different spellings and asked to choose which one they preferred. The audiovisual group were also presented with two spellings, but also heard the nonword spoken. Children in sixth grade and beyond, but not third graders and below, chose the spelling containing a doublet (e.g. ‹tebbif›) more often than the spelling containing a singlet (e.g. ‹tebif› when the word was pronounced with a short first syllable vowel (e.g. /ɛ/ rather than /i/). They found, however, that much younger children had learned about some aspects of the graphotactic context of consonant doublets. They found some evidence that children as young as the first half of first grade have some knowledge about the position of consonant doublets and which letters are allowed to be doubled. In a visual-only forced choice task, children chose nonwords with word final doublets (e.g. ‹baff›) as being more wordlike than nonwords with word initial doublets (e.g. ‹bbaf›). This demonstrated that first-grade children had learned the position of where doublets are allowed. In a similar task, first-graders also demonstrated knowledge of which letters are allowed to double in English orthography, choosing words such as ‹geed› over ‹giid›. This indicates that children as young as first grade have learned not only which consonants may double but also that consonant letter doublets may not occur at the beginning of a word, despite representing the same phoneme in both positions. Cassar and Treiman provide evidence that even in the early stages of learning

to spell, children have already acquired some knowledge of the context in which consonant doublets appear, and this perhaps occurs early than children learn about phonological context. However, these were forced-choice tasks, and may not accurate reflect when children begin to use this information in their own spellings. Additionally, the authors only investigated two simple aspects of doubling's graphotactic context: the word position in which doublets may appear and which consonants may be doubled. They did not investigate whether children have learned that doublets may not appear after a vowel spelled with multiple letters, such as *double*.

Deacon et al. (2011) investigated the effect of phonology and other factors on children's word medial consonant doubling by using a real word spelling to dictation task with English speaking children in second, third, and fourth grades. In their study, third graders, but not second-graders, used doublets more often after short vowel than after long vowels, indicating use of phonological context in their own spellings. This is much earlier than Cassar and Treiman (1997) found. In a second experiment, the researchers simplified the task for use with first graders. Instead of spelling the whole word to dictation, first graders were given the spelling with a blank in the middle to fill in the word medial consonant with either a singlet or doublet (e.g. *kni__er*). First graders' doubling pattern did not differ by vowel length, indicating that they were not yet using phonological context to make decisions about doubling. Deacon et al.'s results indicate that some learning takes place between first and second grade that allows children to begin using phonological context in their own spellings. Cassar and Treiman (1997) had found that children did not lknow about phonological context until some time between third and sixth grade, somewhat later in development. Yet, because Cassar and Treiman's forced choice task is simpler than Deacon et al.'s (2011) spelling to dictation task, one might have expected an effect of phonological context to appear earlier using the simpler task. However, Deacon et al.'s use of

real words rather than nonwords might have led to better performance among younger students. Additionally, presenting two choices of spellings in Cassar and Treiman may have encouraged participants to choose doublets roughly half the time. Because these two studies find conflicting evidence, further research is necessary in order to clarify young children's knowledge of the phonological context of word medial consonant doublets.

When considering prior research on children's use of phonological and graphotactic context, it is important to consider the type of task used, language tested, and the type of stimulus. After comparing these studies, gaps in the research remain. It seems that English-speaking children have some knowledge about the graphotactic context of doublets in the medial position in the first year of schooling (Cassar & Treiman, 1997). Second grade children appear to use both phonological and graphotactic context in their spellings of extended spellings, a similar concept to consonant doubling, but this has only been tested in the word-final position of monosyllabic nonwords (Hayes et al., 2006). In two-syllable words, Deacon et al. (2011) found that third-graders, but not first- or second- graders, used the phonological length of the preceding vowel to decide whether to double in the medial position, but this is at odds with Cassar and Treiman, who found in a different type of task that this knowledge did not emerge until later, between third and sixth grade. French-speaking children appear to have stronger knowledge about some types of graphotactic knowledge (e.g., word position) than others (e.g., doubling after single consonants), and this might also be the case for English speaking children, as the doubling rules are similar.

While it appears that English speaking children may begin to use phonological context to double word medial consonants in third grade, this has not been studied in conjunction with graphotactic context in a spelling production task. Our study, therefore, will test children's use of

phonological and graphotactic context to decide between a single- and double word-medial consonant, addressing a gap in the spelling literature. Past research has been unclear about around what point in development children typically know that doublets occur only after short vowels and has not addressed whether children know that doublets do not occur after a multi-letter vowel. We use nonwords in order to ensure that the children are not drawing upon their stored orthographic forms of words. We compare children's doubling patterns to those of a group of university students who completed the same task. Because this is a difficult pattern to master, it is important to understand how children use both aspects of context together as they develop adult-like spelling abilities.

1.2 Statistical Learning

Anyone who has spent significant time with a child can tell you that children come to know more than they have been explicitly taught. Although some children may explicitly learn the Rabbit Rule, connecting phonological context to doubling, children do not explicitly learn the graphotactic context associated with doubling. For instance, it is safe to assume that the kindergartners in Cassar and Treiman (1997) had not been explicitly taught that consonant doublets do not appear at the beginning of the word, even though they seemed to know that. There are two main theories as to how children might acquire such knowledge that is not explicitly learned: rule based learning and statistical learning.

Rule-based learning is typically supported by proponents of the early theories on spelling development (those who espouse late learning of graphotactic patterns, such as Ehri, 1985, Frith, 1985, and Nunes, Bryant, & Bindman, 1997). A rule-based learning mechanism would mean that children learn about graphotactic patterns of English from a large sample of words, create a rule that works for that sample, and slowly the rule becomes abstracted over time. These rules may

also be explicitly learned, as in the Rabbit Rule taught in some schools. The rules created through this mechanism are all-or-nothing rules. A rule mechanism might be appropriate for a rule such as "Double consonants never occur at the beginning of the word," because that is always true. However, consonant doubling word medially is not all-or-nothing. Because of this, it may be more appropriate to think about how children may learn this skill through statistical learning.

