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Context sensitivity in the spelling of English vowels

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Abstract

Statistical analyses of English sound-to-spelling correspondences (Kessler & Treiman, 2001) show that vowel spellings become more predictable, in some cases, when the preceding and following consonants are taken into account. In four experiments, we asked whether adult spellers are sensitive to such associations. We found evidence for sensitivity to associations involving both preceding and following consonants when examining adults' spellings of vowels in nonwords (Experiments 1 and 2) and their substitution errors on vowels in real words (Experiment 3). The results show that phoneme-to-grapheme mapping is sensitive to a broader array of context than just rime context. Additional findings suggest that the context must be within the same syllable to be influential (Experiment 4). To the extent that rimes play a special role in spelling, this role may derive from the fact that associations between vowels and codas are more common in English than associations between vowels and onsets, not from spellers' greater sensitivity to within-rime associations.

Keywords: spelling, sound-to-spelling correspondence, vowels, syllables, rimes

To be literate, one must know how to read words and how to spell them. There has been a great deal of research on how adults derive the pronunciations of written words in reading. This topic is of particular interest because people who are literate in an alphabetic writing system can pronounce not only words they have seen before but also words they encounter for the first time. For instance, a reader who has never seen the word glebe will probably pronounce it, correctly, as /glib/. This ability shows that knowledge about the spelling-to-sound relationships of the language is represented, in some way, in the mind of the reader. Researchers have studied the nature of this knowledge by examining people's pronunciations of nonwords (e.g., Andrews & Scarratt, 1998). They have also examined mispronunciations of real words to gain further insight into the processes used in spelling-to-sound translation. For example, the fact that great is occasionally mispronounced as /gɹit/ in speeded pronunciation tasks has been interpreted to mean that readers use their knowledge of the most common pronunciation of ea, /i/ (e.g., Glushko, 1979).

Our abilities in spelling are no less impressive than our abilities in reading. A person who has heard a piece of land referred to as a glebe but who has never seen the word in print might spell it as glebe, gleeb, or gleab. Only one of these options is correct, but all three of them reveal the speller's knowledge about the sound-to-letter mappings of English. Although many studies have investigated adults' knowledge and use of spelling-to-sound relationships in English and other alphabetic writing systems, relatively few studies have investigated sound-to-spelling translation. Likewise, there is much less modeling work on spelling than on reading. The goal of the present study was to gain further information about adults' knowledge of English sound-to-spelling relationships, information that can help constrain models of the spelling process and provide a foundation for studies of how this knowledge is acquired.

Of particular interest, in this study, is the spelling of vowels. In English, the spellings of vowel phonemes are more variable than the spellings of consonants (e.g., Kessler & Treiman, 2001). Likewise, adults make more substitution errors on vowels than on consonants (e.g., Fischer, Shankweiler, & Liberman, 1985). We ask how knowledge of sound-spelling relationships is represented for vowels and whether adults use information about the neighboring consonants to facilitate their spelling of vowels. Does consonantal context influence the spelling of vowels? If so, which aspects of the context are important?

Studies that have shown a special bond between the vowel and the following consonant(s) of an English syllable provide a tentative answer to the question of which aspects of context may influence vowel spelling. The link between a vowel and the following consonant is often formalized by saying that the vowel and the consonant (or coda) belong to the rime constituent of the syllable (e.g., Fudge, 1969). The initial consonant or cluster is thought to belong to a separate constituent of the syllable, the onset. Evidence for an onset-rime division of the English syllable comes from several sources. For example, English speakers prefer to divide syllables at the onset-rime boundary in metalinguistic tasks (e.g., Treiman, 1983), and these units play a role in memory for speech (e.g., Treiman & Danis, 1988a) and phonological organization (e.g., Kessler & Treiman, 1997). Also, people appear to use letter groups that correspond to the rimes of spoken syllables when translating from print to speech. A number of studies have found evidence that these units are influential in reading, together with evidence that onset + vowel sequences are less influential (e.g., Taraban & McClelland, 1987; Treiman, Mullennix, Bijeljac-Babic, & Richmond-Welty, 1995; Treiman & Zukowski, 1988). Rime units play a role in several theories of printed word recognition (e.g., Zorzi, Houghton, & Butterworth, 1998). Given the importance of rimes in phonological processing and reading, one might expect them to play a

special role in spelling. In this view, a given vowel may be spelled differently when it occurs before certain codas than when it occurs before other codas. The preceding consonant should not have an effect, as it belongs to a separate constituent of the syllable. According to this rime constituency hypothesis, people weigh the spelling options for a given phoneme according to the rime context in which the phoneme appears.

Treiman and Zukowski (1988) found evidence for the rime constituency hypothesis in a series of experiments with college students. In one study, participants were asked to spell nonwords such as /tʃɛnd/ and /fɹɛθ/. Of interest was how often people used the ie spelling of /ɛ/, which is found only in the real word friend. Spellings with ie were more common for nonwords such as /tʃɛnd/, which shares its rime with friend, than for nonwords such as /fɹɛθ/, which shares its onset and vowel with friend. In another study, participants rated chiend as a reasonably good spelling of /tʃɛnd/, giving it higher marks than frieth as a spelling of /fɹɛθ/. These results suggest that the spelling of a medial vowel is affected by the identity of the coda but not by the identity of the onset, and that rimes play a special role in the spelling of English. However, the effects observed in this study were relatively small.

Barry and Seymour (1988), unlike Treiman and Zukowski (1988), did not find evidence for a special role of rimes in spelling production. Barry and Seymour looked at nonwords such as /ten/, for which the most common spelling of the vowel in the nonword's rime (ai) is not the most common spelling of the vowel overall (a followed by final e). They compared such items to nonwords such as /dʊt/, for which the most common spelling of the vowel in the particular rime (oo) is also the most common spelling overall. In both cases, participants tended to produce the vowel spelling that was most common in the lexicon as a whole. There was no significant difference between the two types of nonwords in this regard, although there was a trend in the

direction of a rime effect. Barry and Seymour (p. 26) concluded, on the basis of these results, that "subjects … utilize sound-to-spelling contingencies abstracted from the lexicon as a whole rather than only from the subset of rhyming words to generate their nonword spellings." That is, people store and use information about the frequencies of various spelling options for each phoneme; these frequencies are global (reflecting how the phoneme is spelled in all rimes) rather than local (reflecting how the phoneme is spelled in particular rimes). However, the analysis that led to this conclusion was post hoc and involved a fairly small number of items.

Perry, Ziegler, and Coltheart (in press) seconded the idea that spelling production involves primarily phoneme units, not rime-based units. These investigators designed a series of experiments to investigate the effects of rime context in spelling. Some of the nonwords in the experiments were similar to those analyzed by Barry and Seymour (1988) in that one of the phonemes in the rime was generally spelled one way in that particular rime but a different way in the lexicon as a whole. An example from the Perry et al. study is /skof/, where /o/ is usually spelled as o followed by final e but is more often spelled as oa in /of/. For another type of nonword, also similar to a type analyzed by Barry and Seymour, the most common spelling of the grapheme in the particular rime was the most common spelling overall. An example is /plem/, where a followed by final e is the most common overall spelling of /e/ and also its most common spelling in /em/. Perry et al. included a third type of nonword for which the rime had two spellings that were roughly equal in frequency but one spelling of the critical phoneme was more common overall than the other. With /tʃɪn/, for example, -ean and -een are roughly similar in frequency but ea is the most common spelling of /i/ in all rimes.

In one experiment, Perry et al. (in press) asked participants to spell the nonwords using the first reasonable spelling that came to mind. This spelling production task is similar to that of

Barry and Seymour (1988). Participants in this experiment generally used the most common overall spelling for the phoneme. This tendency was only weakly modified by the frequency of the phoneme's spelling in the particular rime, in that the difference among the three types of nonwords was significant by subjects but not by items. Perry et al. interpreted their results to mean that adults generally use correspondences at the level of single phonemes and single graphemes in spelling production. These correspondences do not take rime context into account. Perry et al. found clear evidence for use of rimes in other tasks, such as judging which of two spellings was more word-like. However, their conclusion with regard to spelling production was that "in general, people use phoneme-grapheme sized relationships when spelling nonwords" (p. XX).

So far, then, the results concerning the rime constituency hypothesis are mixed. One study of adults' spelling production (Treiman & Zukowski, 1988) found evidence for this hypothesis but two studies (Barry & Seymour, 1988; Perry et al., in press) did not. Results on this issue have important implications for models of spelling. One approach is a dual-route view (e.g., Barry & Seymour, 1988; Kreiner & Gough, 1990). In this view, lexical knowledge and non-lexical knowledge provide two different routes to spelling. Within this framework, it is important to determine whether the non-lexical route is best characterized in terms of associations between individual phonemes and individual graphemes that are not affected by the phoneme's context or in terms of associations that involve larger units and/or that are sensitive to context. Single-route models, based on connectionist principles, provide another potential way to model spelling production (e.g., Olson & Caramazza, 1994). Depending on their structure, such models can handle various types of contextual effects. Behavioral data on whether context

effects occur and whether rime context is particularly important will provide essential information for the development of spelling models.

An understanding of context effects in adult spelling production should have important implications, as well, for our understanding of how children learn to cope with the English writing system. The system is complex, and simple phoneme-to-grapheme rules often yield incorrect spellings. This is especially true for vowels, which cause particular difficulty for English learners (e.g., Treiman, 1993). If adults attempt to cope with the variability of vowel spelling by learning how vowels are spelled in particular environments, when and how does this ability develop? Some researchers (e.g., Goswami, 1988) have suggested that children use rime units from an early age, whereas others (e.g., Frith, 1985) claim that larger units are used only later in development. Information about adults' spelling production provides a foundation for studies of children.

