Phonological and graphotactic influences on spellers' decisions about consonant doubling

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Abstract

Even adults sometimes have difficulty choosing between single- and double-letter spellings, as in *spinnet* versus *spinnnet*. The present study examined the phonological and graphotactic factors that influence adults' use of single versus double medial consonants in the spelling of nonwords. We tested 111 adults from a community sample who varied widely in spelling ability. Better spellers were more affected than less good spellers by phonological context in that they were more likely to double consonants after short vowels and less likely to double consonants after long vowels. Although descriptions of the English writing system focus on the role of phonology in determining use of single versus double consonants, participants were also influenced by graphotactic context. There was an effect of preceding graphotactic context, such that spellers were less likely to use a double consonant when they spelled the preceding vowel with more than one letter than when they spelled it with one letter. There was also an effect of following graphotactic context, such that doubling rate varied with the letters that the participant used at the end of the nonword. These graphotactic influences did not differ significantly in strength across the range of spelling ability in our study. Discussion focuses on the role of statistical learning in the learning of spelling patterns, especially those patterns that are not explicitly taught.

Keywords Spelling · Double letters · Graphotactics · Phonology · Spelling models · Statistical learning

Introduction

Learning to spell is an important task, but it can be difficult when a sound is spelled differently in different words. In English, for example, /n/ is spelled ⟨n⟩ in *panic* and *puny*, ⟨nn⟩ in *inn* and *penny*, ⟨pn⟩ in *pneumonia*, and ⟨kn⟩ in *knob*. (We use slash marks around phonemes, angled brackets to indicate letters or letter sequences, and italics to identify a word or introduce terms.) How do people select a spelling in such cases? In the present study, we examined one choice that can cause difficulty even for adults: whether to spell a medial consonant with a single letter such as ⟨n⟩ or with two identical letter such as ⟨nn⟩. We asked adults to spell novel items and examined the factors that influence their use of single versus double consonants, whether these influences vary as a

function of spelling ability, and the degree to which spellers are consciously aware of the factors that affect their behavior. Such a study can contribute to the development of theoretical models of the spelling process and can provide clues about why some people are better spellers than others. It may also have implications for the teaching of spelling.

According to one theory of the spelling process, as discussed by Barry and Seymour (1988), spellers possess a set of rules that link each phoneme to its most common representation. For example, one rule links /n/ to ⟨n⟩. People use these rules to construct spellings when they employ the *non-lexical route*. This route is involved in producing the spellings of novel items, the task used in the present study. Spellings of known words that deviate from the rules, such as ⟨inn⟩ and ⟨knob⟩, are stored in memory as exceptions and produced using a *lexical route*. Another idea within this *dual-route* framework is that a rule can link a phoneme with several spelling options, each with an associated probability. Options that occur frequently in a language, such as ⟨n⟩ for /n/, are more highly weighted than options that occur less often, such as ⟨nn⟩, and recent use of an option may also increase its weight (Folk & Rapp, 2004). When spellers employ the nonlexical route, they use the options for a phoneme

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in line with their weights. Barry and Seymour favored this probabilistic version of dual-route theory based on data from a spelling production task involving nonwords with vowel phonemes that have more than one possible spelling.

According to the theories described so far, translation between phonemes and letters does not consider a phoneme's position in a word or syllable or the neighboring phonemes. Other views suggest that a phoneme may be mapped to one spelling in some phonological environments but a different spelling in others. That is, *phonological context* may influence the choice among spelling alternatives. Supporting this idea, studies using spelling production tasks have documented cases in which adults' spellings of phonemes are affected by the identity of preceding or following phonemes (Dich, 2010; Perry & Ziegler, 2004; Treiman, Kessler, & Bick, 2002). The results of Cassar and Treiman (1997) suggest that people use phonological context when deciding between single-letter and double-letter spellings of medial consonants, the case of interest here. Data came from a forced-choice task in which participants were shown two nonwords on each trial and were asked to pick the one that corresponded to a spoken nonword. University students preferred single to double consonants after vowels such as /e/, which are often called long vowels, and double consonant after vowels such as /æ/, which are often called short vowels. For example, participants tended to pick <janim> over <jannim> as a spelling of /'dʒenim/ but <jannim> as a spelling of /'dʒænim/. (We follow Flemming and Johnson, 2007, in transcribing the reduced values in the final syllables of such items as /i/). People's behavior reflects a pattern in the English spelling system. Specifically, in morphologically simple two-syllable words with first-syllable stress and a single medial consonant phoneme that corresponds to a consonant that may double in spelling (e.g., not /ʃ/, because <sh> cannot double), a double medial consonant occurs in 69% of words with a short first-syllable vowel but in less than 1% of words with a long first-syllable vowel (Berg, 2016). Discussions of the English spelling system that are oriented toward teachers cover this pattern (Carreker, 2005; Templeton & Morris, 1999), and it is sometimes explicitly taught in elementary schools.