The term statistical learning was coined by Saffran, Aslin, and Newport (1996) in reference to infants' use of transitional probabilities to discern word boundaries in an unbroken stream of speech. Over time, research on statistical learning has come to be domain general, meaning that statistical learning is thought to be a mechanism by which many things can be learned, including spelling. It has come to have a similar definition to implicit learning, in that statistical learning occurs when one adapts to the regularities that they experience, without explicit instruction or conscious awareness of the process (Perruchet & Pacton, 2006). Critically, these are not all-or-nothing rules, as in rule-based learning. Through statistical learning, one takes probabilities into account. In spelling, this is taken to mean that as children gain experience with written text, they learn probabilistic associations between the symbols and sounds as well as between symbols themselves, without necessarily being aware of those associations growing stronger or weaker. For instance, the association between ‹s› and ‹t› might become stronger than the association between ‹ss› and ‹t›, because ‹st› is a letter combination the child sees fairly frequently, while ‹sst› only rarely occurs in morphologically complex words such as *misstep*. When children start spelling words, then, they will use the sequence ‹st› far more often than ‹sst› for the phoneme sequence /st/, showing an adaptation to the regularities they see in written text. When considering the role of statistical learning on children's consonant doubling, it is likely

that graphotactic context is learned through statistical learning, as graphotactic rules are not learned explicitly. Phonological context, on the other hand, is often taught in schools, so there may be more than one learning mechanism at play.

This study assesses both types of context through a statistical learning framework, and is the first study done in English to distinguish the influence of each type of context on children's consonant doubling. To gather behavioral data, we ask elementary school children and university students to spell nonwords which have been designed to vary systematically in the quality of the preceding (i.e. first-syllable) vowel and the phonological form of the word ending. Including a wide range of ages allows us to measure spelling patterns at different points in development. We also included a standardized spelling test to measure the general spelling ability of our sample. If doubling is learned through statistical learning, we would expect adult, and potentially school-age, spellers' behavioral data to mirror that of the written corpus. Therefore, we also included data from a corpus of child-directed written English (Zeno, Ivens, Millard, & Duvvuri, 1995) that includes the frequency of written vocabulary broken down by grade level. Analyses of graphotactic regularities have been done independently of spelling research, as in Kessler and Treiman (2001), and also within studies of children's and adult's graphotactic knowledge (e.g. Hayes et al., 2006; Juul, 2005; Treiman & Kessler, 2006; Treiman & Wolter, 2018). Between the two data types, behavioral and corpus data, we compare the frequency of doublets overall as well as within specific phonological and graphotactic contexts, such as following short vowels or following one-letter vowels. Taken together, the behavioral and corpus data will provide evidence for what type of contextual information (i.e. phonological or graphotactic) children and adults use when making decisions about spelling and how that compares to the printed words to which they have been exposed through text.

Chapter 2: Method

2.1 Participants

Table 1 provides information about the participants at each grade level. Child participants were recruited and tested at their elementary schools (99 children) or at the St. Louis Science Center (7 children). The elementary schools where we collected data were private, religious schools. Adult participants were undergraduate students at Washington University in St. Louis. Six additional children were excluded from data analysis because their parents reported that they had a speech, language, or hearing disorder, and three additional children were excluded from data analysis due to speaking a language other than English natively. All of the adult participants spoke English as their only native language and reported no speech, language, or hearing disorders. Table 1 also includes the mean standardized score for each grade level on the WRAT spelling subtest. These scores are higher than the test norms, likely due to the type of schools and university at which data were collected.

Table 1

Participant Characteristics

Grade	Number	Number Female	Mean Age (years; months)	Mean Standardized score on spelling subtest of WRAT	Mean Grade Equivalency Score
2	32	17	8;0	112	3.8
4	33	15	10;0	111	6.6
6	32	17	11;10	111	8.9
University	32	25	20;2	123	12.9

2.2 Stimuli

2.2.1 Nonword Spelling Task

We used 160 nonwords from Treiman and Wolter (2018) and five filler words. Nonwords were disyllabic with stress on the first syllable. Filler words were monosyllabic words that young

children were likely to know how to spell (e.g. *cat*). The filler words served to ensure that children were paying attention and to prevent children from becoming discouraged. There were 80 pairs of nonwords such that in each pair, the nonwords were identical except for the first syllable vowel length. Forty words contained short vowels /æ/, /ɛ/, /ɪ/, /a/ or /ə/ in the first syllable, and their pairs had corresponding long vowels /e/, /i/, /aɪ/, /o/ or /u/. Medial consonants included English phonemes that could be spelled with a single or double consonant (/b/, /f/, /g/, /l/, /n/, /m/, /p/, and [ɾ]). The nonwords ended with one of /i/, /o/, /ɚ/, /ɪd/, /ɪk/, /ɪs/, /ɪn/, or /ɪl/. The experimental words are listed in the Appendix.

We made four lists of 40 nonwords each from the 160 nonwords. Each list contained five nonwords with each ending and 20 with each vowel type. Each participant was presented with one of the four lists, with the nonwords in a randomized order for each participant and five filler words in fixed points throughout the list. Participants were randomly assigned to one of the four lists of 40 nonwords. Approximately one quarter of the participants in each grade was tested using each list.

2.2.2 Corpus Analysis

From Zeno et al. (1995)'s *Word Frequency Guide,* we chose words that had similar properties to our nonwords in the behavioral task, and for which phonological features and lexical stress were available in the Unisyn Lexicon (The Centre for Speech Technology Research). We chose the Zeno et al. (1995) corpus because it provides a list of words that children are exposed to through texts, as well as the frequency with which those words appear at each grade level. Grade levels included first through twelfth grade, which encompasses American elementary, middle, and high school years. Additionally, Zeno et al. includes what is called a post high school group. This presumably includes texts one would find at the university

level, and we refer to it as such. Thus, we could measure whether consonant doubling in this disyllabic context fluctuates across grades, and whether children's doubling in the behavioral data would reflect that.

