Graphotactics and spelling: Evidence from consonant doubling

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ABSTRACT

Choosing between alternative spellings for sounds can be difficult for even experienced spellers. We examined the factors that influence adults' choices in one such case: single- versus double-letter spellings of medial consonants in English. The major systematic influence on the choice between medial singletons and doublets has been thought to be phonological context: whether the preceding vowel is phonologically long or short. With phonological context equated, we found influences of graphotactic context—both the number of letters in the spelling of the vowel and the spelling sequence following the medial consonant—in adults' spelling of nonwords and in the English vocabulary itself. Existing models of the spelling process do not include a mechanism by which the letters that are selected for one phoneme can influence the choice of spellings for another phoneme and thus require modification in order to explain the present results.

Introduction

Spelling is an important skill. Writers who are good spellers can concentrate on expressing their ideas rather than on spelling the individual words, and their readers will not be hurt by misspellings. Although spell checkers are of some help, they miss errors that form words, such as ‹canon› for ‹cannon› and ‹trail› for ‹trial›. Knowledge of spelling is important for reading as well as for writing. Good spellers possess the precise representations of words that are thought to be important for accurate word identification, and they can devote more attention to higher levels of text comprehension (e.g., Hersch & Andrews, 2012).

Despite the importance of spelling, fewer studies have examined the processes that are involved in spelling than the processes that are involved in reading. The present study focused on one aspect of spelling that can be difficult even for adults: choosing between alternative spellings of a

phoneme. Many phonemes in English and other languages have more than one possible spelling. For example, a number of English consonants may be spelled with either single letters or doublets. Educated adults sometimes make mistakes involving doubling (Holmes & Ng, 1983; Pollock & Zamora, 1983; Wing & Baddeley, 1980; Yannakoudakis & Fawthrop, 1983), although good spellers make fewer such mistakes than less good spellers (Holmes & Ng, 1983). What knowledge do adults possess that allows them, at least most of the time, to make the correct choice? Spelling can involve the spelling of real words or the spelling of novel items, which are potential words. Here we focused on the latter, examining adults' use of singleton versus doublet spellings of medial consonants in a nonword production task.

Previous studies suggest that the phonological properties of the preceding vowel influence people's decisions about whether to spell a medial consonant with a singleton or a doublet. Evidence for the importance of phonology comes from a study in which English speakers heard a series of disyllabic nonwords with single medial consonants and, for each one, were asked to choose between a spelling that included a medial consonant singleton and an

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otherwise identical spelling that included a doublet (Cassar & Treiman, 1997). If the vowel in the first syllable was one of those traditionally called *short* (/æ/, /ɛ/, /ɪ/, /ɑ/, /ʌ/, or /ʊ/ for American English, what phonologists call *lax* vowels), adults and older children favored spellings with consonant doublets. For example, they tended to choose ‹zimmen› over ‹zimen› as a spelling of /ˈzɪmən/. If the first syllable of the spoken nonword contained a *long* vowel or *diphthong* (what phonologists call *tense* vowels), adults and older children strongly preferred single-consonant spellings. Davis (cited in Nunes & Bryant, 2009), working with children of around 8 years old and above in a task in which participants produced spellings of nonwords, found more use of consonant doublets after short vowels than after long vowels. Deacon, Leblanc, and Sabourin (2011) reported a similar result in a spelling production task involving real words. These findings suggest that the phonological context in which a medial consonant occurs influences people's decisions about whether to spell that consonant with a singleton or a doublet. Indeed, many bisyllabic English words with short vowels in the first syllable are written with medial doublets (e.g., ‹happen›), whereas words with long vowels typically have singletons (e.g., ‹open›).

The idea that people use phonological knowledge to make decisions about consonant doubling fits well with *dual-route* models of the spelling process. According to these models, spellers possess a system of rules that relate phonemes to letters—a *phonological* route—as well as a set of stored whole-word spellings—a *lexical* route (e.g., Barry & Seymour, 1988; Houghton & Zorzi, 2003; Kreiner, 1992; Kreiner & Gough, 1990; Tainturier & Rapp, 2001). People use the phonological route when spelling nonwords and words whose spellings are not firmly stored in memory. The experimental findings just reviewed (Cassar & Treiman, 1997; Davis, cited in Deacon et al., 2011; Nunes & Bryant, 2009) suggest that the phonological route includes a rule specifying that a single medial consonant phoneme that follows a stressed vowel and that precedes an unstressed vowel is spelled with a doublet if the preceding vowel is phonologically short and with a singleton if the preceding vowel is long or diphthongized. Although use of this *phonological doubling rule* leads to correct spellings of many words, it causes errors on *exception words* such as ‹canon›, ‹manic›, and ‹leopard›. According to the dual-route view, the lexical route is required to spell such words correctly. In line with these ideas, some educators have suggested that children should be explicitly taught the phonological doubling rule and should individually memorize the spellings of words that do not conform to it (e.g., Carreker, 2005; Scientific Spelling., 1992).

The present study asked whether the choice between singleton and doublet consonants is largely a matter of phonology, as typically assumed, or whether it is influenced by *graphotactic* context. Graphotactics refers to patterns involving the order and arrangement of letters, patterns that relate to spelling alone and not to pronunciation. We hypothesized that graphotactic context would influence the choice between singletons and doublets, and we tested this hypothesis in two experiments in which we asked adults to spell disyllabic nonwords with short

stressed vowels in the first syllable. This context specifies doubling of medial consonants according to the phonological doubling rule. If graphotactic context is influential, however, participants might use doublets at low rates before or after certain letter sequences.