Although most studies of context effects in spelling have focused on phonological context, several recent findings point to a role for *graphotactic context*. That is, people's choice of spellings for a sound may depend on the letters that they use to spell the preceding or following elements. One such case involves /f/, /l/, /k/, and /tʃ/ at the ends of monosyllables. Using a spelling production task, Treiman and Kessler (2016) found that adults were more likely to spell these phonemes with <ff>, <ll>, <ck>, and <tch> when they spelled the preceding vowel with one letter than when they spelled it with more than one letter. This behavior reflects the rarity of sequences such as <aick> and <eell> in English, something that is not explicitly taught in any spelling program that we know of. The best-developed computational model of the spelling process to

date, the dual-route connectionist model of Houghton and Zorzi (2003), does not include a mechanism by which a speller's choice of letters for one phoneme can influence the choice for another and thus cannot account for the experimental findings.

Graphotactic context also appears to play a role in the use of single versus double consonants in the middles of disyllabic items. Treiman and Boland (2017) found evidence for this in a spelling production task involving nonwords such as /'fæpik/ with a short stressed vowel in the first syllable. Given the phonological context—the short vowel before the critical consonant—we would expect spellers to double the consonant letter. However, the adult participants in this study tended not to use a double letter if they spelled the first vowel with more than one letter. Doubling rates were also associated with the letters that followed the consonant, with participants tending to avoid double consonant letters before certain final spelling sequences, including <ic> and <it>. These behaviors reflect patterns in the English vocabulary. Medial consonant doubling occurs only about 1% of the time when the preceding vowel is spelled with more than one letter, and it also varies as a function of the letters that follow the consonant (Berg, 2016; Treiman & Boland, 2017). For example, consonant doubling is less common in words with final /ik/ when this sequence is written as <ic> (e.g., *panic*, *magic*) than when it is written as <ick> or <ock> (*gimmick*, *haddock*). To our knowledge, these patterns are not explicitly taught in schools.

So far, information about adults' use of phonological and graphotactic context in the spelling of medial consonants has come from different experiments using different tasks: a forced-choice task in the case of phonological context (Cassar & Treiman, 1997) and a spelling production task in the case of graphotactic context (Treiman & Boland, 2017). In the present study, we examined the effects of phonological and graphotactic context within a single experiment and a single task. We chose a spelling production task rather than a forced-choice task because it is more representative of what people normally do when they write.

Rather than limiting the study to young adults who were university students, we tested adults of different ages and backgrounds from a community sample. Our participants varied widely in their performance on a standardized test in which they spelled words to dictation, allowing us to ask whether influences of phonological and graphotactic context on consonant doubling differ as a function of spelling ability. One of the experiments reported by Treiman and Boland (2017) used a community sample similar to that of the present study, finding more doubling of medial consonants in better spellers than in less good spellers. Because all of the experimental items in that study had short vowels in the first syllable, however, this result has several possible interpretations. One possibility, as suggested by the findings of Barry and Seymour (1988) and Deacon, Leblanc, and Sabourin (2011),

is that people prefer to use the most common spelling of a phoneme: a single consonant letter in these cases. The weight on the dominant spelling may be higher in less good spellers than in better spellers. Another possibility, which is consistent with Cassar and Treiman's (1997) finding that phonological context has a larger influence on the choice between single- and double-letter spellings of medial consonants in older children and adults than in younger children, is that more skilled adult spellers are more influenced by phonological context than are less skilled adult spellers. If so, better spellers should use more double consonants than poorer spellers after short vowels but fewer double consonants than poorer spellers after long vowels. The present study included items with both long and short vowels in the first syllable, allowing us to test these ideas.

Although phonological context may have more influence on highly skilled adult spellers than on less skilled spellers, some data suggest that spelling ability has little influence on adults' use of graphotactic context. Treiman and Boland (2017) found no differences as a function of spelling ability among adults from a community sample in the tendency to avoid double consonants after vowel spellings of more than one letter. There were at most small differences as a function of spelling ability in the influence of the spelling of the ending. Other studies suggest that adults in basic education classes who read and spell at the level of elementary school children show fairly good knowledge of graphotactic patterns, generally avoiding spellings such as <naamed> and <dilloar> in production tasks and judging them unacceptable in choice tasks (Thompkins & Binder, 2003; Worthy & Viise, 1996).

A final issue that we investigated in our study was the degree to which adults could report on the factors that are associated with medial consonant doubling. Some of the patterns that we examined, as mentioned earlier, are not explicitly taught in schools. To the extent that people follow them, this may reflect *statistical learning*, an important process in language and other domains (e.g., Conway, Bauernschmidt, Huang, & Pisoni, 2010; Saffran, Aslin, & Newport, 1996). Statistical learning occurs when people pick up the patterns in materials to which they are exposed without explicit instruction or feedback, and information learned in this manner is typically not accessible to conscious awareness (Turk-Browne, Jungé, & Scholl, 2005). We addressed the issue of awareness by asking participants, after they had completed the spelling production task, to describe any factors that influenced their use of double consonants and any rules they may have learned about this matter. We expected that some participants would be aware of the phonological pattern, which is sometimes taught in schools, but that few would be able to describe the graphotactic patterns. Because the ability to describe a pattern is important for teaching it, findings on this matter have implications for teachers' knowledge about spelling and their ability to teach it.