Words were included in our corpus if they contained, in the following order: (1) any number of consonant letter (or none), (2) one or more vowel letters that creates any legal vowel spelling as described in Cummings (1985), a comprehensive work detailing American English sound-spelling correspondences (3) any one of the letters ‹c, b, d, f, g, k, l, m, n, p, s, t, v, z›, optionally doubled, (4) one or more vowel letters, according to Cummings (1985), and (5) zero or more consonant letters. Words had to be disyllabic with first-syllable stress, and have no ambiguous stress (i.e. could be stressed on either syllables) or homographs (i.e. words spelled identically, but pronounced differently). We did not specify the number of morphemes.

For each word that fit our criteria, we extracted from Zeno et al. (1995) the grade-level frequencies by both types, the total number of occurrences of each word, and tokens, the number of unique words. We found a total of 1,917 words that fit our criteria. The final list of words included each word's orthography, UNILEX pronunciation, and number of tokens in each grade level's material, according to Zeno et al. (1995). By using this list, we could calculate the regularity and frequency with which doublets appear word medially in two-syllable words.

2.3 Procedure

A phonetically trained experimenter tested each participant individually in a quiet area. The procedure was identical for children and adults, except that children were given a pencil, bookmark, or eraser after participating. The experimenter first administered the nonword spelling task and then the spelling subtest of the Wide Range Achievement Test (WRAT, Wilkinson & Robertson, 2006, green form).

For the nonword spelling task, the experimenter instructed the participant to listen to a list of words, repeat the word, and then write the word how he or she thought the word should be spelled. The participants were told that most of the words would be "made-up" words, but that occasionally there would be a real word. After the participant repeated the nonword or filler real word, the experimenter corrected any mistakes before the participant spelled it. Participants wrote one word on each page of a blank booklet using a pen or pencil. The spelling subtest of the WRAT was administered according to test instructions. The experimenter said the target word aloud, read a sentence with the word in it, and then said the word again. Testing was discontinued after the participant spelled all 42 words, or spelled 10 consecutive words incorrectly.

Chapter 3: Results

3.1 Phonological Context

We included spellings in the analysis of the behavioral data if they: (1) began with any consonant letter (all stimuli began with consonant phonemes), (2) included a letter or letter sequence in the first syllable that was a possible spelling of a vowel according to Cummings (1985), (3) used the intended medial consonant letter in the medial position (e.g. spellings such as ‹smephin› for /smefin/ were excluded because participant used ‹ph› rather than ‹f›), (4) included any orthographic representation for the word ending. These inclusion criteria were set to ensure that the word was heard correctly and that our statistical analyses were interpretable. Based on these inclusion criteria, our analyses included 4,928 nonword spellings. Of the data from second, fourth, sixth grade, and university students, the proportions of spellings that were excluded were 0.24, 0.19, 0.24, and 0.13, respectively.

Table 2 shows mean proportion of doubling in the nonwords and corpus data as a function of vowel length. In both the corpus and behavioral data, doubling was more frequent after short vowels than after long vowels, where it was extremely rare. The behavioral data suggest that doubling increases with grade after short vowels, but not after long vowels. The standard deviations around the mean proportions of doubling are generally large in comparison to the means, which may indicate the presence of individual differences in doubling behavior.

Table 2

Mean Proportion of Consonant Doubling (and Standard Deviation for Behavioral Data) after Long and Short Vowels by Grade

Grade Level	Short Vowel			Long Vowel		
	Behavioral Data	Corpus Types	Corpus Tokens	Behavioral Data	Corpus Types	Corpus Tokens
Grade 2	0.05 (0.10)	0.68	0.53	0.02 (0.04)	0.01	0.00
Grade 4	0.20 (0.16)	0.66	0.45	0.02 (0.04)	0.01	0.00
Grade 6	0.27 (0.17)	0.66	0.40	0.04 (0.06)	0.01	0.00
University	0.48 (0.22)	0.57	0.34	0.02 (0.04)	0.01	0.00

Data were analyzed using logistic mixed effects modeling in order to illustrate the influence of phonological knowledge on consonant doubling. Analyses were conducted in R version 3.5.2 (R Core Team, 2018) using the lme4 package (Bates, Mächler, Bolker, & Walker, 2015). Because the dependent variable of grade could arguably be considered either a continuous or categorical variable, we created two models, each identical except for how grade was treated. Both models included the dependent variable of consonant doubling, a binary variable, fixed effects for vowel length (i.e. long versus short vowel) and grade, the interaction of vowel length and grade, and random effects of participant and word pair.

Table 3

Fixed Effects Table for Model 1 (Grade as continuous)

	Estimate	Standard Error	*p-value*
Intercept	-4.400	0.316	< 0.001
Vowel Length (0 = short, 1 = long)	-0.722	0.152	< 0.001
Grade (2, 4, 6, University)	0.153	0.035	< 0.001
Vowel Length × Grade	-0.136	0.021	< 0.001

Table 3 contains the results of the first model, in which grade is treated as continuous. The results of the model indicate significant main effects of phonological vowel length and grade. Doubling becomes generally more frequent as grade increases, and is more frequent after short vowels than after long vowels. For every one-year increase in grade, doubling increases by 0.153 logits (or a probability of 0.54). The model also indicates a significant interaction of vowel length and grade, such that the effect of vowel length becomes stronger as grade increases. The strength of using grade as a continuous variable is that we can see the general progression of doubling across grades. However, this model does not show at which grades there is a significant effect of vowel length.

For the second model, we applied backward difference coding to grade, now a categorical variable. Using this coding scheme, the fixed effects indicate the difference between the mean of one level of the variable and the mean of the previous variable. In other words, the fixed effects represent the difference in doubling between each grade level in the sample. Thus, for grade, it produces three fixed effects: the difference in doubling from second grade to fourth grade, fourth to sixth grade, and sixth grade to university. Table 4 shows the results of this model.