The idea that contextual effects on the choice among alternative spellings are in some cases better understood as graphotactic than as phonological is supported by a recent study in which adults spelled monosyllabic nonwords such as /hɪf/ and /flok/ (Treiman & Kessler, 2016; see Hayes, Treiman, & Kessler, 2006, for a similar study with children). Participants tended to avoid final sequences such as ‹ff› and ‹ck› if they spelled the preceding vowel with two or more letters, although they did often use these sequences if they spelled the preceding vowel with one letter. Participants' spelling choices for the final consonants were better explained by the number of letters that they used to spell the preceding vowel—graphotactic context—than by whether that vowel was long or short—phonological context. These results are problematic for dual-route models of the spelling process as currently instantiated. This is because the phonological route of these models translates from phonemes to letters and does not include a mechanism by which the spelling that participants select for one phoneme can influence the spelling that they select for another. Indeed, the best developed computational model of the spelling process to date, the dual-route model of Houghton and Zorzi (2003), could not account for the effects of graphotactic context that were observed in the Treiman and Kessler experiment.

In the present study, we asked whether effects of graphotactic context on spelling are limited to the types of monosyllables studied by Treiman and Kessler (2016) and Hayes et al. (2006) or whether they are more widespread. This issue is important not only because of its implications for specific models of the spelling process but also because of its relevance to the broader question of whether writing is purely a reflection of speech or whether it is a system with its own patterns and properties. If the former view (e.g., Frost, 1998) is correct, then the production and interpretation of written language must depend largely on phonology. If the latter view (e.g., Berg, 2016b) is correct, then one must look beyond phonology to understand writing systems themselves and how people learn and use them.

Medial consonant doubling is a good test case for the study of graphotactic context, not only preceding context, as studied by Treiman and Kessler (2016) and Hayes et al. (2006), but also following context—the letters yet to be written. This is because, according to several linguistic studies, there are some graphotactic patterns in the English writing system that might influence spellers' doubling of medial consonants. These include a tendency for consonants not to double after vowel spellings of more than one letter and a tendency for doubling to be less common before ‹ic›, ‹id›, and ‹it› than before many other letter sequences (e.g., Berg, 2016a; Carney, 1994; Rollings, 2004). These patterns are graphotactic in that they reflect the spellings of the preceding and following elements rather than their pronunciations. For example, doubling seems to be less common after /ɛ/ when it is spelled as ‹eo›

or ‹ea› (e.g., ‹leopard›, ‹heading›) than when it is spelled as ‹e› (e.g., ‹bedding›). As another example, doubling seems to be less common before /ɪk/ when it is spelled as ‹ic› (e.g., ‹magic›) than when it is spelled as ‹ick› (e.g., ‹gimmick›).

In the present study, we asked whether the graphotactic patterns described in the linguistic studies (e.g., Berg, 2016a; Carney, 1994; Rollings, 2004) influence adults' spelling of medial consonants in nonwords. If people rely solely on phonological context, as models of the spelling process and previous experimental findings suggest (e.g., Cassar & Treiman, 1997; Houghton & Zorzi, 2003), then graphotactic context should not have an effect. The first step in our research was to verify that the graphotactic patterns of interest hold true for disyllabic words similar to the nonwords that we used in our experiments and to obtain quantitative information about the strength of the patterns. We therefore begin by reporting an analysis of medial consonant doubling in a corpus of English words. We then report two experiments designed to test whether the graphotactic patterns influence adults' spelling of nonwords.

Corpus analysis

The corpus analysis was designed to study graphotactic patterns involving medial consonant doubling in English words that are similar in structure to the nonwords in our experiments. According to some descriptions of the English writing system, especially those that are oriented toward teachers (e.g., Carreker, 2005; Templeton & Morris, 1999), the primary influence on medial consonant doubling in monomorphemic English words is whether the preceding vowel is phonologically long or short. However, as we have mentioned, some linguists have pointed to systematic influences that are graphotactic in nature (e.g., Berg, 2016a; Carney, 1994; Rollings, 2004).

The first question that we addressed in the corpus analysis is how doubling is affected by the preceding graphotactic context, specifically by the number of letters in the spelling of the preceding vowel. We sought to verify the observation of such researchers as Berg (2016a), Carney (1994), and Rollings (2004) that doubling is less common when the first vowel is spelled with more than one letter than when it is spelled with one letter and to investigate the strength of the association.

Our second question was how the doubling of medial consonants is affected by the letters that follow. We examined the frequency of consonant doubling before three types of final sequences. The first category included ‹ic›, ‹id›, and ‹it›. The linguistic descriptions (e.g., Berg, 2016a; Carney, 1994; Rollings, 2004) suggest that these endings, which in some cases are derivational suffixes, discourage doubling of the preceding consonant. We refer to them as a group as *doublet-discouraging* finals. The second category of final sequences in our study included ‹age›, ‹is›, and ‹ow›. These sequences were expected to be associated with more doubling of the preceding consonant than sequences in the first category. Because they are never inflectional suffixes in English, we refer to them as *non-inflectional doublet-encouraging* finals. The third category of final sequences

included ‹en›, ‹er›, ‹est›, and ‹ing›. Because they may be inflectional suffixes, as in *hidden*, *bigger*, *smallest*, and *running*, we label them *inflectional doublet-encouraging* finals. We should note, however, that these spellings also occur at the ends of a number of non-inflected words, including *happen*, *manner*, *modest*, and *inning*. Doubling was expected to be quite common before these sequences.

Method

The analysis used words from the Unisyn lexicon (Fitt, 2008). This database contains around 120,000 words transcribed in symbols that allow the encoding of multiple accents of English. For the present analysis, we used the General American accent. We extracted from the database two sets of disyllabic words with a short stressed vowel in the first syllable, a single medial consonant phoneme that was spelled with either a consonant singleton or a doublet, and an unstressed vowel in the second syllable. The first set, which we call the *restricted corpus*, had the same first-syllable vowels (/æ/, /ɛ/, /ɪ/, or /ɑ/) and medial consonants (/b/, /m/, /n/, or /p/) that we used in our experiments. The second set, which we call the *extended corpus*, included words with additional short vowels (/ʌ/ and /ʊ/) and medial consonants (/d/, /f/, /g/, /l/, and /t/). Fused words such as ‹gonna›, compound words, foreign words, words and spellings that were judged to be specific to British or Australian English, and words that can only be proper nouns were excluded. There were 994 words in the restricted corpus and 3026 in the extended corpus, about one quarter of which were classified in Unisysn as having a single morpheme. We computed the fraction of words of different sorts that had doublet spellings of the medial consonant, weighting each word by the natural logarithm of two plus the frequency of the word given in Brysbaert and New (2009).[1]

Results

Table 1 shows the results relevant to our first question, which concerns the association between the number of letters in the spelling of the first vowel and doubling of the following consonant. Doubling was moderately common when the first vowel was spelled with a single letter. However, it was extremely rare when the preceding vowel was spelled with more than one letter. The only two words with a consonant doublet after a vowel spelling of more than one letter, ‹woolly› and ‹woollies›, have a morpheme boundary between the consonants; these words have alternate spellings with single medial ‹l›. The results were similar for the restricted and extended corpora.