To summarize, our study examined how graphotactic and phonological context influence adult spellers' use of single versus double medial consonants, whether these influences vary as a function of spelling ability, and whether people are conscious of the patterns that affect their spelling. We addressed these issues by asking participants to spell nonwords that contained a medial consonant after a short or a long vowel and by later asking them to describe the influences on their use of single- versus double-letter spellings.

Method

Participants

The participants were 111 residents of the St. Louis area (84 female) who belonged to a registry of community members who had expressed interest in participating in paid research studies at Washington University. The participants' mean age was 52 years (range 20–86), and they reported having completed a mean of 16 years of education (range 9–20). All were native speakers of English.

Stimuli

We constructed 240 experimental nonwords that had an initial consonant or cluster followed by a stressed vowel. The medial consonant was /b/, /f/, /g/, /l/, /m/, /n/, /p/, or /r/, which may realize either /d/ or /t/ in American English. All of these consonant phonemes correspond to letters that may double in English. Half of the nonwords ended with unstressed /id/, /ik/, /is/, /it/, /idʒ/, or /o/, and the other half ended with /il/, /in/, /int/, /ist/, /ə/, or /i/. Of the 20 nonwords with each ending, 10 had a short vowel in the first syllable (/æ/, /ɛ/, /ɪ/, /ɑ/, or /ə/). For each short vowel item, there was an item with a long vowel in the first syllable (/e/, /i/, /a/, /o/, or /u/) that was otherwise identical. For example, /vanid/ was a short vowel item and /vonid/ was the corresponding long vowel item. The 120 experimental nonwords with each set of endings were divided into two lists of 60 such that a short vowel item and the corresponding long vowel item were on different lists. Each list had 10 items with each ending, half with short vowels and half with long vowels. To increase the variety among the items in the spelling tasks, we constructed 30 monosyllabic filler nonwords. The experimental and filler nonwords are shown in the [Appendix](#).

Each participant spelled the items from one list of experimental nonwords together with the fillers. For each list, four different orders were prepared for purposes of presentation. In each order, the experimental and filler items were randomly intermixed. Approximately equal numbers of participants were assigned to each set of endings and, within a set, to each list and each order.

Procedure

Participants were tested individually or, in a few cases, in small groups. They were told that they would be asked to spell a series of “made-up words.” They were asked to spell each item the way they thought it would be spelled in English if it were a real word. The experimenter, a speaker of General American English, pronounced each item and the participant repeated it. The experimenter then pronounced the item again and asked the participant to write it by hand on a prepared answer sheet. The use of live rather than audiotaped presentation allowed participants to use visual as well as auditory cues to interpret the nonwords. After completing the nonword spelling test, participants were given the spelling subtest of the Wide Range Achievement Test (WRAT, Wilkinson & Robertson, 2006, blue form). The 42 words on this test, which are presented in sentences, range from easy ones such as *on* to difficult ones such as *pusillanimous*. Finally, participants completed a written questionnaire on consonant doubling. The introduction to the questionnaire stated that double medial consonants appear in some words, such as *rabbit*, and that single medial consonants appear in other words, such as *habit*. Participants were then asked two questions: (1) whether they had any particular reasons for using single medial consonants for some made-up words and double consonants for others, if they had varied their choices across items, and (2) whether they remembered having been taught any rules about when to double consonants and, if so, to describe the rules.

Results

We scored participants’ spellings of experimental items for whether they contained a single consonant letter or two adjacent identical consonant letters after the spelling of the first vowel. Responses that did not fall into either of these categories, including those with two non-identical medial consonants, no medial consonants, or no vowel letter in the first syllable, were excluded from further analyses. Such responses constituted 4% of the total. The participants varied widely in spelling ability, with standardized WRAT scores ranging from 61 to 145 ($M = 107$, $SD = 14$). We included WRAT score in our statistical analyses, treating it as a continuous variable.¹

In the sections that follow, we examine participants’ use of single versus double consonants as a function of the number of letters they used to spell the preceding vowel, whether the preceding vowel was phonologically long or short, and the

letters they used to spell the ending. The final section reports on participants’ responses to the questionnaire.

Association between vowel spelling and consonant doubling

Table 1 shows the proportion of spellings with double medial consonants as a function of the number of letters that the participant used to spell the vowel of the first syllable. The results indicate that consonant doubling was more common when participants used one letter to spell the preceding vowel than when they used more than one letter.

