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RESEARCH NOTE

Choosing Between Alternative Spellings of Sounds: The Role of Context

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We investigated how university students select between alternative spellings of phonemes in written production by asking them to spell nonwords whose final consonants have extended spellings (e.g., ‹ff› for /f/) and simpler spellings (e.g., ‹f› for /f/). Participants' choices of spellings for the final consonant were influenced by whether they used one letter or more than one letter to spell the preceding vowel. Specifically, participants tended to use extended consonant spellings when they spelled the vowel with one letter and simple consonant spellings when they spelled the vowel with more than one letter. This held true whether the vowel was phonologically short or long. The findings pose problems for models of the spelling process according to which people use different spellings of a phoneme in accordance with the frequency of the phoneme-to-grapheme links in the vocabulary as a whole but in which the choices are not influenced by context. The findings also pose problems for models according to which phonological context but not graphic context can influence the choice among spelling options. Models that behave in this manner, including the best-developed computational model of the spelling process to date, need to be modified so as to take graphic context into account.

Keywords: spelling, phoneme-to-grapheme correspondences, context, phonology, graphotactics

Spelling is difficult, more difficult than reading (Bosman & Van Orden, 1997). One source of difficulty, for English and a number of other alphabetic writing systems, is that some sounds have more than one possible spelling. For example, the spellings of the phoneme /f/ in English include ‹f› as in ‹deaf›, ‹ff› as in ‹stiff›, and ‹ph› as in ‹graph›. Theories of the spelling process propose different accounts of how people choose among alternative spellings of phonemes. In the present study, we examined adults' spellings of final consonants in nonwords as a way of adjudicating among the theories.

According to some views of the spelling process, the links between phonemes and spellings that people use when spelling nonwords or unfamiliar words are weighted by the frequency of occurrence of each correspondence in the vocabulary of the language as a whole but not by the context in which the phoneme appears (Barry & Seymour, 1988; Martin & Barry, 2012). Thus, writers of English generally spell /f/ using the letter that most commonly represents this phoneme across the words of the language, ‹f›. The ‹ff› and ‹ph› options, being less common, are less likely to be chosen. Some evidence is consistent with this view, including the finding that university students are more likely to produce high-frequency spellings than low-frequency spellings when spelling vowels in novel items (Barry & Seymour, 1988; Martin & Barry, 2012; see also Kreiner & Gough, 1990).

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A different view is that the spelling alternatives for a phoneme do not necessarily have the same weightings in all contexts. Rather, the weights may vary depending on the position within the syllable in which the phoneme occurs, the identity of the surrounding segments, and other factors (Goodman & Caramazza, 1986; Sanders & Caramazza, 1990; see Treiman & Kessler, 2014, for discussion). In some contexts, therefore, people may use a spelling that is less common in the vocabulary as a whole rather than one that is more common. Consider American English /ɑ/, which is often spelled ‹o›, as in ‹pond›, but sometimes ‹a›, as in ‹wand›. The university students tested by Treiman, Kessler, and Bick (2002) preferred the spelling that was less common overall, ‹a›, when spelling nonwords such as /skwɑnz/, in which /ɑ/ followed /w/. When the vowel followed other consonants, participants tended to spell it as ‹o›. Such results suggest that people learn about and use contextually based patterns in the vocabulary to which they are exposed, including the fact that /ɑ/ is more likely to be spelled with ‹a› when it follows /w/, such as ‹quash› and ‹wand›, than when it follows another consonant, such as ‹posh› and ‹pond›.

A computational model that can account for effects of phonological context was proposed by Houghton and Zorzi (2003). This is a dual-route model, like that of Barry and colleagues (Barry & Seymour, 1988; Martin & Barry, 2012). That is, it includes a phonological route, which maps between phonemes and graphemes, and a lexical route, which involves retrieval of whole-word spellings. The phonological route of the Houghton and Zorzi model differs from that proposed by Barry and colleagues, however, in that it learns about links from phonemes to graphemes based on training with a corpus of words. To allow for this, the phonological route is implemented as a two-layer associative network. The Houghton and Zorzi model being restricted to mono-