Rimes may play a special role in English spelling and reading because of their status as phonological units. Alternatively, or in addition, the nature of the English writing system may make rimes particularly useful. Evidence on this issue comes from Kessler and Treiman (2001), who analyzed the sound-spelling relationships in virtually all of the monosyllabic, monomorphemic words of English that are familiar to college students. They asked whether the spelling of a phoneme in one position of the syllable -- onset, vowel, or coda -- is significantly affected by the other constituents of the syllable. The results showed that sound-to-letter relations are more variable for vowels than for consonants. However, the coda has a strong and significant influence on the spelling of the vowel, with almost all English vowels showing some associations of this kind. For example, /ɛ/ is more likely to be spelled as <u>ea</u> when followed by /d/ than when followed by other consonants. If spellers take advantage of such associations, vowel

spelling becomes more predictable than it would otherwise be, though by no means perfectly regular. Kessler and Treiman found that the onset has a reliable influence on vowel spelling as well. However, the effect of the onset on the vowel is weaker overall than the effect of the coda on the vowel, and onset effects are only found in some cases.

The results of Kessler and Treiman (2001) document the patterns of sound-to-spelling association in English monosyllabic words, showing what patterns are available for use. In the present study, we ask whether spellers take advantage of these statistical patterns. Coda-to-vowel associations were examined in Experiment 1. When spelling medial vowels in nonwords, do college students take account of the coda in those cases for which Kessler and Treiman found a significant association between vowel and coda? According to the rime constituency hypothesis, the answer to the question should be "yes." Experiment 2 addressed a similar question for onset-to-vowel associations. If rimes play a special role in spelling, as the rime constituency hypothesis claims, then spellers may not be sensitive to associations that cross the onset-rime boundary. Experiment 3 extended the investigation to real words, and Experiment 4 was designed to shed further light on the linguistic domain over which context has its effects.

Experiment 1

In this experiment, we asked whether adults' spellings of medial vowels in nonwords are affected by the identity of the coda. Is the same vowel transcribed differently when it occurs in certain contexts -- those for which Kessler and Treiman (2001) documented a significant coda-to-vowel association -- than when it occurs in other contexts? Such differences are expected according to the rime constituency hypothesis. Six cases of coda conditioning were chosen for study. We selected cases in which spelling variations reflect the identity of the coda (e.g., <u>head</u> vs. <u>hem</u>) rather than the presence versus absence of a coda (e.g., <u>date</u> vs. <u>day</u>).

Table 1 provides information about the six cases that we investigated. In each case, we identified two contrasting environments such that a particular spelling of a vowel, henceforth called the critical spelling, occurs more often in one case than the other. Consider Case 1, which involves the vowel /ɛ/. The critical spelling of this vowel, ea, is found more often when /ɛ/ is followed by /d/ -- the experimental context -- than when /ɛ/ is followed by /b/, /dʒ/, /g/, /k/, /p/, and /tʃ/ -- the control context. In the experimental context, as Table 1 shows, /ɛ/ is spelled as ea in 43% of the familiar monosyllabic, monomorphemic words studied by Kessler and Treiman (2001). The control context was defined so as to minimize the number of critical spellings, and in this context /ɛ/ is never spelled as ea in the monosyllabic words analyzed by Kessler and Treiman. Given the patterns in English monosyllabic words, there is thus a clear difference between how /ɛ/ is spelled in the experimental context and the control context. Experiment 1 was designed to determine whether adult spellers are sensitive to this statistical difference.

Kessler and Treiman's (2001) analysis of sound-spelling relationships was limited to monosyllabic words. All of the nonwords in the present experiment are monosyllabic, but knowledge derived from experience with polysyllabic words might affect people's spelling of monosyllables. To determine whether the statistics are similar when a larger sample of words is examined, we examined the spelling of each vowel phoneme under investigation in a larger sample of familiar words that included the final syllables of polysyllables as well as monosyllables. This and the other reported counts that include polysyllables are based on the words in two machine-readable dictionaries (Ward, 1993; Weide, 1995); we eliminated words that are likely to be unknown to our student population and we counted each morpheme once, even if it appeared in more than one word. As Table 1 shows, the percentage of ea spellings in

the experimental context in the larger set was 40%, similar to the 43% obtained for monosyllabic words. In the larger set, again, /ɛ/ is never spelled as ea in the control context.

Once the experimental and control contexts were defined, we constructed one set of monosyllabic nonwords in which /ɛ/ appeared in the experimental context and a matched set of monosyllabic nonwords in which /ɛ/ appeared in the control context. Sample items are shown in Table 1. According to the rime constituency hypothesis, spellers should be more likely to use ea in the experimental nonwords than the control nonwords.

The logic was similar for the other five cases. The vowel in Case 2 was /i/. The most common spelling of this vowel in medial position is ea, as in beam. In words that end with /d/ and /p/, however, ee as in reed and deep outnumbers ea. Before certain other consonants -- the control contexts listed in Table 1 -- the critical ee spelling is much less common. In Case 3, the vowel was /o/. In medial position, it is most often spelled with o followed by silent final e, as in bone. Before /l/, however, bare o as in toll and control is fairly common. Case 4 involved the vowel /ʊ/. When stressed, it is often spelled as u between a labial onset and the coda /l/, /s/, /ʃ/, or /tʃ/. Examples are full, puss, bush, and butch. Before /f/ and /k/, oo is the typical spelling, as in book and hoof. The vowel examined in Case 5 was /aʊ/. This vowel is usually spelled as ow before final /l/ and /n/, as in howl and clown. In the control contexts listed in Table 1, ou is the more common spelling. The final case was that of /aɪ/. Before /t/, igh as in bright and right is fairly common. In the control contexts, i followed by final e is more typical.

In most of the cases described above, multiple spellings for a single phoneme in present-day English result from a sound change that occurred after the English spelling system crystallized. For example, bread and bred were originally pronounced differently, as reflected in

the spellings. Later, a sound change in the former word caused the two words to be pronounced alike, but the spellings were not updated. Sound changes have not always occurred in the same ways in all parts of the English-speaking world, but for this and the following experiments we tried to select patterns that would apply to most dialects of English. In Case 5 (/aʊ/), the spelling variation does not reflect a sound change, but is related to the fact that /aʊ/ is typically spelled as ow in syllable-final position and ou elsewhere. For reasons that are unclear, the ow spelling also occurs in medial position before /l/ and /n/.

Method

Stimuli. We constructed 10 pairs of experimental and control nonwords for each of our six cases. The nonwords in each pair contained the same onset and the same vowel; they differed only in the coda. All of the nonwords were phonologically legal in English. Sample stimuli for each case are shown in Table 1. In addition to the 60 experimental and 60 control stimuli, there were 20 filler nonwords. The fillers included some vowel and consonant phonemes that did not appear in the experimental and control stimuli, and they had a wider range of syllable structures. The inclusion of the fillers increased the variety among the stimuli and decreased the repetitiveness of the list. A complete list of the stimuli appears in the Appendix.

Three different orders were prepared for purposes of presentation. In each order, the experimental items, control items, and fillers were randomly intermixed with the constraint that no more than two consecutive items had the same onset, vowel, or coda.

Procedure. The participants were tested individually or in small groups. Each individual or group was quasi-randomly assigned to one of the three orders. The participants were 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 it if were a real word. This instruction was designed to counteract any tendency people may have to assume that unfamiliar words are foreign and should therefore be spelled with atypical patterns. The experimenter pronounced each item and the participants repeated it. If a participant did not repeat an item correctly, the experimenter said it again and the participant was asked to say it again. The participants then spelled the item on prepared answer sheets. A rest break was given halfway through the list.

Participants. For this and the following experiments, we tested students at Wayne State University who were native speakers of English and who reported no history of speech, hearing, or reading disorders. The students in this and the following studies participated as volunteers or in exchange for extra credit. Of the 26 such students tested for Experiment 1, data from four students were not analyzed because three or more of their spellings of the 20 filler items were not plausible renditions of the item's phonemic structure. Examples of these implausible spellings are zaspa for /væsp/ and swonith for /ʃɔɪn/. These students may have had unacknowledged spelling problems or may not have been paying full attention to the task. The latter is a potential problem given that Experiment 1, unlike the following experiments, was run at the end of a semester when students are likely to be tired and overworked. When scoring filler spellings as plausible or implausible for this and the following experiments, we considered spellings that were appropriate in any context to be plausible. For example, knith for /naɪð/ was considered plausible because /n/ is spelled as kn in some words and /aɪ/ is spelled with single i in some contexts. We accepted reasonable dialect-based variations. The 22 participants whose data were analyzed for Experiment 1 produced a mean of 0.82 implausible spellings of the 20 filler items.

Results and Discussion

Table 2 shows the mean number of critical spellings for the vowels in the experimental and control nonwords. For each vowel, we carried out t tests by subjects and by items to determine whether there were significantly more critical spellings for the experimental items than the control items. As Table 2 shows, the difference between experimental and control items was reliable by subjects for all cases. By items, the difference was significant for all but Case 4 (/ʊ/), where it was marginal. For each case, we also calculated the number of participants and the number of item pairs for which a difference in the predicted direction was found. These data, presented in Table 2, show substantial differences in the predicted direction for all but Case 4. Given that certain rimes were repeated across the experiment, we also examined participants' responses to the first occurrence of each rime. The proportion of critical vowel spellings was higher for the experimental items than the control items in all six cases, and the results were quite similar to those found in the analysis of all items. Thus, it appears that adults generally honor coda-to-vowel associations in their spelling.