Table 4

Fixed Effects Table for Model 2 (Grade as categorical)

	Estimate	Standard Error	*p-value*
Intercept	-3.46	0.21	< 0.001
Vowel Length (0 = short, 1 = long)	-1.53	0.09	< 0.001
Grade 2 vs. Grade 4	1.27	0.41	0.002
Grade 4 vs. Grade 6	0.56	0.37	0.123
Grade 6 vs. University	0.34	0.36	0.354
Vowel Length × 2 vs. 4	-0.76	0.25	0.002
Vowel Length × 4 vs. 6	-0.03	0.21	0.86
Vowel Length × 6 vs. University	-0.96	0.21	< 0.000

Treating grade as a categorical variable presents a somewhat different interpretation of children's doubling across grades. In this model, vowel length is again a significant predictor of doubling. Grade however, is not significant at every level. Only the difference between second and fourth grade is significant. This indicates that between second and fourth grade, children begin doubling substantially more often. The interaction of vowel length with grade is significant at two levels: second versus fourth grade, and sixth grade versus university. This indicates that some learning occurred between second and fourth grade about doubling following short versus long vowels. Again, between sixth grade and university, this pattern became more prominent. This model gives us a more specific breakdown than the first model of how doubling behavior differs between the four grade levels tested. Overall, frequency of doubling increases with grade, and it appears that children begin to use phonological context sometime between second and fourth grade, and then strengthen that pattern between sixth grade and university. This model indicates that between sixth grade and university, students are still learning about doubling, showing that the process of learning to use doublets in the correct contexts develops over an extended period of time.

In order to discern at which grades vowel length is a significant predictor of doubling, we created one model for each grade, with word pair and participant as random effects and only vowel length as a fixed effect. Vowel length was significant at each grade level: second grade (β = -0.69, *SE* = 0.198, *p* = < 0.001), fourth grade (β = -1.49, *SE* = 0.169, *p* = < 0.001), sixth grade (β = -1.60, *SE* = 0.156, *p* = < 0.001), and university (β = -2.41, *SE* = 0.184, *p* = < 0.001). It is important to note that, although vowel length reached significance at second grade, the difference between doubling after short versus long vowels is small. In fact, most second graders did not use consonant doublets after either long or short vowels. Overall, the analyses indicate that in second grade, there is some evidence of doubling more often after short than long vowels, and this effect strengthens as grade increases.

3.2 Graphotactic Context

Next, we looked at the proportion of doubling following single versus multi-letter vowels in the behavioral and corpus data, as shown in Table 5. Participants in every grade tested rarely, if ever, used doublets following multi-letter vowels, which is a pattern reflected in the corpus data as well. Interestingly, university students' doubling behavior after single versus multi-letter vowels mirrors that of the corpus almost exactly. As we noted in regards to doubling after long and short vowels, doubling in the corpus generally decreases across grade after single letter vowels, while doubling after single letter vowels in the behavioral data steadily increases with grade.

Table 5

Mean Proportion of Consonant Doubling (and Standard Deviation for Behavioral Data) after Single and Multi-Letter Vowel Spellings by Grade

Grade	Single Letter Vowels			Multi-Letter Vowels		
	Behavioral Data	Corpus Types	Corpus Tokens	Behavioral Data	Corpus Types	Corpus Tokens
2	0.04 (0.07)	0.47	0.36	0.01 (0.04)	0.01	0.04
4	0.12 (0.10)	0.45	0.32	0.00 (0.00)	0.01	0.01
6	0.17 (0.11)	0.44	0.28	0.01 (0.06)	0.01	0.01
University	0.31 (0.16)	0.34	0.23	0.01 (0.02)	< 0.01	0.00

We decided not to use mixed effects models to test the effect of number of vowel letters on doubling because of concerns about multicollinearity. According to a Chi square test on a contingency table with the variables vowel length and number of letters, the two variables are moderately related ($\chi^2 = 478.6$, $\phi = 0.31$, $p < 0.0001$). Additionally, we did not control for the number of vowel letters and decided it would be inappropriate to include an uncontrolled variable as a predictor. Instead of mixed effects modeling, then, we coded the combinations of vowels and consonants without reference to phonology and used Fisher's exact tests for each grade.

In this section, V refers to any vowel letter, and C refers to any consonant letter. VV refers to a sequence of any two vowel letters, and CC refers to a sequence of two identical consonant letters. With this, there are four possible first syllable vowel (V) and medial consonant (C) spelling combinations possible in each nonword: VC, VCC, VVC, and VVCC. If the number

of vowel letters did not matter, we would expect the number of VVCC spellings to reflect how often VV and CC occur in any context. This is not how it is in written English, however. VVCC virtually never occurs. In our subset of Zeno et al. (1995), VVCC occurs in only two words: *Johnny* and *Johnnie*, proper names. We hypothesize that if participants have learned that the VVCC pattern is virtually never used in English, they would use VVCC less often than we might expect, given the overall frequencies of VV and CC.

Looking at the raw data, the pattern VVCC was used in only six trials out of 4928. Two of these six trials were the same participant. Numerically, it appears as if participants have picked up on that VVCC is not a graphotactic pattern found in English. We did one-tailed Fisher's exact tests on the combined data and on the data for each grade to test whether VVCC was a rare form. Table 6 shows the results of these tests. Across grades, we found that VVCC occurred less often than expected by chance (Odds Ratio = 0.05, $p = < 0.001$), meaning that participants actively avoided using the VVCC pattern. Because we can assume this is not something participants have been explicitly taught in school, we can infer that this is due to a lack of VVCC spellings in the corpus. According to individual tests for each grade, this effect is found in every grade tested, indicating that as early as second grade, spellers have learned not to use consonant doublets following a vowel spelled with more than one letter regardless of the phonological vowel length.