syllabic words, inputs are represented in terms of phonemes in seven positions within the syllable. Outputs are represented in terms of graphemes in corresponding positions. An individual grapheme in the model may represent a letter or a multiple-letter sequence such as ‹ph›. When a word is presented for training, activation flows from the input units to the output units. The resulting pattern of activation of the output units is compared with the correct string of graphemes, and the weights in the model are adjusted accordingly. Training continues until the model shows little or no improvement on the words in its training set. Once training has been completed, the model is tested by presenting it with inputs on which it was not trained. The model produces output using the weights that it acquired during training. Because all input units are connected to all output units, the spelling that is chosen for any particular slot is a function of all of the phonemes in the syllable. The network's choice among alternative spellings of a certain phoneme may thus depend on other phonemes. Indeed, Houghton and Zorzi reported that their model accounted rather well for the context effects on vowel spelling that were found by Treiman et al. (2002) and for a number of other results.

One issue that has been largely ignored by modelers and experimenters concerns the nature of context effects. It has typically been assumed that the effects are phonological: that spellers favor one spelling of a phoneme when it occurs before or after certain phonemes and another spelling of the same phoneme when it occurs before or after other phonemes (Juul, 2005; Treiman et al., 2002). This is what is directly modeled in the Houghton and Zorzi (2003) network. However, it is also possible that some context effects are graphic in nature. The difference between the two possibilities may be seen in the case of consonant extension, the spelling pattern investigated in the present study. Some final consonants in English have a simpler spelling, such as ‹f› for /f/ and ‹k› for /k/, and also an extended spelling that contains an additional letter, such as ‹ff› for /f/ and ‹ck› for /k/. Spellers may select between these options on the basis of the properties of the preceding vowel phoneme, using the extended spelling when the preceding vowel is what is traditionally called *short* (/æ/, /ɛ/, /ɪ/, /ɑ/, /ʌ/, or /ʊ/ for American English, what phonologists call *lax* vowels) and the simple spelling when the vowel is what is traditionally called a *long* vowel or diphthong (what phonologists call *tense* vowels). Indeed, this pattern reflects how monosyllabic words are often spelled in English. Alternatively, we might explain spellers' behavior by postulating that they following another pattern of English: one that specifies an extended final consonant if the preceding vowel is spelled with a single letter. If the preceding vowel is spelled with two or more letters (e.g., ‹ai› as in ‹tail› or ‹a› together with final ‹e›, as in ‹tale›), the final consonant tends to have its simple spelling. This graphic explanation is difficult to distinguish from the phonological explanation because English speakers often spell short vowels with single vowel letters (as in ‹tell›) and long vowels and diphthongs in monosyllabic words with two or more letters (as in ‹tail› and ‹tale›). In many cases, therefore, use of phonological context and use of graphic context yield the same result.

Hayes, Treiman, and Kessler (2006) found that adults' use of final consonant extension was influenced by context, but they did not report analyses attempting to disentangle graphic and phonological context. This was because the adult participants in their study, who attended a university where students are generally very good spellers, showed a high rate of single-letter spellings for short vowels and a high rate of spellings with more than one letter for long vowels. This made it difficult to determine whether their choice of extended versus simple consonant spelling was more influenced by graphic context or phonological context. Hayes et al. did conduct such analysis for the second-grade children (7 and 8 years old) in their study, finding that children's use of consonant extension was better explained by the number of letters that children used to spell the vowel than by whether the vowel was phonologically short or long.

In the present study, we addressed the question of whether adults' use of extended consonants was influenced by context and whether it was better explained by the phonological properties of the preceding vowel or by the participants' spelling of that vowel. We also asked whether there were differences in participants' use of context for different final consonants. If so, did these reflect differences in the strengths of the contextual effects for these consonants in the English vocabulary? To address these questions, we tested students from a population that was expected to be average in spelling ability rather than students from a population that was expected to be above average, as in the study by Hayes et al. (2006). We expected our participants to produce a variety of vowel spellings, including some two-letter spellings of short vowels and some single-letter spellings of long vowels and diphthongs. This should allow us to determine whether consonant extension is more closely associated with the spelling of the vowel or with whether the vowel is phonologically short. To further help tease apart graphic and phonological context, we used approximately twice as many items with the critical final consonants as in the study by Hayes et al.