The results of Experiment 1 concur with those of Treiman and Zukowski (1988) in showing that adults' spellings of vowels are affected by the identity of the following consonant. The results do not support the view that rimes play little or no role in spelling production and that the weights on phoneme-grapheme correspondences are derived from the lexicon as a whole (Barry & Seymour, 1988; Perry et al., in press). However, our results are consistent with those of Barry and Seymour and Perry et al. in showing that the grapheme option that is over-represented in a particular rime is not necessarily produced more often than the grapheme that typically spells the phoneme. With /aɪ/, for instance, people produced i plus final e spellings more often than igh spellings for words ending in /t/ as well as for other words. Although our results agree in this respect with those of Barry and Seymour and Perry et al., our results go beyond theirs in

showing that igh was produced significantly more often for /aɪt/ than for other rimes. Rime context plays a role in spelling production.

According to the rime constituency hypothesis, spellers use associations within the rime unit but do not go beyond the boundaries of the rime. The results of Treiman and Zukowski (1988) support this hypothesis, in that coda-to-vowel but not onset-to-vowel effects were found in that study. An alternative view is that adults are sensitive to the effects of onsets as well as codas on vowel spelling. The weak results for Case 4 of the present study could be taken to support this alternative explanation. This is because the critical oo spelling of Case 4 tends to occur in real words that have both a labial onset and a coda /l/, /s/, /ʃ/, or /tʃ/. Although all of our experimental items had one of these codas, most did not have a labial onset. That the results were weaker for Case 4 than for the other five cases could be taken to suggest that the onset as well as the coda contributes to the spelling of the vowel.

Experiment 2 used a design similar to that of Experiment 1 to determine whether adult spellers are sensitive to onset-to-vowel associations. According to the rime constituency hypothesis, spellers do not use onset-to-vowel associations even when they exist in the writing system because these associations involve phonemes from different constituents of the syllable.

Experiment 2

The purpose of Experiment 2 was to determine whether adults' spelling of vowels is systematically affected by the identity of the preceding consonant. Kessler and Treiman (2001) found that associations between vowels and onsets are less numerous and less strong overall than associations between vowels and codas. However, they identified four cases in which the vowel spelling is significantly associated with the preceding consonant. The three clearest of these cases were selected for study here.

The first case of onset conditioning involves /ɑ/. This vowel is normally spelled as o, as in pod and slop. However, it is usually spelled as a after /w/, as in wad and swan. The monosyllables studied by Kessler and Treiman (2001) do not contain any exceptions to this latter pattern, and the association is in this sense stronger than any of those studied in Experiment 1. As Table 3 shows, though, there are some exceptions in the first syllables of the larger set of words that we investigated for the present study, including wobble and wombat. Our second case of onset conditioning involves /ɝ/. After /w/, this vowel is usually spelled as or, as in work and worth. Were is a notable exception to this pattern, and there are a handful of others, such as whirl. After phonemes other than /w/, /ɝ/ does not often take on a spelling that begins with o. Instead, it has a variety of spellings, including ur, ir, and er. Ur is particularly common after /k/, /bl/, and /sl/, as in curb, blur, and slur, and these onsets were selected as the control context for the present study. Case 3 involves /u/. When /u/ is preceded by a noncoronal consonant (i.e., one that does not have a dental, alveolar, or palato-alveolar place of articulation), it usually has a spelling beginning with o. The most common such spelling is oo, as in food and spoon. Although there are no exceptions to this pattern in the monosyllables studied by Kessler and Treiman, some exceptions occur in the larger set, including scuba and cuckoo. After coronals, u followed by final e (e.g., rune), eu (e.g., rheum) and ew (e.g., blew) are more common, although oo also occurs (e.g., broom).

Two of the patterns described (Cases 1 and 3) above are due to sound changes that have occurred in many dialects of English. For example, the effect of context on the spelling of /ɑ/ reflects the fact that the vowel of words like wad and swan was originally pronounced the same as the vowel of pad. The influence of the preceding /w/ eventually changed the vowel to /ɑ/, the

same vowel as in pod. Given the conservative nature of the English writing system, the spellings of the vowels remained the same. The other effect (Case 2) is due to spelling conventions. English resists placing u and w ("double u") next to one another, and so vowels that might normally be spelled with u have a special spelling next to w (e.g., worm instead of wurm).

We designed pairs of nonwords to investigate each of the three cases. If adult spellers are sensitive to onset conditioning, the critical vowel spelling should be more common in the experimental items than the control items.

Method

Stimuli. For each case, 10 pairs of phonologically legal experimental and control nonwords were constructed. The experimental and control syllables in each pair had different onsets but the same codas. For example, /skwɑnz/ (experimental syllable for Case 1) was paired with /slɑnz/ (control syllable). For Case 1, we used codas that do not condition the a spelling of /ɑ/. Twenty filler nonwords were constructed. The fillers used different vowels from the critical stimuli, and they included a number of different consonants as well. A complete list of the stimuli appears in the Appendix.

For purposes of presentation, three different random orders were prepared. In each list, the experimental items, control items, and fillers were intermixed with the constraint that no more than two consecutive items had the same onset, vowel, or coda.

Procedure. The procedure was like that of Experiment 1, except that no rest break was provided due to the smaller number of stimuli. The participants were assigned to one of the three lists in the order in which they were run.

Participants. Twenty-one students contributed data. The data of one additional participant were dropped because more than two of this student's spellings of the 20 filler items were not

plausible renditions of the item's phonemic structure. The other participants produced a mean of 0.42 implausible spellings on the filler items.

Results and Discussion

For Case 1 (/ɑ/), we tabulated the number of vowel spellings that began with a for the experimental syllables and the control syllables. Such spellings should be more frequent for experimental syllables such as /skwɑnz/ than for control syllables such as /slɑnz/ if spellers are sensitive to the influence of the preceding consonant on the spelling of the vowel. Spellings of the vowel with au or aw were not counted as critical vowel spellings, since these spellings could reflect a dialect in which /ɑ/ has merged with /ɔ/, which is normally spelled as au or aw. Such spellings were uncommon, however, occurring less than 4% of the time. As Table 4 shows, the critical spellings were substantially more common for the experimental stimuli than the control stimuli, and the difference was significant according to t tests by subjects and by items. All participants showed a difference in the predicted direction, and all pairs of experimental and control nonwords did as well.

For Case 2 (/ɝ/), the critical vowel spellings were those that began with o. As Table 4 shows, such spellings were significantly more frequent for the experimental nonwords such as /wɝdʒ/ than for the control nonwords such as /kɝdʒ/. Although o spellings were more common for the experimental stimuli than the control stimuli, u was the most common type of spelling for both types of items. E was used almost as often as o for the experimental nonwords (28% e vs. 29% o), but e was less common for the control nonwords (15%). Spellers' use of e after /w/ may reflect the influence of were. The most important result, though, is that o spellings were significantly more common for experimental than control nonwords.

For Case 3 (/ʊ/), the critical vowel spellings were those that began with o. These spellings were much more common for the experimental nonwords such as /mʊk/ than for the control nonwords such as /pɹʊk/. In the great majority of cases, the particular o-initial grapheme that was used was oo.

Given that certain onset-vowel sequences were repeated across the experiment, we examined participants' spellings for the first occurrence of each sequence. In all three cases, the proportion of critical vowel spellings was higher for experimental nonwords than for control nonwords. The results were numerically similar to those observed for all items.

Thus, there is strong evidence that adults' spellings of vowels are influenced by the preceding consonant. This evidence was found for all three of the cases that we examined. These results indicate that adults pick up and use onset-to-vowel associations when they exist in English. These findings fail to support the rime constituency hypothesis, which predicts that spellers use associations within the syllable rime but not those that involve the onset and part of the rime. In the General Discussion, we will consider why the adults of Experiment 2 were influenced by onsets in the spelling of vowels whereas those in the study of Treiman and Zukowski (1988) were not.

The findings of Experiment 2 are surprising in light of the view that rimes play a special role in reading and phonological processing in English. Before considering how to explain these findings, we thought it important to determine whether the same sensitivity to onsets appears in a spelling task involving real words. Experiment 3 was designed to address this issue. It also asked whether the coda influences adults' spellings of vowels in real words.

Experiment 3

To determine whether people use consonantal context when spelling the vowels of real words, we can look at their errors. If spellers store only information about the most common spellings of vowels, then a word like wok would have a regular vowel spelling. This is because it uses the typical grapheme for medial /ɑ/, o. Cog, too, is a regular word. In this view, substitutions of a for o should be uncommon for both wok and cog. However, if spellers store information about the spellings of vowels in particular consonantal contexts, then wok would have an irregular vowel spelling. This is because the most common spelling of /ɑ/ after /w/ is a. In this view, substitutions of a for o should be relatively common for wok, more common than for cog. We asked whether substitution errors differ in this way for experimental words like wok and control words like cog.

Experiment 3 used the logic described above to examine both onset-to-vowel and coda-to-vowel associations. For each case of coda-to-vowel association (Table 1) and each case of onset-to-vowel association (Table 3), we selected real words for which the vowel is not spelled in the critical manner. Some of these words had the vowel in the experimental context and an equal number had the vowel in the control context. If context has an effect on spelling, then substitutions of the critical spelling for the correct spelling should be more common for the experimental words than the control words.

Method

Stimuli. For each of the cases examined in Experiment 1 and Experiment 2, we chose as many words as possible that contained the vowel in the experimental context and where the vowel was not spelled in the critical manner. We selected an equal number of such words that contained the vowel in the control context. We attempted to equate the experimental and control words for frequency, length, stress of the critical vowel, and conventional spelling of the critical

vowel. We avoided words that had homophones that might be familiar to our students. Also, we tried to avoid situations in which use of the critical vowel would result in a real word. Because the number of potential stimuli was relatively small, we could not use an equal number of stimuli in all of the cases.

