Running head: RELATIONSHIPS BETWEEN SOUNDS AND LETTERS

Relationships Between Sounds and Letters in English Monosyllables

Brett Kessler and Rebecca Treiman

Wayne State University

Correspondence concerning this article should be addressed to:

Brett Kessler
Department of Psychology
Wayne State University
71 W. Warren Ave.
Detroit MI 48202
USA

Phone 1-313-577-9252
Fax 1-313-577-7636
Electronic mail BrettKessler@ACM.org

Abstract

To get a better understanding of the nature of the English writing system, new techniques are introduced for measuring how strongly the orthography of one part of the syllable (onset, vowel, coda) is influenced by the other two parts. The use of conditional consistency measures with permutation tests of significance determines how much more regular sound–letter correspondences become when other parts of the syllable are taken into account. A study of English monosyllabic words presents results for both reading (letters to sounds) and spelling (sounds to letters), and both adult and child vocabulary. In all cases, vowel and coda (which constitute the rime) are much more strongly conditioned by each other than are other pairs. These techniques and findings improve our understanding of the English writing system and provide a foundation for a better understanding of reading and spelling processes in children and adults.

Key words: spelling, reading, rime, vowel, consistency, context sensitivity

Relationships Between Sounds and Letters in English Monosyllables

The English writing system has attracted a good deal of research from psychologists, linguists, and educators because of its complexity. Although the system is basically alphabetic, with letters standing for sound segments (phonemes), there are many complications. For example, English tends to keep the spelling of morphemes constant even if their pronunciation varies (cf. heal, health); to differentiate homophones (broach, brooch); to echo the orthography of the language from which a word was borrowed (stein from German, nymph from Greek); and to agree with past usage (write with w, which used to be pronounced). As a result, a reader who uses only knowledge about the individual letters of a word or a speller who considers only the individual phonemes will make many errors. Hanna, Hanna, Hodges, and Rudorf (1966) showed that 73% of the phonemes in their dictionary would be spelled correctly if one applied the letter string that most often corresponds to the phoneme. Because most words contain several phonemes, few words would be spelled entirely correctly on the basis of context-free rules that link single phonemes to single graphemes.

Must readers and spellers rely, then, on memorization of whole words? Before drawing such a conclusion, we should explore the possibility of a middle ground between the whole-word memorization approach and the letter-by-letter or phoneme-by-phoneme approach. That middle ground is that readers and spellers use correspondences between spellings and phonemes that are conditioned by context. Two things would need to hold for such an approach to work. First, it would need to be the case that the consistency of letter-to-phoneme and phoneme-to-letter mappings can be improved through a consideration of context. Second, we would need to show that readers and spellers take advantage of the contextual dependencies. The work reported here is directed toward the first of these issues. We report analyses of English letter-to-sound and sound-to-letter correspondences, using new techniques to measure how strongly the pronunciation or spelling of one part of the syllable is influenced by the other parts. (These mappings sometimes operate at a multiphonemic level; we use the term sound as a shorthand for referring to phoneme strings of unspecified length.) By examining adult and first-grade vocabulary separately, we distinguish the patterns that are available only to skilled readers and spellers from the patterns that children may encounter when they are learning to read and spell.

The bulk of research in orthography has been from the standpoint of reading, inspired in part by the systematic but nonquantitative work of Venezky (1970; see also 1999). Venezky laid out a number of context-conditioned rules, such as the fact that a is pronounced /ɑ/ between letters representing /w/ to the left and nonvelar consonants to the right (wad, cf. sad, wag). (For an explanation of the phonetic symbols used in this paper, see International Phonetic Association, 1996, 1999.) Most of the patterns listed by Venezky refer to conditioning elements that are to the right of the letters in question. Thus, the sound of a vowel letter string is more often disambiguated by the following consonant letters than by the preceding ones. However, Venezky did not give quantitative evidence on this point. Berndt, Reggia, and Mitchum (1987) did provide a quantitative description of English grapheme-to-phoneme correspondences, but they did not address the effects of context. Stanback (1992) started with the assumption that syllables should be parsed into onsets (initial consonants) and rimes (vowel–final consonant units). Her results suggest that the pronunciations of rimes are often consistent, a conclusion echoed by Ziegler, Stone, and Jacobs (1997). Aronoff and Koch (1996), however, questioned some of Stanback's conclusions, claiming that only 12 rime letter strings are worth treating differently from their individual components. Moreover, neither Stanback nor Ziegler et al. demonstrated that an onset–rime division of the syllable yields better results than a head–coda division (a head is a grouping of onset and vowel).