Table 6

Graphotactic patterns used by grade

Grade	**Graphotactic Pattern**					
	VC	VCC	VVC	VVCC	Odds Ratio	*p*-value
Combined Grades	3580	678	664	6	0.05	<0.0001
2	1030	43	125	1	0.19	0.04
4	987	138	141	0	0	<0.0001
6	888	187	148	2	0.06	<0.0001
University	675	310	250	3	0.03	<0.0001

Chapter 4: Discussion

We sought to investigate how children use phonological and graphotactic knowledge to decide between single and double consonants word medially. We found that second grade, fourth grade, sixth grade, and university students use both types of contexts when deciding between a single and double word medial consonant letter. Across grade, the proportion of doubling after both short vowels and vowels spelled with one letter increases steadily. Despite steady increases, only university students' doubling patterns looked similar to that of the corpus, which tells us that although statistical learning may be a mechanism through which children learn to spell, it takes place over an exceptionally long time.

This study does support not older theories of spelling development (e.g. Ehri, 1985; Gentry, 1982; Henderson, 1985). These theories are vague in describing when children begin using graphotactic and phonological context in their own spellings, but they generally assume that this does not occur until late in the spelling acquisition process, after children have reached the "correct stage" of spelling, which means they have mastered the spellings of a certain number of words (Gentry, 1982). Although the effect was small, children in our study began using graphotactic context as early as second grade, which is still fairly early in the learning process. The effect of graphotactic context became stronger between second and fourth grade, but then held a similar effect size into university. Additionally, our data suggest that children's use of phonological context becomes stronger and more accurate over a number of years. This is in contrast to the early theories, which suggest that learning occurs quickly and in stages, rather than gradually, as our data suggest.

More recent research has suggested that children learn about phonological and graphotactic context through statistical learning (e.g. Hayes et al., 2006, Juul, 2005). Through

this learning mechanism, children (and adults) learn phonological and graphotactic context through repeated exposure to the writing system. We found a small, but significant, effect of phonological context on doubling in second-grade children, which is younger than Deacon et al. (2011) or Cassar and Treiman (2011) found. This may be due to features of our sample or our design. Deacon et al. found a phonological context effect in third graders for production of real words, whereas we used nonwords. When spelling nonwords, the participant must generate a never before seen spelling using sound to spelling correspondences, but spelling real words may involve other cognitive processes, such as attempting retrieval of orthographic form from memory. It is unclear how spelling real words would be more difficult than spelling nonwords, leading to the later onset of phonological context effects, but the difference in spelling strategies may play a role. Additionally, our sample of elementary school students were particularly good spellers. It is possible that the second graders we tested are more similar to average third graders, as in Deacon et al.'s sample, rather than average second graders.

Cassar and Treiman (1997) did not find an effect of phonological context on doubling until sixth grade through a forced choice task where participants were presented with two spellings of a nonword. We speculate this might be due to the task itself or the characteristics of the stimuli. Because both singlet and doublet options (*tebbif* and *tebif*) were presented simultaneously to the participants, the children younger than sixth grade might be showing an overall preference for single consonants, when that option is presented visually, a preference that Cassar and Treiman argue young children hold. Having both options presented in their entirety as the participant hears the word may prompt a different response than generating a nonword spelling, in which the participant sees the word form incrementally. Additionally, the nonword stimuli from Cassar and Treiman (1997) might not be as word-like as our stimuli. For instance, ‹-

if› is a rare word ending, whereas the word endings in our stimuli were common (see Appendix). The similarity of the nonword stimuli to real words may impact how children choose to spell them, or to what degree they expect real word spelling patterns to apply.

Our results are also similar to Hayes et al. (2006), who found evidence for English-speaking second graders using phonological and graphotactic context for double consonants at the end of monosyllabic nonwords, and that for a small subset of second graders, only graphotactic context predicted doubling. In their study, they examined the same aspects of phonological and graphotactic knowledge as our study, but in a different word position. The similarity of the results might indicate that children learn about doublets word medially and word finally simultaneously, or that doubling in one position is not favored over the other. The similarity of our findings indicates that in second grade, the process of learning to use phonological context for doubling is similar whether the doublet is word medial in a disyllabic word, or word final in a monosyllabic word. Our results differ in whether or not second graders are using phonological context in addition to graphotactic context. While in Hayes et al.'s study, the second graders used graphotactic context alone to decide whether to extend coda spellings of monosyllabic words, the second graders in our study used both phonological and graphotactic context to decide whether to double word medially.

We tested one aspect of graphotactic context in English—the pattern that word medially, consonant doublets may not follow a vowel spelled with more than one letter. This pattern is, to our knowledge, unique to English. French, however, has a similar pattern, wherein medial doublets may not follow a consonant letter. Where there is a consonant cluster in the middle of a word, the first consonant phoneme, but not the second, may be a doublet. In both English and French, the surrounding letters determine whether the medial consonant may legally be doubled.

Pacton et al. (2013) found that French third graders were knowledgeable about the French graphotactic pattern. Although Pacton et al. did not test any other grade level, it is interesting that children of a similar age to the second graders in our study have learned a similar graphotactic pattern in French. This is converging evidence that cross-linguistically, early elementary school children are beginning to use the surrounding letters to make decisions about consonant doubling. Additionally, Hayes et al. (2006) produced a similar result, finding that English speaking second graders used the number of vowel letters to decide whether to extend the final consonant of a monosyllabic word. This provides evidence that around second grade, children are using the surrounding letters to make decisions about doubling in a range of word types and positions.

We did not examine children's knowledge of whether doublets may occur word initially or word finally, like other studies. Knowledge of where in the word doublets may occur is another aspect of graphotactic doubling context that is presumably simpler to learn than knowledge of the relationship between number of vowel letters and number of consonant letters. Cassar and Treiman (1997) found that as early as the second half of kindergarten, English-speaking children have learned that doublets may not occur word initially. Cross-linguistically, Lehtonen and Bryant (2005) found that Finnish-speaking children learned the legal position of doublets around first grade, close to Cassar and Treiman's (1997) findings in English. Our data show that by second grade, students have learned another aspect of doubling's graphotactic context – that doublets may not follow two consecutive vowel letters. Because second graders were the youngest students we tested, we cannot say that younger children also would not show an effect of number of vowel letter. We speculate, however, that children in younger grades would not show an effect of number of vowel letters on doubling, given the small effect found

for second graders. It seems likely, then, that children learn where in the word consonants may double before they learn other aspects of graphotactic context, such the influence of number of vowel letters on doubling.