For the test of coda-to-vowel associations, the number of stimuli per case ranged from a low of 2 (1 experimental word and 1 control word) for Case 4 to a high of 20 (10 experimental words and 10 control words) for Case 3. There were 30 experimental words and 30 control words. Across the six cases, the experimental words and control words were alike in length (mean of 6.2 letters for both). The experimental words were slightly more frequent than the control words (33.5 vs. 28.8 according to Zeno, Ivenz, Millard, & Duvvuri, 1995), but the difference in frequency was not significant ($p = .75$).

For the test of onset-to-vowel associations, the number of stimuli per case ranged from 4 (2 experimental and 2 control) to 12 (6 experimental and 6 control). Altogether, there were 12 experimental words and 12 control words testing onset-to-vowel associations. The experimental and control words were similar in length (5.5 letters vs. 5.4 letters). The experimental words were slightly but not significantly more frequent than the controls (25.3 vs. 19.9; $p = .58$). All of the words used in the experiment are listed in the Appendix.

For purposes of presentation, the 84 words were randomly intermixed with the constraint that no two words with the same critical vowel were adjacent. Two different random orders were prepared.

Procedure. The participants were tested individually or in small groups. Approximately half of the participants received the stimuli in each of the two random orders. The experimenter pronounced each word, said it in a sentence, and then said the word again. The participants were

then asked to spell the word on prepared answer sheets. There was a rest break halfway through the list.

Participants. The participants were 35 students from the same population as the previous experiments, with the exception that one participant was a student at a different college in the same area.

Results and Discussion

The participants generally found the words difficult to spell. The mean overall error rate was 27.6% (range 2.4% - 66.7%). Our primary interest was in the types of spelling errors made for experimental words and control words. Specifically, were participants more likely to substitute the critical vowel for the correct vowel when spelling the experimental words than when spelling the control words? If so, this would indicate that adults show an effect of context on spelling.

For the coda-to-vowel experimental words, 22% of the errors used the critical vowel spelling in place of the conventional spelling. For example, participants sometimes misspelled shred as shread and casserole as casserol. For the coda-to-vowel control stimuli, only 8% of the errors used the critical vowel. That is, errors such as fleak for fleck and isotop for isotope were relatively uncommon. As Table 5 shows, the proportion of errors that used the critical vowel spelling was reliably greater for the experimental words than the control words, both by subjects and by items. The remaining errors on the experimental and control words misspelled phonemes other than the target vowel, as in cassarole and caserole for casserole. In a few cases, the target vowel was spelled with a grapheme other than the critical vowel, as in flak for fleck.

With the onset-to-vowel stimuli, too, spellers were more likely to use the critical spelling for the experimental words than the control words. For the experimental words, 33% of the

errors substituted the critical vowel spelling for the correct spelling. For example, wok was sometimes spelled as wak and wombat was sometimes spelled as wambat. The control stimuli were less likely to give rise to such errors. For these stimuli, just 5% of the errors used the critical vowel spelling. Cog was rarely spelled as cag, for example, and possum was rarely spelled as passum. Statistical tests, shown in Table 5, confirmed that the experimental and control words differed reliably in the proportion of critical errors relative to all errors. Other errors made by participants misspelled phonemes other than the target vowel, as in whombat for wombat, or misspelled the target vowel with a grapheme other than the critical spelling, as in possome for possum. The errors were typically nonwords (86% nonwords pooling over onset-to-vowel and coda-to-vowel stimuli). Given that some dictionaries list coocoo as a slang alternative for cuckoo, we also analyzed the results without this item. The difference between experimental and control words in the proportion of critical errors relative to all errors was still significant (by subjects: $p = .001$, one tailed; by items: $p = .023$, one tailed).

In light of the small numbers of stimuli for some of the individual vowels, statistical tests were not carried out for each case separately. However, the proportion of critical errors relative to all errors was higher for experimental words than for control words for Cases 1, 2, 3, 5, and 6 of the coda-to-vowel stimuli and Cases 1, 2, and 3 of the onset-to-vowel stimuli. The only case that did not show a difference in the predicted direction was coda-to-vowel Case 4, /ʊ/. There was just one experimental word and just one control word for this case, however. The experimental word, swoosh, may not be an ideal test because the critical spelling, u, rarely appears next to w in English.

Because some of the critical rimes and onset-vowel sequences were repeated within the list, we examined participants' performance on the first instance of a given sequence that they

encountered. The proportion of errors that used the critical vowel spelling was larger for the experimental items than the control items for both the coda-to-vowel case and the onset-to-vowel case, with the results numerically very similar to those observed for all items.

Participants who were more sensitive to coda-to-vowel associations (as measured by the difference in proportion of substitution errors of the critical vowel on the experimental and control words) also tended to be more sensitive to onset-to-vowel associations ($r = .61$, $p < .001$, one tailed; the results of 3 participants could not be included in this analysis because they did not make any errors in one or more of the cells). A combined measure of sensitivity to coda-to-vowel and onset-to-vowel associations showed a significant correlation with performance on the spelling test, such that better spellers showed a larger difference between experimental and control items than did poorer spellers ($r = .29$, $p = .048$, one tailed; all participants contributed data to this analysis). These results suggest that good spellers at the college level are more responsive to the statistical patterns that affect vowel spelling than are poorer spellers.

Are spellers more sensitive to those patterns for which stronger evidence exists within the English spelling system itself? Relatively few spelling patterns were examined in each experiment, and few examples of some of the patterns were included in Experiment 3. Nevertheless, we carried out exploratory analyses to address this question. For Experiment 3, we expressed spellers' sensitivity to each pattern in terms of the difference between experimental and control words in the proportion of critical errors relative to all errors. For Experiments 1 and 2, we used the difference between experimental and control items in proportion of critical spellings. We did not include the results for coda-to-vowel Case 4, since this case may also tap onset-to-vowel sensitivity, as mentioned earlier. For the combined data from Experiments 1 and 2, there was a significant Spearman rank-order correlation between the strength of the behavioral

effect and the strength of the pattern in the English writing system when the latter was expressed as the difference in the proportion of real words with the critical spelling in the experimental and control contexts. This held true whether the pattern's strength was calculated on the basis of the monosyllabic words from Kessler and Treiman (2001) or on the basis of the larger word set that was analyzed for the present study (r_s = .73, p = .020, one tailed, for the former analysis; r_s = .84, p = .005, one tailed, for the latter analysis). For Experiment 3, where there were generally fewer items for each case, a significant rank-order correlation was found when we used the data from the larger word set (r_s = .71, p = .023, one tailed). The correlation did not reach significance using the smaller word set (r_s = .55, p = .080, one tailed). These results must be interpreted with caution, as only eight cases were included in the analyses and because there are questions about the best way to assess the strength of a pattern in the writing system. However, the findings provide initial support for the idea that spellers are especially sensitive to those patterns for which strong evidence exists in the words to which they have been exposed.

To summarize, the results of Experiment 3 support the conclusions drawn from Experiments 1 and 2 and show that the findings generalize to real words. Adults are sensitive to the effects of both onset and coda on the spelling of medial vowels. They use this information when spelling real words as well as when constructing spellings for nonwords. With real words, this sensitivity causes certain vowel substitutions to be more common in some consonantal contexts than in other contexts. The results of Experiment 3 do not support the theory that spellers store a list of the grapheme options for each vowel that is weighted by the overall frequency of the graphemes in all consonantal contexts (Barry & Seymour, 1988). For some vowels, the weightings vary as a function of not only the following consonant but also the preceding consonant.

The results obtained so far provide strong evidence against the rime constituency hypothesis, according to which spellers notice and use associations involving phonemes within the rime but do not go beyond this domain. An alternative hypothesis, which is compatible with the results of Experiments 1 to 3, is that linguistic boundaries are not critical at all. In this view, spellers pick up context-sensitive associations involving adjacent phonemes and generalize these associations in a way that is blind to linguistic boundaries. We may call this hypothesis the adjacency hypothesis. Another possibility, which is also compatible with the results of Experiments 1 to 3, is that spellers are sensitive to syllable boundaries in their learning and use of context-sensitive associations. They do not go beyond the syllable when applying patterns like those studied here. This latter hypothesis may be called the syllable hypothesis. We cannot tease apart the adjacency hypothesis and the syllable hypothesis based on the results of Experiments 1 to 3 because the relevant context was always in the same syllable as the vowel in these experiments.

Experiment 4 was designed to distinguish between the adjacency hypothesis and the syllable hypothesis. In this experiment, we took a closer look at coda-to-vowel associations and their effects on nonword spelling. Consider the association between /i/ and following /d/ and /p/ that was examined in Experiments 1 and 3. In English, /i/ tends to be spelled as ee before /d/ and /p/. It is more likely to be spelled as ea before other consonants. The results of Experiments 1 and 3 suggest that spellers are sensitive to this association. However, the stimuli of Experiments 1 and 3 always had the /i/ and the following /d/ or /p/ within the same syllable. It is thus not clear whether membership in the same syllable is critical. To determine whether it is, Experiment 4 examined participants' spelling of /i/ in disyllabic nonwords such as /ʃɹi'dɔk/ (different syllable, experimental) and /ʃɹi'gɔk/ (different syllable, control). In syllable division tasks, English-

speaking adults generally place the syllable boundary after the /i/ and before the following consonant in such cases (Treiman & Danis, 1988b). This outcome is consistent with linguistic theories of syllabification according to which the onsets of stressed syllables are maximized (e.g., Selkirk, 1982). According to the syllable hypothesis, the syllable boundary blocks the use of ee in /ʃɹi'dɔk/ and ee spellings should be no more common in /ʃɹi'dɔk/ than in /ʃɹi'gɔk/. In contrast, the adjacency hypothesis states that the syllable boundary is not critical. By this hypothesis, the rate of ee spellings should be higher in /ʃɹi'dɔk/ than in /ʃɹi'gɔk/ even though the vowel and the following consonant do not belong to the same syllable in /ʃɹi'dɔk/.