Method

Stimuli

We constructed pairs of monosyllabic nonwords that ended with a vowel phoneme followed by /f/, /k/, /l/, or /t͡ʃ/. The nonwords in each pair differed only in that one had a short vowel and the other had a long vowel or diphthong. As the appendix shows, there were 10 pairs for each of /f/, /l/, and /t͡ʃ/ and nine pairs for /k/. (An error was made with one pair that was intended for the /k/ category, and the results on that pair were not included in the analyses.) The stimuli also included 100 monosyllabic nonwords that differed from the experimental items in that their codas (final consonant or clusters) were different from those of the experimental items or in that they ended with vowels. The inclusion of these filler items decreased the repetitiveness of the list. We avoided items with phonologically illegal or uncommon sequences. Three different orders were prepared for purposes of presentation. In each order, the experimental and filler items were randomly intermixed with the constraint that no more than two consecutive items had the same onset, vowel, or coda. Approximately one third of the participants received each order.

Procedure

Participants were tested individually or in pairs. To characterize participants' spelling ability, we administered the spelling subtest of the third edition of the Wide Range Achievement Test (WRAT;

Wilkinson, 1993) at the beginning of the session. Participants were then told that they would be asked to spell a series of "made-up words." They were asked to pretend that these were ordinary, everyday words of English and to spell each item the way they thought it would be spelled if it were a real word. The experimenter pronounced each item and the participants repeated it. When two participants were tested as a group, the experimenter asked one participant and then the other to repeat the item. If a participant did not pronounce an item correctly, the experimenter said it again. The participants then spelled the item on prepared answer sheets.

Participants

The participants were 24 students at Wayne State University in Detroit, Michigan. They were native speakers of English who reported no history of speech, hearing, or reading disorders. They participated as volunteers or in exchange for extra credit in a psychology course. The participants scored close to national norms on the spelling subtest of the WRAT, with a mean standardized score of 103.5 ($SD = 5.6$; range 89–116).

Results

We scored the spellings of experimental items for whether they ended with the appropriate extended spelling of the consonant (‹ff›, ‹ck›, ‹ll›, and ‹tch› for /f/, /k/, /l/, and /t͡ʃ/, respectively) or the appropriate simple spelling (‹f›, ‹k›, ‹l›, and ‹ch› for /f/, /k/, /l/, and /t͡ʃ/, respectively), potentially followed by ‹e›. The 5% of spellings that did not fit either pattern were not included in subsequent analyses. For example, the spelling of the final /f/ in ‹wough› for /wʌf/ does not have an extended counterpart, and this response was excluded from subsequent analyses for this reason. For each experimental item, we also scored whether the vowel was spelled with one letter or more than one letter. Table 1 shows the number of spellings with simple and extended final consonants as a function of whether the vowel was phonologically long or short and whether the vowel was spelled with a single letter or more than one letter. These data suggest that participants' decisions about whether to double the final consonant were influenced by context and that it was the number of letters the participant used to spell the preceding vowel that was the major determinant of this decision.

To permit direct comparison between participants' use of phonological and graphic context, we scored each spelling for its conformity to the phonological rule and the graphic rule for vowel extension. A spelling was considered to fit the phonological rule if the spelling of the rime included the appropriate extended spelling of the consonant, if the vowel was phonologically short, or the appropriate simple consonant, if the vowel was long. A spelling was scored as conforming to the graphic rule if it contained the appropriate extended consonant and just one other letter in the spelling of the rime, or if it contained the appropriate simple consonant and more than one other letter in the rime spelling. Table 2 shows some examples of the scoring.

As Table 3 shows, the proportion of responses that fit the graphic rule was higher than the proportion of responses that fit the phonological rule for all four consonants. To determine whether the difference between the two types of rules was statistically significant, we conducted a multilevel analysis with data at the trial level using random intercepts for participants and item pairs and the fixed factor rule type. A logit link function was used because the dependent variable, adherence to a rule, was binary. The effect of rule type was significant ($\beta = 0.48$, $SE = 0.08$, $p < .001$). The proportion of responses that fit the graphic rule was higher than the proportion of responses that fit the phonological rule for 21 of the 24 participants. One participant showed a tie and two showed the opposite pattern. Responses to 32 of the item pairs were better fit by the graphic rule than the phonological rule, four pairs showed a tie, and three pairs showed the opposite pattern.