To determine whether the difference in consonant doubling as a function of vowel spelling was statistically significant and whether the results varied as a function of spelling ability, we conducted mixed-model analyses using data at the trial level. The dependent variable was whether the consonant was double (coded as 1) or single (coded as 0), and there were random intercepts for participants and items. Data from 6361 trials were included. This and other mixed-model analyses were conducted in R version 3.2.2 (R Core Team, 2015) using the package lme4 (Bates, Mächler, Bolker, & Walker, 2015). We used a logit link function in this and the following analyses because the dependent variables were binary, and we centered continuous variables when interactions were included. We first built a model that included as fixed factors the main effects of interest: number of letters in the spelling of the first vowel (coded as 1 for more than one letter and 0 for one letter) and spelling ability (standardized WRAT score). There was a significant effect of number of letters in the vowel spelling ($\beta = -2.61$, $SE = 0.21$, $p < .001$), such that participants were less likely to double the medial consonant if they spelled the preceding vowel with more than one letter than if they spelled it with one letter. The effect of spelling ability was also significant ($\beta = 0.02$, $SE = 0.01$, $p = .05$), such that consonant doubling was more common among better spellers than among less good spellers. In a second model, we included the interaction between number of letters in the vowel spelling and spelling ability. The more complex model did not account for significantly more variance than the model that did not include the interaction ($p = .69$ by a likelihood ratio test), suggesting that the association between number of letters in the spelling of the preceding vowel and double consonant use held across the range of spelling ability examined here.

Association between vowel quality and consonant doubling

Table 2 provides information about participants’ rate of consonant doubling after phonologically long and short

¹ The WRAT includes eight words with double consonants, raising a potential concern about circularity in defining spelling ability in part based on ability to spell double consonants in words and then examining performance on double consonants in nonwords. However, the proportion of correct spellings on the WRAT when words with double consonants were excluded correlated nearly perfectly (.99) with the proportion of correct spellings including all words.

Table 1 Proportion of spellings with double medial consonants (and numbers on which proportions are based) as a function of number of letters in participant's spelling of first syllable vowel

Number of letters in spelling of vowel	Mean across participants	Standard deviation across participants
One	.29 (1529/5192)	.16
More than one	.03 (35/1169)	.07

vowels. Because participants rarely doubled the medial consonant if they spelled the preceding vowel with more than one letter, the table shows the results for cases in which a single letter was used. The data indicate that participants were more likely to double medial consonants after short vowels than after long vowels. We calculated a difference score for each participant: the proportion of double-consonant spellings after short vowels minus the proportion of double-consonant spellings after long vowels. Figure 1 depicts the difference scores as a function of the standardized WRAT score of the participants. As the figure shows, better spellers tended to have larger difference scores than less good spellers. That is, use of single versus double consonants seemed to be more influenced by phonological context in better spellers than in less good spellers.

To confirm these impressions, we conducted mixed-model analysis using random intercepts for participants and items and the fixed factors vowel quality (1 = short, 0 = long) and spelling ability (standardized WRAT score). Data from 5,192 trials were included. A model that included the interaction between vowel length and spelling ability was a better fit than a model that did not include the interaction ($p < .001$ by a likelihood ratio test), so we interpret the results of the model that included the interaction. There was a main effect of vowel quality ($\beta = 3.16$, $SE = 0.20$, $p < .001$), such that doubling was more common after short vowels than after long vowels. The main effect of spelling ability was also significant ($\beta = -.03$, $SE = .01$, $p = .01$). These main effects were qualified by a significant interaction ($\beta = 0.05$, $SE = 0.01$, $p < .001$). Follow-up analyses showed a statistically reliable effect of spelling ability for items with short vowels in the first syllable, such that more skilled spellers used significantly more double consonants than less skilled spellers for these items ($\beta = 0.03$, $SE = 0.01$, $p = .003$). There was a significant effect in the opposite direction for long vowel items, such that more skilled spellers

used fewer double consonants than less skilled spellers for these items ($\beta = -0.03$, $SE = 0.01$, $p = .02$).

Association between spelling of final sequence and consonant doubling

To determine whether the rate of consonant doubling varied with the spelling of the ending, we took a closer look at cases in which the first vowel was phonologically short and was spelled with a single letter. We asked whether participants were more likely to double the consonant in such cases if they used a final letter sequence that is associated with a higher doubling rate in English (e.g., <ick>) than if they used a final letter sequence that is associated with a lower doubling rate (e.g., <ic>). That is, even when the phonological form of the ending was the same, was there an association between the manner in which it was spelled and the probability of doubling the preceding consonant? We estimated the degree to which a spelling sequence promoted doubling of the preceding consonant in the words of English based on a corpus of disyllabic English words that were similar to the short-vowel words in the experiment. This corpus included the 2,887 disyllabic words from Unisyn lexicon (Fitt, 2008) that had one of the same short stressed vowels in the first syllable and one of the same single medial consonant phonemes that appeared in the experimental items and an unstressed vowel in the second syllable, optionally followed by one or more consonants. We excluded fused words such as <gonna>, compound words, foreign words, archaic words, words that can only be proper nouns, and words and spellings that were specific to British or Australian English. Words in which the first vowel was spelled with more than one letter were also excluded because of the rarity of medial consonant doubling in such cases. For each final spelling sequence, we calculated the proportion of words in the corpus with medial consonant doubling. These proportions were calculated in two ways: by weighting each