Experiment 4 also included stimuli such as /ʃɹid'bɔk/ (same syllable, experimental) and /ʃɹig'bɔk/ (same syllable, control). With such items, the /i/ and the following /d/ or /g/ are virtually always placed in the same syllable in syllabification tasks (Treiman & Zukowski, 1990). This outcome is consistent with linguistic theories stating that clusters such as /db/ and /gb/ cannot belong to the same syllable (e.g., Selkirk, 1982). The adjacency hypothesis and the syllable hypothesis both predict a higher rate of ee spellings for /ʃɹid'bɔk/ than for /ʃɹig'bɔk/. Such a result would show that the findings of Experiment 1 with monosyllabic nonwords generalize to the first syllables of disyllabic nonwords. This result would also forestall the interpretation that a lack of difference between /ʃɹi'dɔk/ and /ʃɹi'gɔk/ is due to polysyllabicity rather than to syllable boundaries.

Experiment 4

Method

Stimuli. We selected three of the vowels that were used in Experiment 1 and constructed disyllabic nonwords in which these vowels appeared in the first syllable and the second syllable was stressed. There were four types of nonwords, which varied in position of the syllable

boundary (target vowel and following consonant in same syllable vs. different syllable) and the identity of the consonant that followed the target vowel (experimental vs. control). To illustrate, consider the vowel /i/ (Case 2 of Experiment 1). In /ʃɹid'bɔk/ (same syllable, experimental), this vowel and the following consonant, /d/, are in the same syllable. In /ʃɹig'bɔk/ (same syllable, control), the syllable boundary is also between the two consonants and so /i/ and /g/ are in the same syllable. In /ʃɹi'dɔk/ (experimental, different syllable) and /ʃɹi'gɔk/ (control, different syllable), the middle consonant is the onset of the second syllable. The syllable hypothesis predicts an interaction between context and boundary, such that critical spellings of the vowel are more common in the experimental context than the control context in the same-syllable case but not in the different-syllable case. The adjacency hypothesis predicts a main effect of context -- more critical spellings for experimental nonwords than for control nonwords -- but no interaction with boundary.

We checked whether there are any English monomorphemic words that our participants might know that contain the target vowel in an environment that is very similar to that of the Experiment 4 stimuli (i.e., target vowel followed by one or more consonants, followed by a stressed vowel word-finally). For /i/, the only such words are cliché and Peking, neither of which contains the critical ee spelling. For /aʊ/, there are no such words. There are a handful of such words for /aɪ/, including Taiwan and ideal, but none that use the critical igh spelling and only one (typhoon) in which the consonant that follows the vowel is one of the consonants used in Experiment 4. Thus, if participants spell /ʃɹid'bɔk/ as shreedboke or /ʃaʊl'wɔst/ as showlwost, their ee and ow spellings cannot reflect experience with highly similar disyllabic words. Instead, such spellings would appear to reflect generalizations from participants' experience with words such as reed and howl. The /ɔ/ vowel that was used in Experiment 1 (Case 3) was not used in

Experiment 4 because a number of disyllabic words that are very similar to the Experiment 4 stimuli use the critical single o spelling, such as Colette and hotel. Also, it could be difficult to differentiate the single o spelling from the o plus final e spelling in the first syllables of disyllabic words. Because long or diphthongized vowels appear to be critical for producing the syllabifications desired here (e.g., Treiman & Danis, 1988b), we could not use /ɛ/ (Case 1 of Experiment 1) or /ʊ/ (Case 4 of Experiment 1) in Experiment 4.

For each of the three vowels used in Experiment 4, we constructed 8 stimuli of each of the four types. In addition, there were 20 filler nonwords. The fillers were more complex than those of the previous experiments in that 12 were monosyllabic and the other 8 were disyllabic. The disyllabic fillers had stress on the first syllable so as to vary the stress patterns of the stimuli in the experiment. The stimuli are listed in the Appendix.

Three different random orders were prepared for purposes of presentation. In each, the test and filler nonwords were randomly intermixed such that no more than two consecutive stimuli had the same critical vowel and no more than two consecutive stimuli were of the same type.

Procedure. The procedure was like that of Experiment 1. However, given the complexity of the nonwords, the experimenter pronounced each nonword twice before asking participants to repeat it. The participants were assigned to one of the three random orders in the order in which they were run.

Participants. Twenty-three participants contributed data. The results of four additional students were dropped because they produced three or more implausible spellings of the filler items. The remaining students produced a mean of 0.87 implausible spellings of the 20 fillers.

Results and Discussion

Table 6 shows the mean proportions of critical spellings of each vowel in the four types of nonwords. Analyses of variance were carried out by subjects and by items using the factors of case, context (experimental vs. control), and boundary type (same syllable vs. different syllable). There was a main effect of case ($F1(2,44) = 16.06$; $F2(2,21) = 48.91$; $p < .001$ for both), such that critical vowel spellings were most common for /i/, next most common for /aʊ/, and least common for /aɪ/. This is the same pattern that was observed in Experiment 1, although the proportion of critical spellings was in each case lower than for the monosyllabic nonwords of Experiment 1. The main effect of context was also significant ($F1(1,22) = 17.91$; $F2(1,21) = 16.05$, $p <= .001$ for both). Critically, this main effect was qualified by an interaction between boundary and context ($F1(1,22) = 16.82$, $p < .001$; $F2(1,21) = 11.90$, $p = .002$). The interaction arose because there were significantly more critical spellings in the experimental same-syllable case than in the control same-syllable case ($t1(22) = 5.06$, $t2(23) = 5.26$; $p < .001$, one tailed for both). Indeed, 22 of the 23 participants showed a difference in this direction, as did 19 of the 24 item pairs. In the different-syllable case, in contrast, there were not significantly more critical spellings in the experimental context than the control context. The patterns were similar when we looked at the results for the first-presented item in each quadruplet.

The ANOVAs also showed an interaction between case and boundary ($F1(2,44) = 10.44$; $F2(2,21) = 14.21$; $p < .001$ for both). For /i/ and /aɪ/, there were generally more critical spellings in the same-syllable cases than in the different-syllable cases. For /aʊ/, there were more critical spellings in the different-syllable case. This is likely because /aʊ/ is a syllable-final vowel in the different-syllable case, and this vowel is more likely to be spelled as ow when it ends a syllable (e.g., how, power) than when it is followed by a consonant in the same syllable (e.g., mouse).

The finding that participants were more likely to use the critical vowel spelling in the experimental same-syllable case than in the control same-syllable case indicates that the results of Experiment 1 generalize to the first syllables of disyllabic items with second-syllable stress. These patterns are not restricted to monosyllabic items like those of Experiment 1. The obtained differences do not seem to depend on the items being highly similar to real words in both segmental pattern and stress pattern, for the items of Experiment 4 were not very similar to existing words.

The most important result of Experiment 4 is that spellers appear to use patterns that involve the syllable rather than patterns that involve mere adjacency. For example, /i/ and /d/ must be in the same syllable for an increased number of ee spellings to be found. Likewise, igh spellings of /aɪ/ almost never occur unless /aɪ/ and /t/ are in the same syllable. For /aʊ/, ow spellings seem to occur in two main circumstances -- when /aʊ/ is followed in the same syllable by /l/ or /n/ or when /aʊ/ is at the end of a syllable. For all three vowels that we investigated, therefore, adjacency between a vowel and a following consonant does not suffice for the critical context-conditioned vowel spelling to occur. What is important is that the vowel and the following consonant belong to the same syllable. These results support the syllable hypothesis over the adjacency hypothesis.

Ideally, one would like to disentangle the factors of adjacency and membership in the same syllable for contextual associations involving vowels and preceding consonants as well as for those involving vowels and following consonants. This would be difficult to do, however. For example, the consonant that conditions several of the changes examined in Experiment 2, /w/, cannot occur in syllable-final position in English.

General Discussion

Vowels are difficult to spell in English. How can one choose the correct spelling of a vowel from among the many possibilities that are offered by the writing system? This problem provides a good test case for questions about how language users deal with irregularity. In the present experiments, we asked how experienced spellers attempt to solve the vowel problem by examining their spellings of vowels in nonwords and their substitution errors on vowels in real words. We asked two specific questions. First, do spellers use the consonantal context to help narrow the range of possible spellings for a vowel? Second, what type of context do spellers use? The answers to these questions have implications for theories of skilled spelling production, views of spelling development, and other issues.

In answer to first question, we found that adults' spellings of syllable-medial vowels are affected by the identity of the surrounding consonants. This result suggests that spellers do not simply store a list of the possible spellings of each vowel weighted by the frequency of the phoneme-to-grapheme correspondence in the language as a whole (Barry & Seymour, 1988). Nor are the weights affected only by frequency in that particular position of the syllable, the factor that Goodman and Caramazza (1986) and Sanders and Caramazza (1990) examined in studies of patients whose spelling ability was compromised by brain damage. In some cases, our results indicate, the graphemes are weighted by their frequency in a specific consonantal environment. The results thus suggest that spellers use context as a way of dealing with the difficulties posed by the English writing system. The findings of Kessler and Treiman (2001) show that the system becomes more reliable, statistically, when context is taken into account. The present results add to this picture by showing that experienced spellers use the statistical patterns. Even with these patterns, the English spelling system is less regular than many other

alphabetic systems. However, the patterns help to rationalize some spellings that would otherwise have to be learned by rote.