In a final set of analyses, we asked whether participants followed the graphic rule more often for those consonants that, in the words of English, show greater conformity to the graphic rule than for those consonants that show lesser conformity. To assess the strength of the rule for each consonant, we examined the monosyllabic English words that ended with each of the single consonant phonemes from the experiment. We included in this analysis all words that fit the criteria from the Carnegie Mellon University (1998) pronouncing dictionary; Celex (Centre for Lexical Information, 1987); Zeno, Ivens, Millard, and Duvvuri (1995); and the words that Houghton and Zorzi (2003) used when training their model. We edited the list to conform to Midwest American pronunciation, and we omitted purely dialectical and obsolete words and words that are always capitalized. We also omitted words with the vowel /ɚ/; these differ from words used in the experiment in that their spelling invariably includes the consonant letter ‹r› (e.g., ‹turf›). The left column of data in Table 4 shows, for each consonant, the proportion of words in the corpus that fit the graphic rule, weighting each word by the natural logarithm of two plus the frequency of the word given in Zeno et al. As in the analyses of participants' spellings, words that did not end with the extended or simple spelling of the consonant, such as

Table 1
Use of Simple and Extended Spellings of Final Consonant as a Function of Phonological Quality of Preceding Vowel and Participant's Spelling of Vowel

Phonological quality of vowel	Number of letters in vowel spelling	Simple (*n*)	Extended (*n*)	Proportion extended
Short	One	142	606	.81
	More than one	120	23	.16
Long	One	51	79	.61
	More than one	681	83	.11

Table 2
Examples of Scoring of Spellings for Conformity to Graphic Rule and Phonological Rule for Consonant Extension

Pronunciation	Spelling	Fits graphic rule	Fits phonological rule
splif	spleaf	Yes	Yes
hɪf	hiff	Yes	Yes
dɹif	driff	Yes	No
splif	splef	No	Yes
dɹɛl	dreil	Yes	No
fɹuk	froock	No	No

Table 4
Proportion of Words That Fit Graphic Rule in Corpus Analysis and in Participants' Responses

Final consonant	Corpus	Participants
f	.92	.82
k	.99	.83
l	.95	.91
t͡ʃ	.87	.77
Overall	.93	.83

‹plaque›, were not included in the calculations. The results in Table 4 show that the graphic pattern is less reliable for /t͡ʃ/ than the other consonants. This reflects the fact that several common words with final /t͡ʃ/, including ‹such› and ‹which›, deviate from the pattern. The right column of data in Table 4 shows the proportion of participants' responses for each consonant that fit the graphic rule. Mirroring the lesser strength of the rule for /t͡ʃ/ than for the other consonants in the English vocabulary, participants followed the graphic rule less often for /t͡ʃ/. A mixed-model analysis using random intercepts for participants and item pairs and the fixed factor consonant showed that the proportion of responses that fit the graphic rule was significantly lower for /t͡ʃ/ than for each of the other consonants ($\beta = 0.37$, $SE = 0.17$, $p = .03$ for the difference between /t͡ʃ/ and /f/; $\beta = 0.46$, $SE = 0.18$, $p = .01$ for the difference between /t͡ʃ/ and /k/; $\beta = 1.12$, $SE = 0.20$, $p < .001$ for the difference between /t͡ʃ/ and /l/).

Discussion

The present study examined the spelling of certain final consonants in English as a way of investigating adults' use of context to select between spelling options. We found that adults' choices between simple (e.g., ‹f›) and extended (e.g., ‹ff›) spellings are influenced by the context in which the consonant occurs, extending the finding of Hayes et al. (2006) to a group of adults who tested as average spellers. This finding poses problems for models of nonword spelling in which people use the spelling options for a phoneme in line with their frequencies in the vocabulary as a whole but are not influenced by the context in which the phoneme appears (Barry & Seymour, 1988; Martin & Barry, 2012). Such models cannot explain the finding that, in some situations, people favor extended spellings such as ‹ff›, which are generally uncommon. Our findings are also problematic for models in which spelling options are weighted for each of the initial, medial, and final positions of the syllable but, within a position, do not vary as a function of the neighboring segments (Goodman & Caramazza, 1986; Sanders & Caramazza, 1990). Although the frequency of a correspondence in general and in a particular position of a syllable may influence people's tendency to use it, the surrounding context is also important.