In order to examine what role statistical learning may play in children's knowledge of phonological and graphotactic doubling context, we compared the behavioral data we collected to the patterns of doubling in a grade-leveled corpus of English vocabulary, Zeno et al. (1995). If children are learning context through statistical learning, we would expect to see children's overall doubling frequency and doubling within appropriate contexts increase until it approximates that of the written English corpus. This is what we see in our data. In the elementary school data that we gathered, doubling generally increased with grade, but did not occur nearly as often as it did in the corpus data. The university students' data, however, looked remarkably similar to the corpus data by types. The patterns of doubling in our university students' data was close to those found in a community sample by Treiman and Wolter (2018). Their mean age of their sample (52 years old) was considerably older than ours, suggesting that doubling patterns are stable throughout adulthood.

By adulthood, doubling patterns are similar to that of the English vocabulary when counted by types, but not tokens. In general, the proportion of doubling by tokens was less than that of types, meaning that two-syllable words with a short vowel followed by a single consonant occurred more frequently than two-syllable words with a short vowel followed by a doublet, even though there were more short vowel with doublet words than short vowel with singlet words. We speculate this is due to the frequency of words such as *any* and *many,* which are among the most frequent two-syllable words in the corpus. That university student's data approximates the frequency of doubling in the corpus by types might indicate how orthographic

forms are stored in memory. Individual's knowledge of phonological context appears to be influenced by the number of individual lexical items with that pattern, rather than the overall frequency of the pattern.

While doubling frequency increases with grade in our behavioral data, doubling in two-syllable words generally decreases with grade level in the corpus, particularly by tokens. We hypothesize that this is due to the introduction of subject specific words in older grades, many of which are of Latin or Greek origin. We did a post-hoc follow up on our corpus data with each word categorized as Latin or Greek or not. Of the 1,917 words in our two-syllable word corpus, 387 had Latin or Greek origin, and 1,530 did not. Of the Latin and Greek words, 12.9% contained medial doublets, as opposed to 41.3% of the non-Latin or Greek words. Moreover, the frequency of Latin and Greek words increased with grade. In the first grade data, 12.9% of words were from Latin or Greek, but in the post high school data, 25% of words were from Latin or Greek. This cursory analysis of the vocabulary suggests that the changing vocabulary throughout the school years may influence the frequency of doubling in the text to which the different grades are exposed. It is interesting to note that doubling in the behavioral data and doubling in the corpus data move in opposite directions. As grade increases, children double more often, but are exposed to less doubling.

While our data overall look like we might expect if doubling was a pattern learned through statistical learning, it appears as though this process takes place over roughly a decade, from second grade to university. This may be a reflection of the quality of orthographic representations one has stored in their mental lexicon. Experienced, automatic decoders have precise orthographic representations stored in their lexicon for vast number of words they encounter. Younger spellers must spend more effort decoding words because they do not

automatically see a spelling, match it to a stored orthographic form, and retrieve the word. If the orthographic forms, or spellings, are not stored precisely in memory, the brain is unable to compute statistical patterns in the writing system. As children get older, the number and quality of orthographic representations improve, making statistical computations of the writing system more accurate. This does not, however, explain why phonological context effects grow stronger across grade, but graphotactic context effects remain constant after about fourth grade. Maybe the connection between orthography and phonology in the lexicon strengthens over time, but ability to glean statistical regularities purely from orthography levels off at some point. Further research could investigate whether knowledge of other graphotactic patterns follows a similar pattern. The difference in trajectory of effect sizes between graphotactic and phonological context may be due to how each is learned. Statistical learning might not be the only mechanism through which some aspects of doubling are learned. At least some students are taught about the phonological context of doublets, but to our knowledge, no children are taught about the relationship between consonant doublets and the preceding number of vowel letters. To our knowledge, this is not included in any instructional materials used in classrooms or in any information directed towards teachers.

That university students as a group use doublets after a short vowel in only 48% of opportunities is intriguing. If students were using the Rabbit Rule that they learned in elementary school, we would expect this number to be much higher, as it is essentially taught as an all or nothing rule. This tells us that statistical learning might play some effect in learning the phonological context of doublets, even though students have been taught an explicit rule, although they may or may not remember it explicitly. Of note, the frequency of doubling had a wide range among participants. Several university students appeared to follow the Rabbit Rule,

doubling the medial consonant after a short vowel in 90% or more of opportunities, and doubling after long vowels in less than 1% of opportunities. Because there was such a wide range in doubling behavior, it is impossible to say whether the group similarity to the corpus is due to statistical learning, or the presence of large individual differences in doubling behavior.

Further research may illuminate how these findings can be applied to spelling and reading pedagogy. Our results may be evaluated in multiple ways. One might read our results and be impressed that children learn doubling context through experience with text, and interpret this as indicating no need for explicit instruction. On the other hand, one might see our results and be astonished that it takes over a decade to develop adult-like doubling patterns, and argue that explicit instruction is necessary in order to accelerate this learning. Although we know some teachers present the Rabbit Rule in classrooms, many do not. Spelling and reading curricula vary widely across states, districts, and individual teachers. What is clear, however, is learning to spell is important, if only because it can have a positive impact on reading ability. When one has a clear, strong orthographic form stored in memory, that form can be easily accessed when coming across it in print. Although some research considers spelling ability analogous to phonological awareness and letter knowledge (Mann, 1993; McBride-Chang, & Ho, 2005), other studies have found that good spellers are more efficient readers (Ouellette, Martin-Chang, & Rossi, 2017), and that spelling ability at the end of kindergarten predicts reading scores as far out as ninth grade (Treiman et al., 2019). In fact, spelling ability accounts for some of the unique variance seen in reading ability throughout elementary school. Further research may help us better understand where explicit instruction is necessary, in addition to text experience.