The second question that motivated the present study dealt with the types of context used by spellers of English. The results of Experiments 1 to 3 show that the relevant context for a medial vowel includes consonants from the same constituent of the syllable -- the coda -- and consonants from a different constituent of the syllable -- the onset. However, the results of Experiment 4 indicate that the following consonant must be within the same syllable to have an effect, at least for the patterns studied here. That is, spellers appear to extend the associations that they have learned in a way that is sensitive to syllable boundaries. Syllables may play a role in English spelling if people segment to-be-spelled items into syllables and spell one syllable at a time. A slightly different interpretation is that spellers consider only phonemes in the same syllable when deciding how to transcribe a target phoneme. To our knowledge, the present findings are the first to show a role for syllables in the spelling of normal adults. However, several studies have pointed to a role for syllables or syllable-like units in the recognition of printed words (e.g., Mewhort & Beal, 1977; Prinzmetal, Treiman, & Rho, 1986).

Our finding that vowel spelling is influenced by the onset as well as the coda is surprising on some interpretations of the view that rimes play a special role in phonological processing and reading. The present results suggest that people pick up onset-to-vowel associations when these associations exist and that they are as sensitive to them as to coda-to-vowel associations. To the extent that rimes play a special role in English spelling, this may be because associations between vowels and codas are more numerous in this writing system than associations between vowels and onsets (Kessler & Treiman, 2001). This interpretation is consistent with the conclusions of Martensen, Maris, and Dijkstra (2000), who found that consideration of the rime

unit does not improve spelling-to-sound predictability in Dutch and that this unit does not play a special role for Dutch readers. Martensen et al. suggested that the characteristics of spelling-to-sound relationships in a particular writing system shape the units that readers use. Our findings suggest that the same is true for spellers. In English, spellers take advantage of associations between onsets and vowels when these exist. However, associations between vowels and codas are more influential overall because the spelling system has more associations between vowels and codas than between vowels and onsets. The same may be true for English reading, but this remains to be examined.

Recall that Treiman and Zukowski (1988) did not find a sensitivity to onsets in the spelling of vowels. For example, their participants rarely spelled /fɹɛθ/ as frieth on the basis of friend. Also, frieth was not rated as a particularly good spelling of /fɹɛθ/. How can we reconcile the lack of an onset-to-vowel effect in the Treiman and Zukowski study with the substantial onset-to-vowel effect observed here? An answer is suggested by the fact that Treiman and Zukowski investigated very unusual vowel spellings. For example, the ie spelling of /ɛ/ appears only in the word friend. The onset-conditioned vowel spellings investigated in the present study occur more widely. For example, /ɑ/ is written as a in wad, wan, swan, swatch, and so on. The present results suggest that adults are sensitive to onset-to-vowel associations that appear in a number of different words. In such cases, they are willing to extend the patterns to items they have not encountered before. The results of Treiman and Zukowski suggest, in contrast, that spellers do not develop generalizable knowledge of onset-to-vowel associations from single words with unusual spellings like friend. Having observed that associations between vowels and codas are more common in English than associations between vowels and onsets, adults may sometimes generalize a coda-to-vowel association from a single word. A single word may not

provide a basis for a generalizable onset-to-vowel association. When better evidence for an association between onset and vowel exists, as with the use of a for /ɑ/ in wad, wan, swan, swatch, and so on, spellers are not restricted by the onset-rime boundary. This interpretation is consistent with the view described above -- that the role of the rime in English spelling derives from the fact that the writing system includes more associations between vowels and codas than between vowels and onsets.

Our results demonstrate context effects on the spelling of English vowels, and they show that these effects can involve the preceding consonant as well as the following one. An issue that we have not yet considered is whether the observed contextual effects operate on sound-to-letter correspondences or on letters alone. Consider the fact that /ɛ/ has several spellings, including ea and e, and that participants in Experiment 1 used ea a higher proportion of the time before /d/ (or its spelling d) than before /p/ (or its spelling p). We have assumed that the choice between ea and a takes into account the phoneme that is being spelled. However, an alternative hypothesis is that spellers favor the letter sequence ea more before d than before p, regardless of the phonemes being represented. Such a preference could arise if the proportion of ea spellings in English text is higher before d than before p and if spellers adjust their own productions to reflect this. According to this alternative hypothesis, which we will call the letter frequency hypothesis, participants may generate possible spellings of /ɛ/ without regard for context and then choose the spelling that yields a more typical letter sequence. Letter frequency could well be influential, especially because these experiments look at a complete spelling that takes some time to produce.

Our experiments were not designed to tease apart the two hypotheses discussed above. However, we conducted a post-hoc check by examining the results for those items for which the

distributions of spellings in texts do not fit the patterns expected by the letter frequency hypothesis. For each test vowel in Experiments 1 and 2, such as /ɛ/, we considered each pair of experimental and control contexts, such as /d/ and /p/. We chose a priori the expected spellings in those environments, using the critical vowel spelling and the other most likely vowel spelling. For each of the four spellings – ead, eap, ed, and ep in this example – we counted how often they appear at the appropriate edges of words in English text, based on Zeno et al. (1995). Then we computed whether the proportion of critical vowel spellings (ea) was higher in the experimental environment (d) than the control environment (p). If so, the letter frequency hypothesis could potentially explain the experimental results. For 68 of the 90 experimental-control pairs in Experiments 1 and 2, the pattern in text fit the letter frequency hypothesis and so the results for these pairs cannot help in disentangling the two hypotheses. In the remaining 22 instances, the pattern in text was contrary to the letter frequency hypothesis. For /ɛ/, for instance, the proportion in text of ea spellings out of both ea and e spellings is .05 before d but .23 before p. For these items, we looked at responses that used one of the four predicted spellings. The proportion of spellings using the critical vowel relative to the total of the total number of spellings using the critical vowel and the other most likely vowel was significantly higher for the experimental items than the control items (.54 vs. .24; $t(21) = 4.24$, $p < .001$, one tailed). For the experimental nonword /glɛd/, for instance, ea was used in 4 of the 20 spellings that used either ead or ed, yielding a proportion of .20. For the control nonword /glɛp/, there were no eap spellings and 16 ep spellings (.00). Because a difference is found even in situations where the frequency of the letter patterns should influence participants in the opposite direction, some of the effects in the present study must operate at the level of sound-to-letter correspondences.

In other instances, the text counts align with the letter frequency hypothesis and so the observed effects may operate at the letter level. Consider the experimental-control pair /gaɪt/-/gaɪf/ (Experiment 1, Case 6). Word-final ight is a more common letter sequence than word-final ite, whereas final ife is more common than ighf. Indeed, no English word ends with ighf. The unusual nature of the ighf sequence is sufficient to explain why the participants in Experiment 1 avoided it. However, a simple view of letter frequency is not sufficient to explain the results of Experiment 4. Participants in this experiment used ight more often than ighf when the corresponding phonemes were in the same syllable, but they did not use ight more often than ighf when the phonemes were in different syllables. The notion of a syllable appears to be necessary in order to explain these results.

Models of the spelling process are less fully developed and less explicit than models of the reading process. The present findings provide some constraints on the form that spelling models should take and some data that they will need to explain. One issue that modelers confront is the architecture of the spelling system. Researchers such as Barry and Seymour (1988) and Kreiner and Gough (1990) have espoused a dual-route view of spelling, similar to dual-route models of reading. In this view, lexical knowledge and non-lexical knowledge provide two different routes to spelling. Within this framework, our results suggest that the mappings used by the non-lexical route consider the consonantal context in which a vowel phoneme occurs. They do not represent only the most common spelling of each phoneme or the spelling that is most common in that particular position of the syllable. Single-route models, based on connectionist principles, are another possible architecture (e.g., Olson & Caramazza, 1994). To the extent that such models pick up the statistical regularities in the writing system, they may account well for human performance. Single-route models have the potential to explain evidence

pointing to a role of analogies in spelling (e.g., Campbell, 1983). For example, the /gɹol/ of Experiment 1 is similar to the real word /tɹol/ (troll) and people might therefore spell it in a similar way. However, the disyllabic stimuli of Experiment 4 were not highly similar to any real words and yet the same-syllable items in this experiment showed the same pattern of results found in the experiments with real words. A simple analogy-based model would have difficulty explaining the results of that experiment. This and other models of spelling need to be more fully developed before they can be clearly distinguished.

Modelers also confront the issue of whether sound-to-spelling conversion is serial (one phoneme at a time) or parallel. Our results suggest that sound-to-spelling translation is not strictly a phoneme-by-phoneme process. The choice of graphemes for a given vowel is influenced by the following context, implying that spellers do not complete the selection of a spelling for a medial vowel before they have processed the next phoneme. Most likely, our results suggest, other phonemes from the same syllable are considered when determining how to spell a particular phoneme. This conclusion is of particular interest given that one of the major models of the non-lexical route in reading assumes serial, letter-by-letter processing (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001).

Models of the spelling process must also confront the issue of whether feedback from reading plays a role in spelling and, if so, how and when. This issue is analogous to the one of whether feedback from spelling plays a role in reading, an issue that has led to some controversy (Peereman, Content, & Bonin, 1998; Ziegler, Stone, & Jacobs, 1997). As discussed above, our results suggest that the end result in spelling production can be influenced by both knowledge of sound-to-spelling translation (a feedforward effect) and knowledge of common letter patterns (a feedback effect).