Table 3
Mean (Standard Deviation) Proportion of Spellings That Fit Graphic Rule and Phonological Rule

Final consonant	Graphic rule	Phonological rule
f	.82 (.17)	.75 (.20)
k	.83 (.12)	.79 (.13)
l	.91 (.11)	.79 (.18)
t͡ʃ	.77 (.16)	.72 (.12)
Overall	.83 (.08)	.76 (.09)

Our results further show that context effects on final consonant extension are better described as graphic effects than as phonological effects. That is, university students' decisions about whether to use an extended spelling of a final consonant are influenced by the spelling that they select for the preceding vowel. The choice of spellings for the vowel considers the vowel's phonological identity, but having chosen a particular spelling for the vowel, people select a spelling of the final consonant in a way that allows them to avoid rimes such as ‹aick› and ‹uk› that are graphotactically odd. Hayes et al. (2006), in the only previous attempt to tease apart the roles of phonological and graphic context, found a similar result for 7- to 8-year-old children. Use of graphic context to make decisions about consonant extension thus appears to be an early developing and long-lasting feature of spelling production.

Our final question was whether people show differences among the tested consonants in context use and whether these differences mirror patterns in the English vocabulary. We found, as Hayes et al. (2006) also reported for a somewhat different sample of words, that the effects of graphic context are less reliable for /t͡ʃ/ than for the other consonants in the words of English. Correspondingly, our adult spellers followed the graphic rule less often for /t͡ʃ/. This result suggests that spellers internalize the patterns in the vocabulary to which they are exposed, learning both about patterns that apply to sets of consonants and patterns that apply to individual consonants.

Our finding that skilled spellers use graphic context poses problems for the model of Houghton and Zorzi (2003), the best-developed computational model to date of the processes involved in spelling. Although the phonological route of this model can account for effects of phonological context, it cannot in principle account for effects of graphic context. This is because this route is based entirely on mappings from phonemes in various slots to graphemes in the analogous output slots that were acquired during the training phase. The model uses the learned mappings when tested on novel items, and so there is no meaningful sense in which an output spelling in one slot could have any effect on an output spelling in another slot. Moreover, the Houghton and Zorzi model does not have a notion of which graphemes contain one letter and which contain more than one letter because it treats graphemes as

unanalyzed units. To verify these ideas and to examine their effects on the performance of the model, we built a version of the phonological route and trained it using the same set of words used by Houghton and Zorzi, with the same parameters. After confirming that the model worked as expected, we modified the model and the training set to make it appropriate for General American English. To do this, we adjusted the network to take account of the fact that /ɹ/ can occur in the coda in General American English, and we modified the training set to cope with differences in vocabulary between General American English and British English. Also, we placed a greater emphasis on familiarity in the choice of training items: If the university students tested by Nusbaum, Pisoni, and Davis (1984) rated a word's familiarity at 4 (the meaning is unknown) or lower, it was dropped; if above 4, it was added. The training corpus for the Americanized version of the model was similar in size to the training corpus used by Houghton and Zorzi: 3,156 words as compared to 3,160.

As a first test of the Americanized model, we examined its spellings of the words on which it was trained. On words with the final consonants of interest here, the model produced 83 spellings that obeyed the phonological rule but not the graphic rule, including ‹cof› for ‹cough›, ‹scal› for ‹scale›, ‹hol› for ‹whole›, ‹wak› for ‹walk›, and ‹poch› for ‹poach›. These errors on words in the training corpus could have been avoided if the model were sensitive to graphic effects on consonant extension. The model produced only four errors that obeyed the graphic rule but not the phonological one (three of these involved the vowel /ʊ/, which English orthography often treats as the long vowel /u/ as in ‹book›). We then examined the model's spellings of the nonwords that were used in the present experiment. We found a similar pattern, with the model producing three responses (e.g., ‹dral› for /drel/) that obeyed the phonological rule but not the graphic one and no responses that did the opposite. The participants in our experiment showed a different pattern, in that they were more likely to follow the graphic rule than the phonological rule. Thus, although the Houghton and Zorzi (2003) model accounts for much data on human spelling performance, it fails to account for people's use of graphic context to make decisions about consonant extension.