There are several limitations to our study that warrant further consideration and research. First, our spellers were generally good at spelling, scoring well above the average speller. This is

likely due to the nature of the schools we were able to collect data from. Therefore, our results might not generalize to poorer spellers. Additionally, we do not know if children are interpreting the nonwords as single morphemes or multiple morphemes, for which the rules are different. Finally, the corpus from which we gathered vocabulary data from is now more than two decades old, and may not contain a representative sample of text to which children are typically exposed. Finally, it is unclear in this corpus what genre of text each word typically appears in, making it difficult to know what type of text is most influential on children's spelling. Finally, we do not have data on precisely how elementary school teachers teach spelling across the United States, just our intuitions based on conversations with educators and familiarity with curricula. Despite these limitations, this study extends the scientific literature regarding children's spelling.

Overall, our study found evidence that children second grade and older use phonological and graphotactic context to decide whether to spell a word medial consonant with a single or double letter, although the effect of phonological context is minute in the second grade sample. Children in fourth grade and above used doublets more often after short vowels than after long vowels, a phonological context effect, and children in second grade and above use doublets more often after single letter vowels than after multi-letter vowels. This strength of the phonological effect increased with each grade. The strength of the graphotactic effect increased between grades two and four, but then remained steady. Given the similarity of university students' doubling patterns to that of the Zeno et al. (1995) corpus, it is likely that children learn doubling through statistical learning, but that it takes a long time for them to approximate patterns that they see in written text. Further research should explore whether explicit instruction on the graphotactic and phonological regularities of consonant doubling can accelerate the process of learning to spell, and how that may affect children's overall literacy abilities.

References

Baayen, H., Piepenbrock, R., & Gulikers, L. (1995). The CELEX lexical database (release 2). Philadelphia: Linguistic Data Consortium.

Barry, C., & Seymour, P.H.K. (1988). Lexical priming and sound-to-spelling contingency effects in nonword spelling. *The Quarterly Journal of Experimental Psychology A: Human Experimental Psychology, 40,* 5 – 40. https://doi.org/10.1080/14640748808402280.

Berg, K. (2016). Double consonants in English: graphemic, morphological, prosodic and etymological determinants. *Reading & Writing: An Interdisciplinary Journal, 29,* 453 – 474. https://doi.org/10.1007/s11145-015-9610-z.

Cassar, M., & Treiman, R. (1997). The beginnings of orthographic knowledge: Children's knowledge of double letters in words. *Journal of Educational Psychology, 89,* 631–644. https://doi.org/10.1037//0022-0663.89.4.63

Deacon, S. H., Leblanc, D., & Sabourin, C. (2011). When cues collide: Children's sensitivity to letter- and meaning-patterns in spelling words in English. *Journal of Child Language, 38,* 809 – 827. https://doi.org/10.1017/S0305000910000322

Ehri, L. (1985). Effects of printed language acquisition on speech. In D. Olson, N. Torrence, & A. Hildyard (Eds.), *Literacy, language, and learning: The nature and consequences of reading and writing* (pp. 333–367). New York: Cambridge.

Ferreiro, E., & Teberosky, A. (1982). *Literacy before schooling.* Portsmouth, NH: Heinemann Educational Books Inc.

Frith, U. (1985). Beneath the surface of developmental dyslexia. In K. Patterson, M. Coltheart, & J. Marshall (Eds.) *Surface dyslexia* (pp. 301–329). Hillsdale, NJ: Lawrence Erlbaum.

Gentry, J.R. (1982). An analysis of developmental spelling in "GNYS AT WRK." *The Reading*

Teacher, 36, 192 – 200.

Hayes, H., Treiman, R., & Kessler, B. (2005). Children use vowels to help them spell consonants. *Journal of Experimental Child Psychology, 94,* 27 – 42.

Henderson, E. (1985). *Teaching Spelling*. Boston, MA: Houghton Mifflin.

Houghton, G., & Zorzi, M. (2003). Normal and impaired spelling in a connectionist dual-route architecture. *Cognitive Neuropsychology, 20,* 115 – 162. https://doi.org/10.1080/02643290242000871

Juul, H. (2005). Knowledge of context sensitive spellings as a component of spelling competence: Evidence from Danish. *Applied Psycholinguistics, 26,* 249 – 265.

Kessler, B. & Treiman, R. (1997). Syllable structure and the distribution of phonemes in English syllables. *Journal of Memory and Language, 37,* 295–311. http://dx.doi.org/10.1006/jmla.1997.2522

Kessler, B., & Treiman, R. (2001). Relationships between sounds and letters in English monosyllables. *Journal of Memory and Language, 44,* 592 – 617.

Lehtonen, A., & Bryant, P. (2005). Doublet challenge: Form comes before function in children's understanding of their orthography. *Developmental Science, 3,* 211 – 217. https://doi.org/10.1111/j. 1467-7687.2005.00409.x

Martin, D.H., & Barry, C. (2012). Writing nonsense: The interaction between lexical and sublexical knowledge in the priming of nonword spelling. *Psychonomic Bulletin & Review, 19,* 691 – 698.

Nunes, T., Bryant, P., & Bindman, M. (1997). Morphological spelling strategies: Developmental stages and processes. *Developmental Psychology, 33,* 637 – 649. http://dx.doi.org/10.1037/0012-1649.33.4.637

Mann, V.A. (1993). Phoneme awareness and future reading ability. *Journal of Learning Disabilities, 26,* 259 – 269. https://doi.org/10.1177/002221949302600406

McBride-Chang, C. & Ho, C. (2005). Predictors of Beginning Reading in Chinese and English: A 2 Year Longitudinal Study of Chinese Kindergartners, *Scientific Studies of Reading, 9,* 117 – 144.