Our results have implications for the study of spelling development as well as for the modeling of skilled spelling. If experienced spellers attempt to cope with the challenges posed by the English writing system by using context that extends beyond the single phoneme, then what about less experienced spellers? One hypothesis is that spelling development, like reading development, proceeds from small units to larger units (e.g., Frith, 1985). Our results support the idea that larger units are important in adult spelling production, contrary to some previous claims (Barry & Seymour, 1988; Perry et al., in press). If these units become important only for experienced spellers, then young children should not show contextual effects of the kinds documented here. Another hypothesis is that large units, especially rimes, are used from the beginning of literacy development (e.g., Goswami, 1988). On this view, contextual effects should be found in young children. We are currently carrying out research to address these questions.

Our results further suggest that care needs to be taken in classifying words for studies of spelling and reading. The assumption that spellers transcribe phonemes without regard to context may have led to problems in some previous work. For example, Kreiner and Gough (1990) used a measure of the relative probability of phoneme-grapheme correspondences that assumed that spellers consider the spelling options for a phoneme in proportion to their frequency in the lexicon as a whole. If spellers give most weight to the options that are appropriate for a particular consonantal context, however, such a measure may not be ideal. As another example, Waters, Bruck, and Malus-Abramowitz (1988) included a category of words (labeled regular* words) in their study of third- to fifth-grade children in which the words had one or more problem phonemes that could be represented by several different graphemes. The researchers expected children to perform poorly on these words, as there appeared to be no principled basis for

selection of the correct grapheme from among the several possibilities. However, the children performed better than expected on the regular* words. The children may have been able to use statistical patterns of the kind examined here to boost their performance on these words. For example, food was considered to be a regular* word because /u/ has several possible spellings. However, oo is by far the most common spelling of /u/ after noncoronal consonant such as /f/, and children may not have given serious consideration to other options.

In other cases, problems may arise because of an assumption that spellers use rime-based units but not other large units (Stone, Vanhoy, & Van Orden, 1997; Ziegler et al., 1997). In their study of feedback effects in word reading, for example, Ziegler et al. classified /ɑp/ as an inconsistently spelled rime because it may be spelled as ap (as in swap) as well as op (as in chop). However, the a spelling only occurs after w and so the rime may not be inconsistent for those who are sensitive to this pattern. Measures of sound-spelling consistency that do not consider onset-to-vowel associations may not provide an ideal basis for selecting stimuli for experiments or drawing conclusions about underlying processes.

Our findings also have implications for what makes some people good spellers and others poor spellers. In English, differences in spelling ability have traditionally been attributed to differences in visual memory ability (see Fischer et al., 1985). The assumption has been that the English writing system is so irregular and so illogical that the only way to become a skilled speller is through rote memorization. However, research has not shown a clear connection between nonverbal memory skills and spelling ability (Fischer et al., 1985; Giles & Terrell, 1997). The results of Experiment 3 provide initial evidence that good spellers at the college level are more sensitive than poor spellers to the contextual factors influencing vowel representation. That is, good spellers have a higher degree of linguistic sensitivity than poor spellers do. The

results of Fischer et al. (1985) point to a similar conclusion. Our results suggest that differences in linguistic sensitivity are found for monomorphemic words, not just for the morphologically complex words that were the focus of the Fischer et al. research. Moreover, our results point to some of the relevant linguistic dimensions.

In our view, research and modeling in the area of spelling (and in reading) must be based on a good understanding of the characteristics of the writing system under study. The finding that the spelling of English vowels can be systematically affected by the identity of the surrounding consonants (Kessler & Treiman, 2001) set the stage for the present demonstration that adult spellers are attuned to context in their spelling of vowels. This combination of statistical studies of language and behavioral work holds promise for studies of spelling and reading, as for psycholinguistic research more generally. We look forward to further applications of this approach in the study of more complex words and in the study of spelling development.

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Appendix

Stimuli for Experiment 1

Case 1: ɛ

Experimental: klɛd, gɹɛd, stɹɛd, gɛd, glɛd, jɛd, θɛd, vɛd, kwɛd, smɛd

Control: klɛb, gɹɛdʒ, stɹɛg, gɛtʃ, glɛp, jɛb, θɛk, vɛp, kwɛg, smɛk

Case 2: i

Experimental: ʃɹid, fip, gid, jid, snip, pɹid, θip, skɹip, smip, zip

Control: ʃɹig, fiθ, gim, jið, snim, pɹig, θist, skɹiθ, smið, zist

Case 3: o

Experimental: dwol, gɹol, jol, klol, kwol, plol, skwol, snol, spɹol, wol

Control: dwot, gɹok, jop, klob, kwon, plotʃ, skwof, snoð, spɹoð, wog

Case 4: ʊ

Experimental: ʃʊtʃ, fʊʃ, jʊʃ, klʊs, lʊtʃ, θʊl, sʊl, slʊtʃ, smʊl, zʊl

Control: ʃʊf, fʊf, jʊf, klʊf, lʊf, θʊk, sʊf, slʊk, smʊf, zʊf

Case 5: aʊ

Experimental: ʃaʊl, maʊl, naʊl, θaʊn, vaʊn, zaʊl, spaʊl, pɹaʊn, bɹaʊl, smaʊn

Control: ʃaʊdʒ, maʊtʃ, naʊdʒ, θaʊs, vaʊs, zaʊtʃ, spaʊdʒ, pɹaʊdʒ, bɹaʊtʃ, smaʊtʃ

Case 6: aɪ

Experimental: dɹaɪt, glaɪt, gɹaɪt, gaɪt, jaɪt, θaɪt, staɪt, zaɪt, pɹaɪt, paɪt

Control: dɹaɪb, glaɪb, gɹaɪv, gaɪf, jaɪs, θaɪf, staɪb, zaɪf, pɹaɪb, paɪf

Fillers:

his, fɹɪp, des, fɛsk, glæθ, θɹʌd, hɔɪf, gɔɹb, flʌn, naɪð, ʃɔɪn, splaʊt, jit, ʃɹɪg, zeb, skɛnt, væsp, gɹæk, dɔ, spʌŋ

Stimuli for Experiment 2

Case 1: ɑ

Experimental: skwɑnz, kwɑts, kwɑbd, wɑbz, twɑn, wɑdʒ, skwɑmp, kwɑtʃ, kwɑp, gwɑt

Control: slɑnz, kɹɑts, klɑbd, tɹɑbz, glɑn, blɑdʒ, nɑmp, flɑtʃ, blɑp, kɹɑt

Case 2: ɜ˞

Experimental: wɜ˞dʒ, wɜ˞p, wɜ˞tʃ, wɜ˞g, wɜ˞ʃ, wɜ˞f, wɜ˞b, wɜ˞n, wɜ˞pt, wɜ˞θt

Control: kɜ˞dʒ, kɜ˞p, kɜ˞tʃ, kɜ˞g, kɜ˞ʃ, blɜ˞f, slɜ˞b, blɜ˞n, kɜ˞pt, kɜ˞θt

Case 3: ʉ

Experimental: budʒ, guθ, muk, hus, hun, sput, skudʒ, smud, swu, muθ

Control: fludʒ, ʃɹuθ, pɹuk, klus, plun, ʃɹut, fɹudʒ, flud, plu, ðuθ

Fillers:

bis, bɹɪp, dek, fɛg, flæθ, gʌd, hob, kɔɹb, lʌn, maɪð, pɔɪn, splaʊ, ɹit, ʃig, seb, snɛp, tæsp, tɹɔk, vɔ, zʌŋ

Stimuli for Experiment 3

Coda-to-vowel associations:

Case 1, experimental: shred, bled, moped

Case 1, control: fleck, wretch, trek

Case 2, experimental: centipede, mead, plead, reap, impede, stampede

Case 2, control: academe, ream, sheath, bequeath, blaspheme, theme

Case 3: experimental: cajole, camisole, casserole, console, Creole, dole, oriole, parole, shoal, tadpole

Case 3, control: abode, anecdote, isotope, cyclone, microbe, lobe, antidote, corrode, croak, diode

Case 4, experimental: swoosh

Case 4, control: nook

Case 5, experimental: afoul, pronoun

Case 5, control: vouch, slouch

Case 6, experimental: contrite, extradite, finite, ignite, parasite, smite, sprite, termite

Case 6, control: confide, pesticide, capsize, entice, diatribe, fife, snide, chastise

Onset-to-vowel associations:

Case 1, experimental: wok, wombat, whopper, wonk

Case 1, control: cog, possum, nozzle, pomp

Case 2, experimental: whir, whirlpool

Case 2, control: blurt, kerchief

Case 3, experimental: Budapest, cuckoo, Fuji, guru, scuba, Buddha

Case 3, control: jubilant, sushi, Juneau, judo, sumo, frugal

Stimuli for Experiment 4

Case 2, /i/:

Experimental, same syllable: /ʃɹidˈbok/, /snipˈnɔɪ/, /θipˈneb/, /skɹipˈtɑʊd/, /smipˈnɑʊs/, /zipˈnef/, /klidˈlɔɪ/, /ipˈdek/

Control, same syllable: /ʃɹigˈbok/, /snimˈnɔɪ/, /θigˈneb/, /skɹiθˈtɑʊd/, /smiðˈnɑʊs/, /zimˈnef/, /kliθˈlɔɪ/, /igˈdek/

Experimental, different syllable: /ʃɹiˈdok/, /sniˈpɔɪ/, /θiˈpeb/, /skɹiˈpɑʊd/, /smiˈpɑʊs/, /ziˈpef/, /kliˈdɔɪ/, /iˈpek/