Treiman, Mullennix, Bijeljac-Babic, and Richmond-Welty (1995) made the first systematic attempt to measure the overall consistency of vowel–consonant (rime) combinations and to compare it to the consistency of individual segments or other combinations, such as the head. Those investigators studied the links from letters to sounds for 1,329 CVC (consonant–vowel–consonant) words of English. These are monosyllables that have exactly one consonant phoneme in the onset and one consonant phoneme in the coda. Treiman et al. showed that the letter strings comprising rimes map more consistently to sounds than do the letter strings comprising heads. For each word, they computed its rime consistency by counting the number of words that share both its rime spelling and pronunciation (e.g., ead = /ɛd/ in head, dead) and dividing that by the number of words with the same spelling (e.g., head, dead, bead). Then they averaged those ratios across all words to get a mean consistency for rimes. That number was higher than the equivalent measure computed over heads.

Although the results of Treiman et al. (1995) suggest that a consideration of rimes improves the letter-to-sound regularity of English, the study has some limitations. First, the study examined only monosyllables with CVC structure. In the present study, we extended the purview to all familiar monosyllabic words, not just the CVC ones. It might be asked why we did not go farther and compute over all words, including polysyllables. One problem is that polysyllabic words raise difficult questions of where syllable boundaries lie. In a word like lemon it is unclear whether the /m/ is the coda of the first syllable, the onset of the second syllable, or perhaps both, ambisyllabically (e.g., Treiman & Danis, 1988). Polysyllables also have much higher proportions of foreign, Latinate, and technical words, and so may differ substantially in orthographic structure from monosyllables. In addition, thorny issues of stress assignment arise in the reading of polysyllables which do not occur for monosyllables (e.g., Rastle & Coltheart, 2000). If there is any important difference between the two sets of words, it is useful to start with monosyllables. Stanback (1992) also pointed out that about three quarters of the word tokens used in text are monosyllabic: They are disproportionately important.

Another limitation of the study by Treiman et al. (1995) is that it examined the links from letters to sounds but not those in the reverse direction. In the present study we looked at both directions. The two cases are not symmetrical. While ight always spells /aɪt/, /aɪt/ can be spelled other ways (e.g., right, rite); the reading consistency is much higher. The phoneme /ð/ is always spelled th, but th can be pronounced /ð/ (that) or /θ/ (thick); the spelling consistency is much higher in this case. Although the era of large-scale computerized vocabulary studies was introduced by the phoneme-to-letter study of Hanna et al. (1966), less work has been done on analyzing English orthography from the standpoint of the speller than from that of the reader. One exception is the work of Cummings (1988). Like Venezky's (1970), Cummings' work was informal and nonquantitative, and did not directly address which parts of the syllable most strongly condition the spelling of other parts. Ziegler et al. (1997) reported a quantitative study of rime-level sound-letter consistencies, but they did not compare the consistencies of rimes to the consistencies of other units. A recent quantitative study by Peereman and Content (1998) suggested that there is no rime advantage in English spelling, so it is important to look further into this issue.

An important consideration in studies of this nature is the selection of a consistency measure. Treiman et al. (1995) improved on earlier measures of letter-to-sound consistency by using a measure that takes into account the frequencies of all letter-sound correspondences, not just the one or two most frequent pronunciations for a letter string. As mentioned above, they computed consistency by dividing the number of words with a particular letter-to-sound correspondence by the number of words with the particular letter string, and averaged those ratios across all words.[1] Consistency of a letter string thus decreases as the number of different pronunciations increases. And for a fixed number of pronunciations, the more equiprobable they are, the lower the consistency. The summary measure is therefore much more informative than simply measuring what fraction of the words have the modal pronunciation for a particular vowel letter string.

To address the question of whether rime spellings are especially consistent, Treiman et al. (1995) compared the average consistencies of CV combinations with those of VC combinations. However, this approach is not ideal because the numbers are determined in part by the independent frequency distributions of the consonants in the onset and coda. For example, even if the correspondences were completely independent across onset, vowel, and coda, then CV combinations would have higher consistency than VC combinations if the onset was independently consistent but the coda was not. The measure therefore is meaningful only under certain circumstances. In the reading study of Treiman et al., the fact that VCs were more consistent than CVs even though onsets were more consistent than codas by themselves strongly suggests a special connection between vowel and coda. But when Peereman and Content (1998), using the same measures as Treiman et al. but in the sound-to-letter direction, found that CVs were more consistent than VCs while onsets were more consistent than codas, the implications were less clear. Such a finding in itself neither supports nor refutes the idea of any special connection between vowel and coda. Also, even when the measure used by Treiman et al. is capable of revealing a special connection between two parts of the syllable, one does not know the direction of the influence: Does the vowel help predict the coda, or is it the other way around?