Table 2 Proportion of spellings with double medial consonants (and numbers on which proportions are based) as a function of phonological quality of first-syllable vowel when vowel was spelled with single letter

Phonological quality of vowel	Mean across participants	Standard deviation across participants
Short	.47 (1371/2935)	.23
Long	.07 (158/2257)	.10

Fig. 1 Proportion of spellings with consonant doubling after short vowels minus proportion of spellings with consonant doubling after long vowels (i.e., difference score) as a function of the standardized Wide Range Achievement Test (WRAT) score of the participant

word equally and by weighting each word by the natural logarithm of 2 plus the frequency of the word given in Brysbaert and New (2009).²

We conducted mixed-model analyses of consonant doubling using random intercepts for participants, phonological ending sequences, and items nested within ending sequences. The fixed factors were the standardized spelling score of the participant and the doubling proportion of the ending spelling. The analyses included data from the 2,620 trials on short-vowel items in which the participant used one letter to spell the first vowel and in which the participant used a final spelling sequence that occurred in the corpus. As expected from the results presented above for short vowel items, the rate of medial consonant doubling varied with spelling ability ($\beta = 0.02$, $SE = 0.01$, $p = .004$, in analysis using doubling proportions that weighted each word equally and analysis using frequency-weighted doubling proportions). A new result is that participants' tendency to use double consonants was associated with the doubling proportion of the ending ($\beta = 1.29$, $SE = 0.25$, $p < .001$, in analysis using doubling proportions that weighted each word equally; $\beta = 1.23$, $SE = 0.24$, $p < .001$, in analysis using frequency-weighted doubling proportions). For example, participants were more likely to double the medial consonant before <et> than before <it>, both of which typically spell the same phonological sequence in General American English. Adding the interaction between spelling ability and the doubling proportion of the ending did not significantly

improve the models' fit ($p = .14$ and $p = .18$, for analysis using doubling proportions that weighted each word equally and analysis that weighted words by frequency, respectively).

Figure 2 shows the proportion of double consonants used by participants for short vowel items with single-letter spellings of the vowel as a function of the doubling proportion of the ending, calculated by weighting each word equally. The figure shows data for endings that participants used five or more times, and each point is labeled by the ending that it represents. The darkness of a point is scaled by the log of the number of words in the corpus with the ending, such that points are darker for endings that appear in more words than for endings that appear in fewer words. In line with the results just presented, endings with higher doubling proportions in the corpus tended to elicit more doubling by participants. However, the doubling proportions for participants were generally lower than the doubling proportions in the corpus ($p < .001$ by a two-tailed t test across the 37 endings according to analyses using both methods of calculating doubling proportions). Inspection of Fig. 2 suggests that some of the endings that showed the largest deviations from the corpus statistics occurred infrequently in the corpus. To test this impression, we conducted linear regression analyses at the level of endings to predict the absolute value of the difference score between the doubling proportion of the participants and the doubling proportion in the corpus. The predictors were the doubling proportion of the ending in the corpus and the ending's log-transformed frequency in the corpus. Endings with higher doubling proportions in the corpus showed larger difference scores ($\beta = 0.48$, $SE = 0.09$, $p < .001$, in both analysis using doubling proportions that weighted each word equally and

² We added 2 rather than 1 to the frequency of the word as listed by Brysbaert and New (2009) because some words in the Unisyn corpus were not in Brysbaert and New and adding 1 would drop them entirely from the computations.

Fig. 2 Proportion of spellings with consonant doubling as a function of doubling proportion of ending in corpus, calculated by weighting each word equally, for endings that participants used five or more times. Darkness of each point is scaled by log of number of words in corpus with the ending

analysis using frequency-weighted doubling proportions), reflecting the underestimation by participants that was mentioned earlier. A new finding is that endings that occurred more frequently in the corpus showed smaller difference scores than endings that occurred less frequently ($\beta = -0.14$, $SE = 0.04$, $p = .003$, when doubling proportions were calculated by weighting each word equally; $\beta = -0.13$, $SE = 0.04$, $p = .002$, when frequency-weighted doubling proportions were used). Other things being equal, this result shows, participants' doubling values more closely mirrored the corpus doubling values for more common endings than for less common endings.