Table 2 shows the results pertaining to use of doublets before different types of final sequences for words in which

Table 1

Frequency-weighted proportion of words in corpus analysis with medial consonant doublet as a function of number of letters in spelling of preceding vowel (number of words contributing data in each cell in parentheses).

Corpus	Number of letters in spelling of vowel	
	One	More than one
Restricted	.72 (*n* = 978)	.00 (*n* = 16)
Extended	.81 (*n* = 2909)	.01 (*n* = 117)

the first vowel was spelled with a single letter. Medial consonant doubling was fairly uncommon before ‹ic›, ‹id›, and ‹it›, more common before ‹age›, ‹is›, and ‹ow›, and most common before ‹en›, ‹er›, ‹est›, and ‹ing›. These patterns were found in both the restricted and the extended corpus. The fact that the restricted corpus did not contain many words with certain endings (see Table 2) may explain the apparent differences between the two corpora for non-inflectional doublet-encouraging endings. The patterns were similar for words with one morpheme and words with more than one morpheme but were somewhat stronger for the latter. Thus, whereas the consonants we examined almost always double before ‹en›, ‹er›, ‹est›, and ‹ing› when these are separate morphemes, approximately 10% of one-morpheme words with these endings have a single medial consonant, as in ‹modest›.

Discussion

The results show that English has a number of graphotactic patterns involving medial consonant doubling, some of which involve associations between doubling and preceding elements and others of which involve associations between doubling and following elements. The findings support the idea (e.g., Berg, 2016a; Carney, 1994; Rollings, 2004) that doubling is associated with both preceding and following graphotactic context. The results do not support the idea, which is common in pedagogically-oriented descriptions of English spelling (Carreker, 2005; Templeton & Morris, 1999), that the only systematic contextual influence on medial consonant doubling within a morpheme is whether the preceding vowel is phonologically long or short. The present results show that the graphotactic patterns described by linguists are found in words that contain the same number of syllables as the nonwords used in our experiments. The results also provide quantitative information about the strength of the effects.

We now turn to the question of whether adults' tendency to double medial consonants in a spelling production task is influenced by graphotactic context. To do so, we asked participants to spell disyllabic nonwords with short stressed vowels in the first syllable. If context effects are phonological, as previous experimental and modeling work (e.g., Cassar & Treiman, 1997; Houghton & Zorzi, 2003) has assumed, then people should generally use doublets because the preceding vowel is phonologically short. If graphotactic context is influential, then people should often use singletons if they spell the preceding vowel with more than one letter or if they use certain final spelling sequences. The nonwords in Experiment 1 were designed to elicit spellings that ended with the doublet-discouraging ‹ic›, ‹id›, and ‹it› and the non-inflectional doublet-encouraging ‹age›, ‹is›, and ‹ow›. Experiment 2 also included nonwords that were designed to elicit spellings ending with ‹en›, ‹er›, ‹est›, and ‹ing›.

Experiment 1

Method

Stimuli

There were 48 experimental nonwords, all disyllabic. All had an initial consonant or cluster, a stressed short vowel (/æ/, /ɛ/, /ɪ/ or /ɑ/), medial /b/, /m/, /n/, or /p/, and then a final syllable, which was unstressed. There were 8 nonwords that ended with each of /ɪd/, /ɪk/, /ɪt/, /ɪd͡ʒ/, /ɪs/, and /o/. The first three phonological sequences may be spelled with the doublet-discouraging ‹id›, ‹ic›, and ‹it›, respectively, among other possibilities, and the last three may be spelled with non-inflectional doublet-encouraging ‹age›, ‹is›, and ‹ow›. None of the experimental items rhymed with a real word. There were also 24 filler nonwords, all monosyllabic. Half of the fillers had final /f/ or /l/ after a vowel that is normally spelled with a single letter, a context that encourages use of ‹ff› and ‹ll› (Hayes et al., 2006; Treiman & Kessler, 2016). The other fillers did not include any phonemes that were expected to be spelled with doublets. The filler items increased the variety among the stimuli and potentially helped inform participants that some consonants in the experiment were spelled with doublets. However, the specific doublet spellings that were appropriate for fillers were not appropriate for the experimental items. The items are listed in the Appendix.

Four different orders of the items 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 order.

Table 2

Frequency-weighted proportion of words in corpus analysis with medial consonant doublet as a function of type of final spelling sequence for words with single-letter spelling of first vowel (number of words contributing data to each cell in parentheses).

Word set	Final spelling sequence		
	Doublet discouraging (‹ic›, ‹id›, ‹it›)	Non-inflectional doublet encouraging (‹age›, ‹is›, ‹ow›)	Inflectional doublet encouraging (‹en›, ‹er›, ‹est›, ‹ing›)
Restricted	.11 (*n* = 31)	.47 (*n* = 14)	.95 (*n* = 323)
Extended	.19 (*n* = 54)	.74 (*n* = 59)	.97 (*n* = 789)

Table 3
Mean proportion of spellings with medial consonant doublet as a function of number of letters in participant's spelling of preceding vowel (standard deviations in parentheses).