To overcome these problems, a new measure was used here: conditional consistencies. A conditional consistency is a consistency that is calculated on one part of the word when we require that some other part of the word has a particular value. For example, one could compute the reading consistency of the vowel letter string ea when the coda is d. By taking weighted averages, one can speak of the conditional consistency across different letter strings, and thus for the vowel as a whole. For each part of the syllable, we calculated its consistency, and then the conditional consistency that is obtained when one holds constant the other parts of the syllable.

Even the use of conditional consistencies does not settle all questions: There remains the issue of significance. Treiman et al. (1995) were correct in asserting that significance testing is not required because they were reporting population statistics, not sample statistics. There is no danger that random fluctuations will lead us to draw conclusions that will not be valid for another sample. But random fluctuations can cause trouble when using conditional consistencies. Conditional consistencies are equivalent to regression: The more variables one uses as predictors, the more accurately one can model the value of a result variable. In a finite sample, consistency will generally go up even if there is no real association between the predictor and the result. It is particularly easy to get spurious associations when the predictor variables take on several categorical values, and the sample size is not large enough to ensure that for each value of the result variable the predictor variables will take values in a reasonable approximation of their independent frequency distribution. These issues can become particularly important when we wish to compare two variables that have different distributions. For example, there are 145 different letter strings in the codas in the word lists we have prepared, but only 89 different letter strings in the onsets. If we find that vowel letters are more unambiguously pronounced when one takes into consideration the coda than when one takes into account the onset, that could simply be because there are more different types of codas. It would be useful to be able to go beyond that fairly trivial mathematical effect and see whether the coda is more effective a conditioner even when the different number of types is controlled for.

We want to know whether there is any special connection between parts of the syllable beyond what is attributable to chance. How much higher is the conditional consistency than the figure one would get if all the syllable parts were rearranged at random? That latter figure can be determined by literally rearranging at random the parts of the syllable under consideration. For example, to determine the chance-level conditional consistency of the vowel spelling given the coda, one would randomly redistribute the codas across all the words on the list. If the entire list consisted of cat=/kæt/, dog=/dɔg/ and horse=/hɔrs/, one would start off with the vowel-coda pairs at=/æt/, og=/ɔg/ and orse=/ɔrs/, and one possible rearrangement would be ag=/æg/, orse=/ɔrs/ and ot=/ɔt/. Note that the spellings and pronunciations for each word are kept together during a rearrangement. When one computes the conditional consistency over that rearranged list, one gets a conditional consistency that is due to chance. Of course one such rearrangement may by chance have an atypical conditional consistency value, so we smooth the answer by averaging together the results of computing the conditional consistency over ten thousand such random rearrangements. Such a procedure yields an average permuted conditional consistency, which we will use as a baseline against which to compare the actual conditional consistency. In addition, finding how close the actual conditional consistency falls to the tail of the distribution of those ten thousand rearrangements tells us the significance of the actual conditional consistency. This is a Monte Carlo computation of a permutation test of significance. Because the distribution is derived from the data itself, we do not need to consult any standard distribution to determine the significance level (Good, 1995). Statistical tests of this kind have not been used in prior studies of letter-sound relationships.

Because our goal was not to examine English as an autonomous entity but rather to examine the relationships between spellings and sounds that might be picked up and internalized by typical readers and writers, the selection of a word list is extremely important. We cannot rule out the possibility that unknown words, such as <u>thegn</u> or <u>veldt</u>, may have letter–sound correspondences that form no part of the typical reader's experiences. In order to ensure that the CVC words they analyzed were known by college students, Treiman et al. (1995) relied on the familiarity data of Nusbaum, Pisoni and Davis (1984). We used the same data as the basis of our word list, but found reason to question some of the individual data points. Nusbaum et al.'s study was based on self-reporting of the familiarity of words presented entirely in upper case letters. Consequently their data do not speak to whether a word like brad, which in upper case is confounded with the name Brad, is really familiar. In addition, several low-frequency words that are similar to medium-frequency words (e.g., cruse, which is easily mistaken for cruise), were rated suspiciously high. In the present study we controlled for such problems by cross-checking words with other, less comprehensive, familiarity ratings; by checking for dispersion across several dictionaries and word lists; and by removing items that in our judgment were not well known to college students.