Questionnaire

Participants were considered to show explicit knowledge about the association between consonant doubling and the phonological form of the preceding vowel if they mentioned using or having been taught such a pattern. We similarly coded for knowledge of the relation between consonant doubling and the number of letters in the preceding vowel and knowledge of the relation between consonant doubling and ending letters. To be coded as reflecting explicit knowledge about a pattern, a response had to describe a specific pattern. Vague answers such as “some of the words sounded like they should have double letters in them” or “I went with what looked right” did not qualify. Coding was carried out by two individuals who agreed 99% of the time; the few disagreements were resolved by discussion. Of the 111 participants, 26 showed some explicit knowledge that the phonological form of the preceding vowel is associated with consonant doubling. Such responses were more likely to occur among participants with higher scores on the standardized spelling test than among those with lower scores ($r = .31$, $p = .001$, two tailed).

No participant said that the number of letters in the spelling of the preceding vowel was influential, and only one mentioned that the ending can play a role. When we repeated the analyses examining rate of consonant doubling after long and short vowels for participants who did not show awareness of the phonological pattern, we found very similar results to those reported earlier, including a significant interaction between spelling ability and vowel quality.

Discussion

Discussions of English spelling that are oriented toward teachers portray the use of single- versus double-letter spellings of medial consonants as governed by phonology. Single consonants should be used after long vowels and double consonants should be used after short vowels, and spellings that do not fit this pattern must be individually memorized as exceptions (Carreker, 2005; Templeton & Morris, 1999). Most researchers have implicitly accepted these ideas, considering spellings such as <dagit> for the nonword /'dægɪt/ or <palor> for the word *pallor* to show a lack of knowledge about the regularities of English (e.g., Cassar & Treiman, 1997; Deacon et al., 2011). However, quantitative studies of the English vocabulary demonstrate that phonological context is not the only influence on consonant doubling (Berg, 2016; Treiman & Boland, 2017). That is, the lack of medial consonant doubling in words like *valor* and *panic* is not a surprise given the ending sequences, and these spellings do not necessarily have to be memorized as exceptions. Our study examined the influence of phonological and nonphonological context on adults' consonant doubling.

We found that phonological context influences adults' use of single versus double consonants, extending the results of

Cassar and Treiman (1997) with a forced-choice task to a spelling production task. The phonological influence, our results show, is stronger in better spellers than in less good spellers. The better spellers in our study used significantly more double consonants after short vowels than the less good spellers, in line with a previous report (Treiman & Boland, 2017). A new finding was that better spellers used significantly fewer double consonants after long vowels than poorer spellers. These results are consistent with the widespread view that phonology is an important aspect of spelling and one that is deficient in poor spellers (e.g., Dietrich & Brady, 2001; Moll et al., 2014).

Phonological context was not the only systematic contextual influence on adults' use of single versus double medial consonants, however. Graphotactic context was also important. One graphotactic influence was a tendency not to double consonants after spelling a vowel with more than one letter. This influence was found across the range of spelling ability investigated here, in line with the results of Treiman and Boland (2017). Adults' use of single versus double medial consonants also varied with the spelling sequence that they used at the end of the nonword. Specifically, people were more likely to use double consonants before ending sequences that are usually associated with doubling in English, such as <le> and <en>, than before ending sequences that are less often associated with doubling. The magnitude of this effect, like the magnitude of the effect of preceding graphotactic context, did not differ significantly as a function of spelling ability. Thus, the different results for more skilled and less skilled spellers in the case of phonological context do not reflect a lesser sensitivity to all types of context in the less skilled spellers or a lesser sensitivity to preceding context. Within the range of spelling ability examined here, the less good spellers seemed to be as sensitive to context as the good spellers for context that can be described in terms of letters.

Statistical learning plays an important role in a number of domains (e.g., Conway et al., 2010; Saffran et al., 1996; Turk-Browne et al., 2005), and it is likely to be involved in the learning of the spelling patterns studied here. Statistical learning may be especially important for the graphotactic patterns, for no instructional program that we know of explicitly teaches these patterns. Our participants must have used their visual statistical learning skills to learn that English words are more likely to include certain kinds of letter sequences than others. When spelling nonwords, they tried to produce spellings that followed the learned graphotactic patterns and that represented the phonemes that they heard. Implicit statistical learning may also be involved in learning about the link between short vowels and consonant doubling, especially for people who are not explicitly taught about this link. Although statistical learning contributes to the learning of both graphotactic and phonological patterns, learning of the two types of patterns seems to differ in some ways. Statistical

learning of graphotactic patterns requires exposure to printed words, as when reading, but it could occur whether or not readers generate the words' pronunciations and whether or not the pronunciations are correct. Statistical learning about the links between phonological forms and spellings requires people to consider both a word's spelling and its phonological form and to link elements of the two representations.