Experiment and participant group	Number of participants	Number of letters in spelling of vowel	
		One	More than one
1	44	.37 (.27)	.04 (.11)
2			
All participants	52	.46 (.26)	.07 (.15)
Better spellers	28	.58 (.22)	.10 (.18)
Poorer spellers	24	.32 (.22)	.04 (.09)

Procedure

Participants were tested 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 if it were a typical English word. The experimenter pronounced each item and the participants repeated it as a group. The experimenter then pronounced the item again and asked participants to spell it. Participants wrote their spellings by hand.

Participants

The participants were 44 students (37 female) at Washington University in St. Louis. Their mean age was 19.3 years (range 19–24). All were native speakers of English. They participated in exchange for pay or for extra credit in a psychology course.

Results

Spellings of experimental items were scored for whether they contained the phonologically expected single medial consonant or the phonologically expected double medial consonant. Spellings that included some other medial consonant (e.g., ‹b› or ‹bb› for medial /p/) or no medial consonant at all constituted less than 1% of spellings of experimental items. Because these responses could have reflected mishearing or other difficulties, they were not scored. Spellings of filler items were not analyzed.

Influence of vowel spelling on consonant doublet use

As Table 3 shows, the proportion of spellings with medial doublets was .37, averaging across participants, on trials in which participants spelled the preceding vowel phoneme with a single letter. It was much less common for participants to spell the vowel phoneme of the first syllable

with more than one letter (6% of scorable trials) than to spell it with one letter (94% of trials), but participants were very unlikely to double the following consonant when they did spell the vowel with more than one letter. As Table 3 shows, the mean proportion of spellings with medial doublets was just .04 in such cases. Thus, participants were less likely to produce a doublet after a vowel spelling like ‹au› (as in ‹draubbidge› for /drɑbɪd͡ʒ/) than after a vowel spelling like ‹a› (as in ‹drabbidge› for /drɑbɪd͡ʒ/).

To test whether participants' tendency to use consonant doublets differed significantly as a function of whether they chose to spell the preceding vowel with one letter or more than one letter, we conducted a mixed-model analysis using data at the trial level. The fixed factor was vowel spelling, which was coded as more than one letter (1) or one letter (0). The model included random intercepts for participants and items and random slopes for participants by vowel spelling. Data from 2098 trials were included. We used a logit link function for this and the other mixed-model analyses reported in this paper because the dependent variable, whether the consonant was double (1) or single (0), was binary. The analyses were conducted in R version 3.2.2 (R Core Team., 2015) using the package lme4 (Bates, Mächler, Bolker, & Walker, 2015). The results, shown in Table 4, reveal a statistically significant effect of vowel spelling. Even though the preceding vowel was phonologically short, participants' tendency to spell the medial consonant with a doublet was influenced by whether they spelled the preceding vowel with a single letter or more than one letter.

Influence of final spelling sequence on consonant doublet use

For these analyses, we examined those responses (n = 873) in which participants spelled the vowel phoneme of the first syllable with a single letter and used final ‹ic›,

Table 4
Results of mixed-model analyses examining effects of preceding vowel spelling on consonant doubling.

Random effects and slopes	Experiment 1				Experiment 2			
	Variance	SD			Variance	SD		
Item (Intercept)	0.59	0.77			0.76	0.87		
Participant (Intercept)	2.89	1.70			1.83	1.35		
Vowel spelling	0.49	0.70			8.02	2.83		
Fixed effects	β	SE	z	p	β	SE	z	p
Intercept	−0.90	0.29	−3.12	.002	−0.20	0.22	−0.89	.373
Vowel spelling	−2.06	0.66	−3.12	.002	−5.35	1.29	−4.16	<.001
WRAT	–	–	–	–	0.06	0.01	3.93	<.001
Vowel spelling × WRAT	–	–	–	–	−0.03	0.06	−0.52	.604

‹id›, ‹it›, ‹age›, ‹is›, or ‹ow› for /ɪk/, /ɪd/, /ɪt/, /ɪd͡ʒ/, /ɪs/, and /o/, respectively. We excluded responses in which participants spelled the vowel of the first syllable with more than one letter (6% of scorable trials) because consonant doubling is unusual in such contexts and because, according to the preceding analysis, participants generally avoided it. We also excluded responses with final spellings not listed above (52% of trials) because alternative spellings, such as ‹ick› for /ɪk/, are sometimes associated with different patterns of consonant doubling in English. As shown in Table 5, the mean proportion of medial consonant doublets, averaging across participants, was .32 when participants used a doublet-discouraging final. The proportion of doublets was higher, .53, when participants used a non-inflectional doublet-encouraging final. Table 6 shows that the effect of final was statistically significant according to a mixed-model analysis with type of final (doublet discouraging, coded as 0, or non-inflectional doublet encouraging, coded as 1) as the fixed factor, random intercepts for participants and items, and random slopes for participants by final type. These results confirm that spellings such as ‹blebbage›, with a doublet before ‹age›, were more common than spellings such as ‹vibbic›, with a doublet before ‹ic›.

Discussion

Experiment 1 was designed to determine whether adults' decisions about whether to spell a medial consonant with a singleton or a doublet are influenced by graphotactic context. We found that they are. One influence involved preceding context, such that participants were more likely to use a doublet if they spelled the preceding vowel with a single letter than if they spelled it with more than one letter. The only previous study to have addressed this issue, an unpublished study by Faizal (2011), found a similar result. Another influence of graphotactic context involved following context, such that participants were more likely to use a consonant doublet before some letter sequences than before others. Such an effect on medial consonant doubling has not previously been reported.

Our results suggest that, contrary to the assumptions of previous experimental and modeling work (e.g., Cassar & Treiman, 1997; Houghton & Zorzi, 2003), phonological context is not the only type of context that influences spellers' decisions about whether to double a medial consonant. Graphotactic context is also influential. Even in a phonological context that would suggest use of doublets, people tend to avoid them after vowel spellings that contain more than one letter or before certain final letter sequences.