Ouellette, G., Martin-Chang, S., & Rossi, M. (2017). Learning from our mistakes: Improvements in spelling lead to gains in reading speed. *Scientific Studies of Reading, 21,* 350 – 357. https://doi.org/10.1080/10888438.2017.1306064

Pacton, S., Sobaco, A., Fayol, M., & Treiman, R. (2013). How does graphotactic knowledge influence children's learning of new spellings? *Frontiers in Psychology, 4,* 701.

Perruchet, P. & Pacton, S. (2006). Implicit learning and statistical learning: one phenomenon, two approaches. *Trends in Cognitive Sciences, 10*, 233 – 238. https://doi.org/10.1016/j.tics.2006.03.006

R Core Team (2018). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Saffran, J. R., Aslin, R. N., & Newport, E. L. (1996). Statistical learning by eight-month-old infants. *Science, 274,* 1926 – 1928. https://doi. org/10.1126/science.274.5294.1926

Sobaco, A., Treiman, R., Peereman, R., Borchardt, G., & Pacton, S. (2015). The influence of graphotactic knowledge on adults' learning of spelling. *Memory & Cognition, 43,* 593 – 604.

Taraban, R., & McClelland, J. L. (1987). Conspiracy effects in word pronunciation. *Journal of Memory and Language, 26,* 608 – 631. https://doi: .org/10.1016/0749-596x(87)90105-7

The Centre for Speech Technology Research. *Unisyn Lexicon Release.* Retrieved from

http://www.cstr.ed.ac.uk/projects/unisyn/

Treiman, R. (1983). Phonemic analysis training helps children benefit from spelling-sound rules. *Memory & Cognition, 11*, 382 – 389.

Treiman, R., Hulslander, J., Olson, R.K., Willcutt, E.G., Byrne, B., & Kessler, B. (2019). The unique role of early spelling in the prediction of later literacy performance. *Scientific Studies of Reading, 23,* 437 – 444.

Treiman, R. & Kessler, B. (2006). Spelling as statistical learning: Using consonantal context to spell vowels. *Journal of Educational Psychology, 98*, 642 – 652. https://doi.org/0.1037/0022-0663.98.3.642

Treiman, R., Mullennix, J., Bijeljac-Babic, R., Richmond-Welty, E.D. (1995). The special role of rimes in the description, use, and acquisition of English orthography. *Journal of Experimental Psychology: General, 124,* 107 – 136. https://doi.org/10.1037//0096-3445.124.2.107

Treiman, R. & Wolter, S. (2018). Phonological and graphotactic influences on spellers' decisions about consonant doubling. *Memory & Cognition, 46,* 614 – 624.

Treiman, R., & Zukowski, A. (1988). Units in reading and spelling. *Journal of Memory and Language, 27*, 466 – 477. https://doi.org/10.1016/0749-596X(88)90068-X

Treiman, R., Kessler, B., & Bick, S. (2002). Context sensitivity in the spelling of English vowels. *Journal of Memory and Language, 47*, 448 – 468.

Zeno, S. M., Ivens, S. H., Millard, R. T., & Duvvuri, R. (1995). The educator's word frequency guide. Brewster, NY: Touchstone Applied Science Associates.

Appendix

Nonword List 1

bruli, glæfi, praɪpi, vobi, smǝmi, brɛpo, graɪɾo, rɑno, stogo, zɛɾo, gɑpɚ, tɛbɚ, θægɚ, vunɚ, pefɚ, hulɪd, bɪfɪd, tʃɛlɪd, skunɪd, zæmɪd, blɛnɪk, drobɪk, pɪfɪk, sprubɪk, zɪgɪk, brimɪl, lubɪl, gɪpɪl, præmɪl, stomɪl, bripɪn, fɑɾɪn, træbɪn, skunɪn, zaɪgɪn, brupɪs, pluɾɪs, fɛpɪs, sprɪbɪs, tʃenɪs

Nonword List 2

brəli, glefi, prɪpi, vɑbi, smumi, bripo, grɪɾo, rono, stɑgo, ziɾo, gopɚ, tibɚ, θegɚ, vənɚ, pæfɚ, həlɪd, baɪfɪd, tʃilɪd, skənɪd, zemɪd, blinɪk, drɑbɪk, paɪfɪk, sprəbɪk, zaɪgɪk, brɛmɪl, ləbɪl, gaɪpɪl, premɪl, stɑmɪl, brɛpɪn, foɾɪn, trebɪn, skənɪn, zɪgɪn, brəpɪs, pləɾɪs, fipɪs, spraɪbɪs, tʃænɪs

Nonword List 3

klɛɾi, θrɪgi, slæni, gomi, sprifi, pɪfo, smuno, væmo, θebo, flumo, klegɚ, prɛbɚ, zɑmɚ, vefɚ, t͡ʃaɪbɚ, θopɪd, pɪfɪd, gribɪd, smegɪd, vɑnɪd, sulɪk, vɑɾɪk, gɛɾɪk, depɪk, t͡ʃemɪk, flɑmɪl, krifɪl, strifɪl, plɪpɪl, smɪnɪl, ˈt͡ʃælɪn, ˈdrəɾɪn, ˈglaɪgɪn, smɛfɪn, vonɪn, teɾɪs, vɑlɪs, smɪfɪs, lomɪs, dɛgɪs

Nonword List 4

kliɾi, θraɪgi, sleni, gɑmi, sprɛfi, paɪfo, smǝno, vemo, θæbo, fləmo, klægɚ, pribɚ, zomɚ, væfɚ, t͡ʃɪbɚ, θɑpɪd, digɪs, grɛbɪd, smægɪd, vonɪd, sǝlɪk, voɾɪk, giɾɪk, dæpɪk, t͡ʃæmɪk, flomɪl, krɛfɪl, strɛfɪl, plaɪpɪl, smaɪnɪl, t͡ʃelɪn, druɾɪn, glɪgɪn, smifɪn, vɑnɪn, tæɾɪs, volɪs, smaɪfɪs, lɑmɪs, digɪs

Filler Words

bug, cat, dog, car, day