The Houghton and Zorzi (2003) model would need substantial modification to allow it to explain the present data. One possibility would be for the phonological route to include a feedback loop that allows the spellings of phonemes to serve as input, together with the phonemes themselves. This could potentially allow the model to learn that the choice of spellings for certain phonemes is influenced by the grapheme that is chosen for another phoneme. Another possibility would be to add a step to the process by which the model produces a spelling for a novel input. At this step, a potential output would be checked for its conformity to graphotactic patterns. A string such as ‹draf› would fare poorly on such a check, lowering its activation and potentially allowing an alternative such as ‹draff› to come to the fore. Such an approach would require a model of the learning of graphotactic patterns as well as a procedure for integrating a graphic-checking process into the model. It is also possible, within a dual-route framework, that the spelling of a nonword sometimes involves the lexical route as well as the phonological route (e.g., Patterson & Folk, 2014). That is, the presentation of a nonword may activate the phonological and orthographic representations of similar-sounding words, and the effects observed in our experiment might reflect that activation. To implement this idea, one would need to specify how similarity is defined and how choices are made when the spellings activated by the lexical route include different graphemes from those activated by the phonological route. Single-route connectionist models of spelling are another possibility, but only a small amount of work has been done with such models (Brown & Loosemore, 1994; Olson & Caramazza, 1994). It is beyond the scope of the present study to implement a new computational model of spelling. Any model would need to be thoroughly tested to ensure that it accounts for the data that the Houghton and Zorzi (2003) model can explain as well as for the present data. Clearly, however, further work is needed to develop computational models that can explain the effects of graphic context on human spelling performance.

In the present study, we used final consonant extension in English as a test case to show that skilled spellers are influenced by patterns that can only be described graphically. Our findings show that people have a sense of what a word should look like, tending, for example, to avoid ending sequences like ‹eaff› because they contain too many letters. The results of the present study are consistent with other recent evidence that knowledge and use of graphic patterns are important aspects of spelling performance across languages (e.g., Carrillo & Alegría, 2014; Pacton, Borchardt, Treiman, Lété, & Fayol, 2014; Pacton, Fayol, & Perruchet, 2005; Samara & Caravolas, 2014). Models of the spelling process have concentrated on phonology, but it is time to extend the models to incorporate graphic knowledge.

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Appendix

Experimental Stimuli

/f/

Short vowel: dɹʌf, kɹɪf, wʌf, hɪf, splɪf, gʌf, kɪf, swʌf, nɪf, jʌf

Long vowel or diphthong: dɹif, kɹif, wif, hif, splif, gaɪf, kaɪf, swaɪf, nuf, juf

/k/

Short vowel: glɛk, nʌk, swɪk, dæk, jɑk, pɹɛk, flʌk, ʃɹæk, fɹæk (the experiment was conducted before this term was in common use to refer to hydraulic fracturing)

Long vowel or diphthong: glik, nik, swik, dek, jek, pɹok, flok, ʃɹaɪk, fɹuk

/l/

Short vowel: dɹɛl, kɹɛl, zɪl, fɹʌl, gɛl, dɹʌl, stʌl, θɪl, zɛl, stɹɪl

Long vowel or diphthong: dɹel, kɹel, zel, fɹil, gil, dɹɔɪl, stɔɪl, θul, zaɪl, stɹil

/t͡ʃ/

Short vowel: dæt͡ʃ, dræt͡ʃ, fæt͡ʃ, gæt͡ʃ, hɑt͡ʃ, jɑt͡ʃ, klɛt͡ʃ, lɑt͡ʃ, mɛt͡ʃ, sɛt͡ʃ

Long vowel or diphthong: daut͡ʃ, drit͡ʃ, fit͡ʃ, got͡ʃ, haut͡ʃ, jaut͡ʃ, klit͡ʃ, lot͡ʃ, mit͡ʃ, sit͡ʃ

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