Experiment 2 was carried out to confirm and extend the findings of Experiment 1. It included, in addition to the endings examined in Experiment 1, items that ended with /ən/, /ɚ/, /əst/, and /ɪŋ/. We expected that people would often spell these with the doublet-encouraging spellings ‹en›, ‹er›, ‹est›, and ‹ing›, respectively. Another change from Experiment 1 was that participants were members of the wider community rather than students at a selective university. This allowed us to test the generality of the results. In addition, we gave participants in Experiment 2 a standardized spelling test in order to characterize their spelling ability and to explore whether there are any differences in use of consonant doubling as a function of spelling skill.

Table 5
Mean proportion of spellings with medial consonant doublet as a function of type of final spelling sequence when participant spelled preceding vowel with single letter (standard deviations in parentheses).

Experiment and participant group	Number of participants	Final spelling sequence		
		Doublet discouraging (‹ic›, ‹id›, ‹it›)	Non-inflectional doublet encouraging (‹age›, ‹is›, ‹ow›)	Inflectional doublet encouraging (‹en›, ‹er›, ‹est›, ‹ing›)
1	44	.32 (.28)	.53 (.37)	–
2				
All participants	52	.43 (.35)	.55 (.30)	.65 (.34)
Better spellers	28	.53 (.29)	.65 (.32)	.77 (.29)
Poorer spellers	24	.30 (.27)	.44 (.23)	.51 (.36)

Table 6
Results of mixed-model analyses examining effects of final spelling sequence on consonant doubling.

Random effects and slopes	Experiment 1				Experiment 2			
	Variance	SD			Variance	SD		
Item (Intercept)	0.57	0.75			0.92	0.96		
Participant (Intercept)	3.66	1.91			2.16	1.47		
Doublet discouraging vs. non-inflectional doublet encouraging	0.78	0.88			–	–		
Fixed effects	β	SE	z	p	β	SE	z	p
Intercept	−1.37	0.37	−3.74	<.001	−0.58	0.32	−1.77	.077
Doublet discouraging vs. non-inflectional doublet encouraging	1.49	0.35	4.22	<.001	0.77	0.37	2.08	.038
Doublet discouraging vs. inflectional doublet encouraging	–	–	–	–	1.23	0.36	3.46	<.001
WRAT	–	–	–	–	0.05	0.02	2.54	.011
Doublet discouraging vs. non-inflectional doublet encouraging × WRAT	–	–	–	–	0.01	0.01	0.61	.544
Doublet discouraging vs. inflectional doublet encouraging × WRAT	–	–	–	–	0.03	0.01	2.58	.010

Experiment 2

Method

Stimuli

The experimental nonwords had an initial consonant or consonant cluster, a stressed short vowel (/æ/, /ɛ/, /ɪ/, or /ɑ/), a medial consonant (/b/, /m/, /n/, or /p/), and a final syllable, which was unstressed. There were 6 nonwords that ended with /ɪd/ and 7 nonwords that ended with each of /ɪk/ and /ɪt/. (One item originally constructed for the /ɪd/ category was actually a rare word; we excluded it from the analyses in order to be conservative even though few participants appeared to know it.) There were also 7 experimental nonwords that ended with each of /ɪd͡ʒ/, /ɪs/, and /o/ and 6 with each of /ən/, /ɚ/, /əst/, and /ɪŋ/. The initial consonants and consonant clusters differed from those used in Experiment 1, meaning that no items were repeated across experiments. None of the experimental items rhymed with an English word that we expected participants to know. We used the same 24 filler items as in Experiment 1, except that we changed one filler to make it less word-like. The items are listed in the Appendix.

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 order.

Procedure

The procedure was like that of Experiment 1, except that we administered the spelling subtest of the Wide Range Achievement Test fourth edition (WRAT, Wilkinson & Robertson, 2006; we used the blue form) at the end of the session. The words on this test range from easy ones such as *on* to difficult ones such as *pusillanimous*, and they are presented in sentences. Because we tested participants in small groups, we did not stop participants after eight consecutive errors, as is stated in the WRAT administration guidelines, but gave all 42 words to all participants. We calculated the standardized score for each participant.

Participants

The participants were 52 residents of the St. Louis area (36 female) who belonged to a registry of community members who had expressed interest in participating in research at Washington University. The participants' mean age was 52 years (range 23–84), and all were native speakers of English. They were paid for their participation. The data of one additional person were dropped from the analyses because of failure to follow the instructions. The participants varied widely in spelling ability, with standardized scores on the WRAT ranging from 80 to 145 ($M = 113$, $SD = 14$).

Results

We coded responses to experimental items as containing medial singletons or doublets. Spellings that included no medial consonant or an inappropriate singleton or doublet, which constituted 5% of all spellings of experimental

items, were not included in the analyses. Spellings of filler items were not analyzed.

Influence of vowel spelling on consonant doublet use

As in Experiment 1, participants were more likely to spell the first vowel with a single letter (90% of scorable trials) than with more than one letter (10%). Table 3 shows the proportion of spellings with consonant doublets on trials in which participants spelled the preceding vowel with more than one letter and trials in which they spelled it with one letter. The results are shown for all participants as a group and also for better spellers (those with a standardized score on the WRAT at or above the median of 114) and poorer spellers (those below the median).

We conducted a mixed-model analysis with the fixed factors of vowel spelling (one letter, coded as 0, vs. more than one letter, coded as 1), standardized WRAT score, and their interaction. The model included random intercepts for participants and items and random slopes for participants by vowel spelling. WRAT scores were centered, and 3203 trials were included in the analysis. The results are shown in Table 4. There was a significant effect of vowel spelling, such that participants were more likely to use a consonant doublet when they spelled with preceding vowel with a single letter than when they spelled it with more than one letter. There was also a main effect of spelling ability, such that people with higher WRAT scores were more likely to use doublets than were people with lower WRAT scores. The interaction between vowel spelling and ability was not significant.