Control, different syllable: /ʃɹiˈgok/, /sniˈmɔɪ/, /θiˈgeb/, /skɹiˈθɑʊd/, /smiˈðɑʊs/, /ziˈmef/, /kliˈθɔɪ/, /iˈgek/

Case 5, /aʊ/:

Experimental, same syllable: /ʃaʊlˈwost/, /zaʊlˈwug/, /spaʊlˈwɪnθ/, /smaʊnˈleb/, /faʊnˈlib/, /aʊnˈlef/, /laʊnˈluf/, /gɹaʊnˈlæsp/

Control, same syllable: /ʃaʊdʒˈwost/, /zaʊtʃˈwug/, /spaʊdʒˈwɪnθ/, /smaʊtʃˈleb/, /faʊtʃˈlib/, /aʊdʒˈlef/, /laʊtʃˈluf/, /gɹaʊdʒˈlæsp/

Experimental, different syllable: /ʃaʊˈlost/, /zaʊˈlug/, /spaʊˈlɪnθ/, /smaʊˈneb/, /faʊˈnib/, /aʊˈnef/, /laʊˈnuf/, /gɹaʊˈnæsp/

Control, different syllable: /ʃaʊˈdʒost/, /zaʊˈtʃug/, /spaʊˈdʒɪnθ/, /smaʊˈtʃeb/, /faʊˈtʃib/, /aʊˈdʒef/, /laʊˈtʃuf/, /gɹaʊˈdʒæsp/

Case 6, /aɪ/:

Experimental, same syllable: /glaɪtˈnɑʊs/, /gɹaɪtˈkɑʃ/, /zaɪtˈpɑʊd/, /stɹaɪtˈlef/, /ʃɹaɪtˈmis/, /jaɪtˈfug/, /klaɪtˈnɑn/, /dʒaɪtˈkeb/

Control, same syllable: /glaɪbˈnɑʊs/, /gɹaɪvˈkɑʃ/, /zaɪfˈpɑʊd/, /stɹaɪzˈlef/, /ʃɹaɪfˈmis/, /jaɪbˈfug/, /klaɪbˈnɑn/, /dʒaɪfˈkeb/

Experimental, different syllable: /glaɪˈtɑʊs/, /gɹaɪˈtɑʃ/, /zaɪˈtɑʊd/, /stɹaɪˈtef/, /ʃɹaɪˈtis/, /jaɪˈtug/, /klaɪˈtɑn/, /dʒaɪˈteb/

Control, different syllable: /glaɪˈbɑʊs/, /gɹaɪˈvɑʃ/, /zaɪˈfɑʊd/, /stɹaɪˈzef/, /ʃɹaɪˈfis/, /jaɪˈbug/, /klaɪˈbɑn/, /dʒaɪˈfeb/

<u>Fillers:</u>

/ˈbɪntə/, /ˈtɹæb/, /ˈtɪpko/, /ˈpʊk/, /ˈfɛgɪs/, /ˈgænɪd/, /ˈplɑksə/, /ˈflʌn/, /ˈwɪkəl/, /ˈpæsk/, /ˈgɪmbə/, /ˈlʌθ/, /ˈmʊl/, /ˈdɪlæb/, /ˈɪkɪn/, /ˈɛstæk/, /ˈpædo/, /ˈʃɹʌŋ/, /ˈtɪvət/, /ˈkɹɑb/

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Table 1

Case in which Vowel Spelling is Affected by Coda in the Words of English

	Case 1: /ɛ/	Case 2: /i/	Case 3: /o/	Case 4: /ʊ/	Case 5: /aʊ/	Case 6: /aɪ/
Following context for experimental nonwords	/d/	/d/, /p/	/l/	/l/, /s/, /ʃ/, /tʃ/	/l/, /n/	/t/
Following context for control nonwords	/b/, /dʒ/, /g/, /k/, /p/, /tʃ/	/ð/, /g/, /m/, /st/, /θ/	/b/, /d/, /ð/, /f/, /g/, /k/, /n/, /p/, /t/, /tʃ/	/f/, /k/	/dʒ/, /s/, /tʃ/	/b/, /d/, /f/, /s/, /v/, /z/
Sample experimental nonword	/klɛd/	/ʃɹip/	/dwol/	/jʊʃ/	/maʊl/	/dɹaɪt/
Sample control nonword	/klɛb/	/ʃɹig/	/dwot/	/jʊf/	/maʊtʃ/	/dɹaɪb/
Critical vowel spelling	<u>ea</u>	<u>ee</u>	<u>o</u>, no following <u>e</u>	<u>u</u>	<u>ow</u>	<u>igh</u>
Proportion real words with critical spelling, experimental context[a]	.43 (.40)	.74 (.64)	.36 (.33)	.88 (.73)	.88 (.89)	.54 (.39)
Proportion real words with critical spelling, control context[a]	.00 (.00)	.14 (.15)	.00 (.00)	.00 (.00)	.00 (.00)	.00 (.00)

[a]First value is based on the familiar monosyllabic words from Kessler and Treiman (2001); second value is based on the final syllables of familiar words, polysyllabic as well as monosyllabic. See text for details.

Table 2

Results of Experiment 1

	Case 1: /ɛ/	Case 2: /i/	Case 3: /o/	Case 4: /ʊ/	Case 5: /ɑʊ/	Case 6: /aɪ/
Mean (s.d.) proportion of critical spellings, experimental nonwords	.11 (.21)	.72 (.31)	.23 (.24)	.54 (.23)	.51 (.24)	.27 (.33)
Mean (s.d.) proportion of critical spellings, control nonwords	.05 (.01)	.45 (.30)	.12 (.12)	.43 (.27)	.08 (.13)	.00 (.00)
p value for difference, one tailed t test by subjects	p = .023	p < .001	p = .005	p = .031	p < .001	p < .001
No. participants (of 22) showing predicted difference (+), opposite pattern (-), and tie	7 + 1 - 14 tie	19 + 0 - 3 tie	12 + 5 - 5 tie	11 + 5 - 6 tie	21 + 0 - 1 tie	14 + 0 - 8 tie
p value for difference, one tailed t test by items	p = .039	p < .001	p = .01	p = .08	p < .001	p < .001
No. item pairs (of 10) showing predicted difference (+), opposite pattern (-), and tie	6 + 2 - 2 tie	9 + 1 - 0 tie	8 + 1 - 1 tie	5 + 5 - 0 tie	10 + 0 - 0 tie	10 + 0 - 0 tie

Table 3

Cases in which Vowel Spelling is Affected by Onset in the Words of English

	Case 1: /ɑ/	Case 2: /ɝ/	Case 3: /u/
Preceding context for experimental nonwords	/w/	/w/	Noncoronal consonant
Preceding context for control nonwords	Any other consonant	/bl/, /k/, /sl/	Coronal consonant
Sample experimental nonword	/skwɑnz/	/wɝdʒ/	/muk/
Sample control nonword	/slɑnz/	/kɝdʒ/	/pɹuk/
Critical vowel spelling	a initial	o initial	o initial
Proportion real words with critical spelling, experimental context[a]	1.00 (.86)	.78 (.67)	1.00 (.87)
Proportion real words with critical spelling, control context[a]	.09 (.11)	.00 (.15)	.49 (.30)

[a]First value is based on the familiar monosyllabic words from Kessler and Treiman (2001); second value is based on the first syllables of familiar words, polysyllabic as well as monosyllabic. See text for details.

Table 4

Results of Experiment 2

	Case 1: /ɑ/	Case 2: /ɝ/	Case 3: /u/
Mean (s.d.) proportion of critical spellings, experimental nonwords	.87 (.20)	.29 (.31)	.87 (.13)
Mean (s.d.) proportion of critical spellings, control nonwords	.15 (.13)	.01 (.02)	.29 (.17)
p value for difference, one tailed t test by subjects	$p < .001$	$p < .001$	$p < .001$
No. participants (of 21) showing predicted difference (+), opposite pattern (-), and tie	21 + 0 - 0 tie	15 + 0 - 6 tie	21 + 0 - 0 tie
p value for difference, one tailed t test by items	$p < .001$	$p < .001$	$p < .001$
No. item pairs (of 10) showing predicted difference (+), opposite pattern (-), and tie	10 + 0 - 0 tie	10 + 0 - 0 tie	10 + 0 - 0 tie

Table 5

Results of Experiment 3

	Coda-to-vowel	Onset-to-vowel
Proportion (and number) critical errors relative to all errors, experimental words	.22 (49/225)	.33 (54/162)
Proportion (and number) critical errors relative to all errors, control words	.08 (24/269)	.05 (8/155)
p value for difference in proportions, one tailed t test by subjects	p = .004	p < .001
No. participants (of 35) showing predicted difference (+), opposite pattern (-), and tie	21+ 7 - 6 tie[a]	26 + 1 - 6 tie[b]
p value for difference, one tailed t test by items	p = .048	p = .012

[a] One additional participant made no errors on coda-to-vowel items

[b] One additional participant made no errors on onset-to-vowel items, and another made no errors on onset-to-vowel experimental items

Table 6

Mean and Standard Deviation of Proportion of Critical Spellings in Experiment 4

	Case 2: /i/	Case 5: /aʊ/	Case 6: /aɪ/
Experimental, same syllable	.52 (.34)	.25 (.23)	.09 (.22)
Control, same syllable	.35 (.29)	.10 (.18)	.00 (.00)
Experimental, different syllable	.34 (.32)	.28 (.30)	.01 (.03)
Control, different syllable	.30 (.31)	.29 (.29)	.01 (.03)