Several aspects of our findings shed light on how statistical learning plays out in spelling. Consider the finding that participants' rate of consonant doubling before an ending showed more agreement with the language statistics when the ending was more common in English than when it was less common. This result points to the importance of frequency of exposure in statistical learning. Because the patterns for different endings are to some extent idiosyncratic, people need to have experience with words with a particular ending to learn how often consonants double before it. They have more experience with endings such as <le>, which occur in many English words, than with endings such as <ick>, which occur less often. Another finding was that, although people showed more agreement with the language statistics for some endings than for others, they tended to use fewer medial double consonants than would be expected given the frequency of such doublets in English. The most likely explanation for this finding is that, pooled across contexts, double consonants are less common than singletons. People learn about context-conditioned spelling patterns to the point that, in some contexts, they prefer a spelling that is less common in the language as a whole to one that is more common. However, context-conditioned patterns are more difficult to learn than simpler ones, in spelling as in other domains (Warker & Dell, 2006). The consequence, for spelling, is that people tend to be drawn to the most common spelling of a phoneme (Barry & Seymour, 1988; Deacon et al., 2011).

We did not find significant differences as a function of spelling ability in adherence to the graphotactic patterns studied here, and Treiman and Boland (2017) likewise found few differences. Null results must be interpreted with caution, and we must keep in mind that the less skilled spellers in the present study and that of Treiman and Boland were mostly in the average range. Still, the paucity of differences as a function of spelling ability for the graphotactic patterns coupled with the significant difference as a function of spelling ability for the phonological pattern invites explanation. The differences between the two types of patterns, if replicable, might reflect different time courses of learning. Learning about the links between phonological units and spellings typically begins when children enter school and begin formal literacy instruction. Children begin to learn about some of the graphotactic patterns of their written language before this point (Lehtonen & Bryant, 2005; Pollo, Kessler, & Treiman, 2009). Adults who have not progressed beyond the elementary-school level in reading and spelling show fairly

good knowledge of common graphotactic patterns (Thompkins & Binder, 2003; Worthy & Viise, 1996), as do some adults who have developed serious spelling problems as a result of brain damage (Fischer-Baum, McCloskey, Mathis, & Wilson, 2011). Graphotactic influences may have reached an asymptote for the less skilled spellers in our adult population, with no further increase for the better spellers. Another potential explanation for the different results for graphotactic and phonological patterns stems from the idea that implicit statistical learning plays a larger role in the learning of the graphotactic patterns than in the learning of the phonological patterns and that people vary less in their implicit learning skills than in their explicit learning skills (Reber, Walkenfeld, & Hernstadt, 1991).

Information acquired through statistical learning is often not very accessible to conscious awareness. That was the case for the patterns investigated here. About a quarter of our participants described how the phonological form of a preceding vowel influences whether the following consonant is spelled with a single or a double consonant, and less than 1% described any graphotactic influence. Although we might have found somewhat different figures if we had probed for explicit knowledge in a different manner, the results suggest that participants were less aware of the graphotactic patterns than of the phonological one. This difference may reflect the fact that statistical learning plays a larger role in the learning of the former patterns than in the learning of the latter.

Lack of conscious awareness about the factors that influence consonant doubling is not a problem for most people. However, it is a potential problem for teachers because awareness of patterns in the spelling system and ability to describe them can help teachers develop instructional materials, draw learners' attention to patterns, and correct learners' misspellings. Our results support the idea that teacher training should include systematic instruction about the spelling system (Moats, 2014), and they suggest that such instruction should go beyond the phonological patterns that are covered in currently available materials.

Our results speak against dual-route models of the spelling process in which the nonlexical route operates at the level of single phonemes and does not take context into account (e.g., Barry & Seymour, 1988). The results also speak against models that allow a role for phonological context but not graphotactic context (Houghton & Zorzi, 2003). The development of spelling models has lagged behind the development of reading models, and further work will be required to develop models that can account for effects of various types of context on human spelling performance and for how context effects develop. A successful model, it appears, will need to incorporate statistical learning principles (Mano, 2016; Treiman & Kessler, 2014).

The present study examined one case in English in which spellers must choose among alternative spellings of a phoneme. English has many other such cases, as do other

languages (e.g., Sobaco, Treiman, Peereman, Borchardt, & Pacton, 2015, for French). Further research will be needed to determine whether the conclusions drawn here—that people use graphotactic as well as phonological context to decide among spelling options and that the former is in some ways easier than the latter—hold true more broadly. Studies that include participants with an even wider range of spelling ability and that characterize their skills not just in spelling but also in other areas are another direction for future research, and the results of such studies may help us to understand how and why people differ.

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Appendix

Experimental items

Final /id/: 'bɪfɪd, 'bɑfɪd, 'grɛbɪd, 'grɪbɪd, 'həlɪd, 'hulɪd, 'pɪfɪd, 'pɑfɪd, 'skənɪd, 'skunɪd, 'smægɪd, 'smegɪd, 'vənɪd, 'vonɪd, 'zæmɪd, 'zemɪd, 'θəpɪd, 'θopɪd, 'tʃɛlɪd, 'tʃɪlɪd.