Influence of final spelling sequence on consonant doublet use

For these analyses, we examined the results on those 1353 trials in which the vowel of the first syllable was spelled with a single letter and in which final ‹ic›, ‹id›, ‹it›, ‹age›, ‹is›, ‹ow›, ‹en›, ‹er›, ‹est›, or ‹ing› was used for /ɪk/, /ɪd/, /ɪt/, /ɪd͡ʒ/, /ɪs/, /o/, /ən/, /ɚ/, /əst/, or /ɪŋ/, respectively. The 10% of scorable trials in which the vowel of the first syllable was spelled with more than one letter were not included in these analyses, nor were the 48% of scorable trials that had a final spelling sequence not listed above. Table 5 shows the proportion of doublet spellings, averaged across participants, before the three types of final spellings. The results are shown for all participants and also for better and poorer spellers defined as described above.

Table 6 shows the results of a mixed-model analysis with random intercepts for participants and items and the fixed factors final type, WRAT, and their interaction. Final type was coded in terms of two contrasts: doublet-discouraging versus non-inflectional doublet-encouraging and doublet-discouraging versus inflectional doublet-encouraging. A model with random slopes for participants by final type did not converge, so we report the results of a model that did not include random slopes. The contrast between doublet-discouraging finals (mean proportion of doublets .43) and non-inflectional doublet-encouraging finals (.55) was statistically reliable, as was the contrast between doublet-discouraging finals (.43) and inflectional doublet-encouraging finals (.65). Consistent with the results of the preceding analysis, there was a main effect

of spelling ability, such that people who scored higher on the standardized spelling test were more likely to use doublets than those who scored lower. The contrast between doublet-discouraging finals and non-inflectional doublet-encouraging finals did not interact with spelling ability. The contrast between doublet-discouraging finals and inflectional doublet-encouraging finals was slightly but significantly larger in better spellers than in less good spellers, as shown by an interaction between this contrast and spelling ability. An additional analysis confirmed that the model that included the interactions with spelling ability fit the data significantly better than a model that did not (p = .033 according to a likelihood ratio test).

Discussion

The goal of Experiment 2 was to replicate and extend the finding of Experiment 1 that adults' choices between medial singletons and doublets are influenced by preceding and following graphotactic context. We did so by testing a sample of participants who varied widely in spelling ability and by including doublet-encouraging finals as well as doublet-discouraging and non-inflectional doublet-encouraging finals. The participants in Experiment 2, like those in Experiment 1, were more likely to double a medial consonant when they spelled the preceding vowel with a single letter than when they spelled it with more than one letter. Also as in Experiment 1, participants were more likely to double a medial consonant when they used a non-inflectional doublet-encouraging final spelling than when they used a doublet-discouraging final. Thus, we replicated the graphotactic influences found in Experiment 1. A new finding is that doubling was most common when participants used an inflectional doublet-encouraging final spelling.

Interestingly, the effects of graphotactic context were not as large as would be anticipated given the results of the corpus analysis. For example, participants' proportion of consonant doubling after single-letter vowel spellings and before ‹en›, ‹er›, ‹est›, and ‹ing› was relatively high (.65), but it was significantly lower than the doubling proportion for the same consonants in words in the corpus that fit this description. This held true whether participants' doubling proportion was compared to the doubling proportion for all such words in the corpus, .97, or for single-morpheme words, .90 (p < .001 for both comparisons by two-tailed t tests). This difference may reflect a tendency on the part of spellers to use the simplest and most common spellings of phonemes, which in this case are single consonants (e.g., Deacon et al., 2011; Pacton, Borchardt, Treiman, Lété, & Fayol, 2014). People's attachment to the most common spelling of a phoneme in spelling production (and to the most common pronunciation of a letter in reading) may help to explain why our participants, like those in several previous studies (e.g., Treiman & Kessler, 2006; Treiman, Kessler, & Bick, 2003), showed contextual influences that were smaller than those in the language itself. Although the most common spelling of a phoneme is not spellers' top choice in all contexts, as it is according to the phonological route of some versions of dual-route theories (e.g., Barry & Seymour, 1988, who

made this argument for vowels), it does seem to exert a pull.

The results of Experiment 2 showed that people who scored higher on the standardized spelling test were more likely to double medial consonants than were less good spellers. That is, spelling ability is associated with the large differences that we observed across participants in the proportion of medial consonants that were spelled with doublets (from 0 to .85 in Experiment 1 and from .02 to .88 in Experiment 2). One possible explanation for the association between medial consonant doubling and spelling ability is based on the idea, mentioned above, that people tend to prefer spellings that are common in the language as a whole. The pull toward the more common singleton consonant spellings might be stronger in less skilled spellers than in more skilled spellers. Another possible explanation is that more skilled spellers are more sensitive to the fact that phonologically short vowels in English tend to be followed by doublets. Further research will be required to test these and other possible explanations for better spellers' greater use of medial consonant doublets in items of the type studied here, as well as to replicate the finding that differences in doublet use as a function of spelling skill were larger before ‹en›, ‹er›, ‹est›, and ‹ing› than before other final sequences. The most important point for present purposes, however, is that graphotactic context affected the doubling choices of adults with a range of spelling ability.

The influence of number of letters in the vowel spelling that we found in Experiments 1 and 2 must be a graphotactic effect, for this effect was seen for each of the vowel phonemes in the experiments. However, additional evidence is needed to show that the influence of the following context is graphotactic rather than phonological. It is possible, for example, that participants showed a low rate of consonant doubling before /ɪk/ regardless of whether they spelled this phonological sequence as ‹ic› or in some other way. We addressed this issue in the analyses reported in the next section. We asked, for example, whether participants were more likely to double the medial consonant when they spelled final /ɪk/ as ‹ick› or ‹ock›, contexts in which the preceding consonant often doubles in English words, than when they spelled this ending as ‹ic›. If graphotactic context is influential, we should find such a difference. We combined the data from the two experiments for these analyses because participants used certain final sequences, including ‹ock›, at low rates. When we pooled the data across experiments there were more trials with each final sequence than there would have been if we analyzed each experiment separately.

Combined analysis

Method and results

For each final phonological sequence that appeared in the experimental nonwords, we determined the spellings that were used for that sequence in the words of the extended corpus. Words that were coded as having minor pronunciation variations in the sequence, such as /əd/ for

/ɪd/, were included. We calculated for each spelling sequence the frequency-weighted fraction of words with medial consonant doubling. We refer to this value as the *spelling doubling proportion*. Words in which the first vowel was spelled with more than one letter were excluded from the calculations because, as we have seen, consonant doubling is very uncommon in such cases.

We conducted a mixed-model analysis with experimental data at the trial level in which the dependent variable was whether the participant spelled the medial consonant with a doublet. The model had random effects for participants and items. It also included a random effect for phonological endings in order to account for differences in doubling that are associated with the phonological forms or other aspects of the endings themselves. The fixed factor was the spelling doubling proportion for the final spelling that the participant used on the trial. Trials on which a participant spelled an ending using a letter sequence that was not used in the extended corpus or that was not used for that ending were excluded from the analysis, as were trials on which a participant used more than one letter to spell the vowel of the first syllable. Data from 22% of trials were dropped for these reasons, leaving 4150 trials in the analysis.

The results of the model, shown in Table 7, reveal a significant effect of spelling doubling proportion. Participants were more likely to use a consonant doublet when the final spelling sequence that they used was associated with a higher proportion of doubling in the words of the corpus than when it was associated with a lower proportion of doubling. When we calculated spelling doubling proportion based on single-morpheme words in the corpus rather than all words and repeated the analysis, the results were very similar to those shown in Table 7.

Discussion

The results show that people's tendency to use a double consonant before a certain phonological sequence varies depending on how they will go on to spell that sequence. Doubling is more common if people spell the sequence using a letter string that is associated with a higher doubling rate in the words of English (e.g., ‹ock› for /ɪk/) than if spellers use a letter string that is associated with a lower doubling rate (e.g., ‹ic› for /ɪk/). Spellers may consider the letters that they plan to write next when choosing between singleton and doublet spellings of medial consonants, or their choice of letters for the final sequence may be conditioned by the spelling they have already chosen for the preceding consonant.

General discussion

English, like other writing systems, does not have one-to-one links between phonemes and letters. Selecting among alternative spellings of a phoneme can be a challenge for spellers, just as selecting among alternative pronunciations of a letter can be a challenge for readers. The present study focused on one choice that spellers of English must make: whether to use a singleton or doublet for a medial consonant. It is widely believed that this choice should be based on the phonological properties of the morpheme in question. Specifically, a doublet should be used if the vowel that precedes the medial consonant is short and a singleton should be used if the vowel is long or diphthongized. Discussions of the English spelling system that are oriented toward teachers (e.g., Carreker, 2005; Templeton & Morris, 1999) portray words that follow this phonological doubling rule as regular and words that deviate from it as exceptions that must be individually memorized. The phonological doubling rule is sometimes explicitly taught to children (e.g., Scientific Spelling, 1992), and the doubling choices of experienced adult spellers do vary according to whether the preceding vowel is phonologically long or short (Cassar & Treiman, 1997).

Our results show that graphotactic context is a systematic influence, above and beyond phonology, on medial consonant doubling in English words and on adults' use of doublets in the spelling of nonwords. We found an effect of preceding graphotactic context, with less doubling when a participant spelled the vowel that came before the critical consonant with more than one letter than when the participant spelled it with one letter. We also found an effect of following graphotactic context, with less doubling before some letter sequences than before others. Even when the preceding vowel was phonologically short, as it was in all of the items in our experiments, people tended to avoid consonant doubling in some graphotactic contexts. We observed graphotactic effects in adults with a wide range of spelling ability, both young adults who were university students (Experiment 1) and older community members who were not (Experiment 2). Our results may help to explain why participants in the study of Cassar and Treiman (1997) did not choose doublets at extremely high rates after short vowels: several of the final letter sequences in that study were not ones that encourage doublets.

Current models of the spelling process have difficulty explaining the graphotactic effects found in our study. The most popular models of spelling are dual-route models according to which people use a phonological route to construct spellings for nonwords and in which the phonological route works at the level of individual phonemes (e.g., Barry & Seymour, 1988; Houghton & Zorzi, 2003; Kreiner, 1992; Kreiner & Gough, 1990; Tainturier & Rapp, 2001). The phonological route of these models, as currently conceived, cannot in principle account for effects of graphotactic context. This is because the phonological form of the item to be spelled serves as input to the spelling process

Table 7
Results of mixed-model analysis examining effects of doubling proportion for final spelling sequence in corpus using combined data from Experiments 1 and 2.

Random effects and slopes	Variance	SD		
Item (Intercept)	0.37	0.61		
Participant (Intercept)	2.43	1.56		
Ending (Intercept)	0.31	0.56		
Fixed effects	β	SE	z	p
Intercept	−0.99	0.28	−3.50	<.001
Spelling doubling proportion	1.26	0.21	6.02	<.001

and determines which letters are used. The output, a spelling, cannot serve as input. Thus, the choice between a singleton and a doublet cannot be influenced by the letters that people used for the preceding vowel or the letters that they plan to use for the following part of the item. We can envision a number of possibilities for improved models. One possibility would be to include a feedback loop that allows the spellings of phonemes to serve as inputs, together with the phonemes themselves. A second possibility would be for the phonological route to use units larger than single phonemes. A third possibility would be to supplement a phonological route that works at the level of individual phonemes with a system that activates spellings of known words and combines these with spellings that are activated by the phonological route. It will be important to develop testable models that incorporate these ideas and determine whether these models can account for the effects of preceding and following graphotactic context that we found here.