Final /ik/: 'blɛnɪk, 'blɪnɪk, 'dæpɪk, 'depɪk, 'drabɪk, 'drobɪk, 'gɛrɪk, 'gɪrɪk, 'pɪfɪk, 'pɑfɪk, 'səlɪk, 'sulɪk, 'sprəbɪk, 'sprubɪk, 'vərɪk, 'vorɪk, 'zɪgɪk, 'zægɪk, 'tʃæmɪk, 'tʃɛmɪk.

Final /is/: 'brəpɪs, 'brupɪs, 'degɪs, 'dɪgɪs, 'fɛpɪs, 'fɪpɪs, 'lɑmɪs, 'lɒmɪs, 'pləɪs, 'plurɪs, 'smɪfɪs, 'smɑfɪs, 'sprɪbɪs, 'sprɑbɪs, 'tæɪs, 'tɛɪs, 'vəlɪs, 'volɪs, 'tʃɛnɪs, 'tʃɛnɪs.

Final /ɪdʒ/: 'drəbɪdʒ, 'drobɪdʒ, 'fæpɪdʒ, 'fɛpɪdʒ, 'hərɪdʒ, 'hurɪdʒ, 'lɛbɪdʒ, 'libɪdʒ, 'nəfɪdʒ, 'nufɪdʒ, 'prɪmɪdʒ, 'pramɪdʒ, 'slɛmɪdʒ, 'slɪmɪdʒ, 'snɪmɪdʒ, 'snamɪdʒ, 'swagɪdʒ, 'swogɪdʒ, 'zælɪdʒ, 'zelɪdʒ.

Final /o/: 'brɛpɒ, 'brɪpɒ, 'fləmo, 'flumo, 'grɪro, 'grairo, 'pɪfo, 'pɑfo, 'rɑno, 'rono, 'sməno, 'smuno, 'stago, 'stogo, 'vəmo, 'vemo, 'zɛro, 'zɪro, 'θæbo, 'θɛbo.

Final /ɪl/: 'brɛmɪl, 'brɪmɪl, 'flɑmɪl, 'flɒmɪl, 'gɪpɪl, 'gɑpɪl, 'krɛfɪl, 'krɪfɪl, 'lɒbɪl, 'lubɪl, 'plɪpɪl, 'plɑpɪl, 'præmɪl, 'preml, 'smɪnɪl, 'smamɪl, 'stamɪl, 'stomɪl, 'strɛfɪl, 'strɪfɪl.

Final /ɪn/: 'brɛpɪn, 'brɪpɪn, 'drɛɪn, 'drurɪn, 'fɑɪn, 'forɪn, 'glɪgɪn, 'glɑgɪn, 'skənɪn, 'skunɪn, 'smɛfɪn, 'smɪfɪn, 'træbɪn, 'trebɪn, 'vənɪn, 'vonɪn, 'zɪgɪn, 'zægɪn, 'tʃɛlɪn, 'tʃɪlɪn.

Final /ɪnt/: 'blɛnɪnt, 'blɪnɪnt, 'drɛfɪnt, 'drufɪnt, 'prəmɪnt, 'prumɪnt, 'prɪnɪnt, 'pramɪnt, 'smɑpɪnt, 'smopɪnt, 'tægɪnt, 'tigɪnt, 'væɪnt, 'vɛɪnt, 'zəlɪnt, 'zɒlɪnt, 'zɪbɪnt, 'zɑbɪnt, 'θæpɪnt, 'θɛpɪnt.

Final /ɪst/: 'fəbɪst, 'fubɪst, 'frænɪst, 'frenɪst, 'gerɪst, 'gɪrɪst, 'krɪfɪst, 'karfɪst, 'kræɪst, 'kreɪst, 'pralɪst, 'proɪst, 'snɛgɪst, 'snɪgɪst, 'sprəpɪst, 'sprupɪst, 'stamɪst, 'stomɪst, 'tʃɪbɪst, 'tʃɑbɪst.

Final /ə/: 'gapə, 'gopə, 'klægə, 'klegə, 'pæfə, 'pefə, 'prebə, 'pribə, 'tebə, 'tibə, 'væfə, 'vefə, 'vənə, 'vunə, 'zamə, 'zomə, 'θægə, 'θegə, 'tʃibə, 'tʃaibə.

Final /i/: 'brəli, 'bruli, 'gami, 'gomi, 'glæfi, 'glefi, 'kləri, 'kliri, 'pɪpi, 'praɪpi, 'sləni, 'sleni, 'sməmi, 'smumi, 'spɛfi, 'sprifi, 'vabi, 'vobi, 'θɪgi, 'θaɪgi.

Filler items: baim, bev, brək, dæs, fik, flɪs, fraz, frep, frub, glɪz, hæg, həz, nef, nəz, nob, præk, sæb, saɪp, smub, snem, sprəs, vak, vev, vul, waɪb, zæm, zas, zek, tʃab, tʃop.

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