The effects of following graphotactic context that we found in the present study pose problems for the idea, instantiated in some theories of the spelling process (e.g., Olson & Caramazza, 1994), that people choose and produce letters for phonemes serially across a word, starting with the first phoneme and proceeding one phoneme at a time. Other models see spellers as planning ahead, placing letters that they have selected but not yet produced into what has been called a graphemic output buffer (Tainturier & Rapp, 2001) or orthographic working memory (Jones, Folk, & Rapp, 2009). The present results indicate that spelling is not a serial, phoneme-by-phoneme process. They suggest that spellers plan ahead and that choices for earlier and later phonemes influence one another.

The items in our experiments were all nonwords, and additional work is needed to determine whether graphotactic context also influences the spelling of words. For example, is ‹attic› more difficult to spell than expected on the basis of its frequency, length, and other factors because it has a consonant doublet before ‹ic›, which does not normally encourage doublets? We found a number of errors involving consonant doubling on the standardized spelling test that was given in Experiment 2, but the words were not selected so as to address such questions. Another issue for future research concerns the balance between graphotactic and phonological influences on medial consonant doubling. To address this issue, studies will need to include items with long vowels in the first syllable as well as items with short vowels, as used here.

Although questions remain, our results shed light on how experienced spellers usually manage to make the correct choice when there is more than one way to spell a phoneme. In some cases, our results show, there are graphotactic patterns in the writing system that can help them. Spellers use these patterns to help select among alternative spellings and reduce the need for rote word-by-word memorization. This occurs in English, according to the results of the present study and other studies (Hayes et al., 2006; Treiman & Kessler, 2016), and in other languages as well (Spanish: Carrillo & Alegría, 2014; French: Pacton, Fayol, & Perruchet, 2005; Sobaco, Treiman, Peereman, Borchardt, & Pacton, 2015; Sénéchal,

Gingras, & L'Heureux, 2016). Our results draw attention to the fact that there are patterns that characterize the written forms of words in a language that do not make reference to the words' phonological forms (e.g., Berg, 2016b). Much research and theory (e.g., Frost, 1998) has focused on the role of phonology in reading and spelling and has overlooked the role of graphotactic patterns. However, these patterns benefit writers and readers (e.g., Chetail, 2015). It is time for researchers and educators to devote more attention to the learning and use of graphotactic patterns.

Author note

Appendix. Experimental items for Experiment 1

Final /ɪd/: ˈblapɪd, ˈgrɛbɪd, ˈslɛbɪd, ˈslɪnɪd, ˈsmɛbɪd, ˈsnamɪd, ˈzæmɪd, ˈzɪnɪd

Final /ɪk/: ˈdrabɪk, ˈfæpɪk, ˈgrapɪk, ˈgrɛbɪk, ˈspræmɪk, ˈtʃæmɪk, ˈvɪbɪk, ˈzɪpɪk

Final /ɪt/: ˈdræpɪt, ˈfɛmɪt, ˈfɪpɪt, ˈsmænɪt, ˈsmanɪt, ˈtʃanɪt, ˈvɛmɪt, ˈvɪnɪt

Final /ɪd͡ʒ/: ˈblɛbɪd͡ʒ, ˈdrabɪd͡ʒ, ˈdræpɪd͡ʒ, ˈfæpɪd͡ʒ, ˈslɛmɪd͡ʒ, ˈtʃabɪd͡ʒ, ˈzɛmɪd͡ʒ, ˈzɪnɪd͡ʒ

Final /ɪs/: ˈfamɪs, ˈfɪpɪs, ˈgranɪs, ˈslɛmɪs, ˈsmɪpɪs, ˈsnɪbɪs, ˈtʃænɪs, ˈvæmɪs

Final /o/: ˈgrano, ˈgrɪbo, ˈsmæbo, ˈsmæno, ˈsprapo, ˈvɛno, ˈvɛpo, ˈzɪmo

Experimental items for Experiment 2

Final /ɪd/: ˈflɛbɪd, ˈflɛnɪd, ˈsæmɪd, ˈzamɪd, ˈzapɪd, ˈθɛbɪd

Final /ɪk/: ˈbrabɪk, ˈlæmɪk, ˈlɪbɪk, ˈrɪpɪk, ˈsæbɪk, ˈzabɪk, ˈθɛnɪk

Final /ɪt/: ˈbræpɪt, ˈbrɪpɪt, ˈflɛmɪt, ˈpræpɪt, ˈprɪnɪt, ˈspɛmɪt, ˈzɪnɪt

Final /ɪd͡ʒ/: ˈlɛbɪd͡ʒ, ˈprabɪd͡ʒ, ˈprɪnɪd͡ʒ, ˈsɛbɪd͡ʒ, ˈsɛmɪd͡ʒ, ˈspɛmɪd͡ʒ, ˈzæpɪd͡ʒ

Final /ɪs/: ˈbrɪpɪs, ˈpranɪs, ˈrænɪs, ˈramɪs, ˈsnɛpɪs, ˈsprɪbɪs, ˈθæbɪs

Final /o/: ˈflæmo, ˈpræno, ˈrapo, ˈsprɛno, ˈzɛmo, ˈzɪno, ˈθæbo

Final /ən/: ˈbrɪpən, ˈflɛbən, ˈlɛbən, ˈprɛbən, ˈprɪpən, ˈspɪpən

Final /ɚ/: ˈbramɚ, ˈflamɚ, ˈsnamɚ, ˈspamɚ, ˈzamɚ, ˈθamɚ

Final /əst/: ˈbrɛpəst, ˈflɛnəst, ˈrɛbəst, ˈsænəst, ˈsnapəst, ˈsprænəst

Final /ɪŋ/: ˈlamɪŋ, ˈsamɪŋ, ˈsnamɪŋ, ˈspamɪŋ, ˈspramɪŋ, ˈθamɪŋ

Filler items for Experiments 1 and 2

bɛf, daʃ, dɪθ, d͡ʒʌl, gæsk, gok, grʌl, jæf, nal, prɪl, rɛft, rɛmp, rʌl, sov, stræf, tɛlt, tɪmp, trʌf, wæf, waf, zæb, zɛl, zɪb, sam (Experiment 1)/zam (Experiment 2)

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