In addition to that full list, which we call the adult word list, we identified a subset, the child word list, comprising words that are reasonably frequent in reading material presented to first-grade pupils in the United States. Almost all previous studies have concentrated on the adult vocabulary, and it is not clear whether those results will apply to the vocabulary of children. There may be systematic differences in the vocabulary of children, such as a relative lack of learned borrowings from foreign languages, which may change the picture. Even absent such systematic differences, smaller vocabulary size leaves less room for significant patterns to unfold. If there are significant effects in the adult word list, such that the spelling of one part of the word becomes more consistent when one considers some other part, is that something that young children encounter in their reading and writing vocabulary? Or can these effects at best be picked up only years later as vocabulary size increases? By running identical tests on the two different vocabularies, we begin to address these questions.

Reading

Our first analysis studied the orthography of English monosyllables from the viewpoint of the reader. We looked at the letter-to-sound consistencies of onset, vowel, and coda, computing for each of those three parts the conditional consistencies that are obtained by taking into account the letter strings of each of the other two parts of the syllable. Our interest was in the degree to which the pronunciation of one part of the syllable is influenced by the other parts. Would the strongest influences be found between the vowel and the coda, as suggested by the findings of Treiman et al. (1995) with CVCs?

Method

Selection of adult word list. For the adult word list, our goal was to select English monosyllabic words that most American college undergraduates would be familiar with in print. Because we wished to concentrate on the core orthographic system, we rejected abbreviations, letters, numerals, and the like. We also excluded proper nouns. When a word has multiple spellings, we used the predominant U.S. spelling, relying on the main entry of Flexner (1987) in case of doubt.

We used both automated and manual procedures to select words that met our criteria. Candidates were gleaned from a set of dictionaries, both online (Centre for Lexical Information, 1987; Milton, 1992; Sejnowski & Rosenberg, 1988; Ward, 1993; Weide, 1995; Wilson, 1987) and printed (Flexner, 1987). We also consulted two corpora (Francis & Kučera, 1982; Zeno, Ivenz, Millard & Duvvuri, 1995), and lexical data provided by other researchers (Metsala, 1997; Nusbaum et al., 1984). Words were rejected if they did not appear with monosyllabic pronunciations in at least one of the pronouncing dictionaries, if their pronunciation included non-English phonemes, or if their spelling included any character other than a lower-case letter, a–z. To reduce redundancy, we also rejected any word that can be analysed as a suffixed form of some simpler word whose pronunciation is already in the list.

To decide whether a candidate word was familiar enough to be included in our list, we first examined its rating in Nusbaum et al. (1984). If this rating is 4 (the meaning of the word is unknown) or lower, the word was rejected. If the Nusbaum rating is above 4, the word was normally accepted. But it was rejected if none of the other sources that have familiarity or frequency information (Metsala, 1997; Milton, 1999; Wilson, 1987; Zeno et al., 1995) map to a Nusbaum value higher than 4 (the values were converted by means of linear regression equations that were calculated on the basis of words that appeared in both Nusbaum and the other sources). If there is no Nusbaum rating for a word, we accepted it if it appears in Flexner (1987) and there is strong evidence that it is familiar: It is rated at Nusbaum 5 or above by two different sources; or it is rated at Nusbaum 6 or above in some source and it is listed in at least two other American sources. This criterion pulls in many words that Nusbaum et al. did not test because they are extremely frequent (e.g., a, and, as), as well as several missing for less clear reasons (e.g., bay, beach, bed).

The automated processes reduced the list of candidates to a size conducive to manual editing. Several words were discarded after we judged that they were unlikely to be familiar as lower-case words (e.g., brad), or that they had likely been mistaken for more common words in the Nusbaum et al. (1984) study (e.g., cruse). When there are two words spelled alike but with different pronunciations, we used judgment to decide which word is actually familiar, or if both are. For example, the meaning of mow as a stack of hay, pronounced as /maʊ/, was rejected. We also rejected words that were primarily paralinguistic, such as animal cries; names of letters and musical notes; and words marked slang, dialectal, or archaic in Flexner (1987).

Our final list contained 3,117 words: 1,329 CVCs and the rest with other structures. This is similar in size to the lists of Hanna et al. (1966) and Harm and Seidenberg (1999). The smaller size of some other studies on monosyllables (less than 2900 words in Seidenberg & McClelland, 1989, and Ziegler et al., 1997) was often due to the fact that they were based on the corpus of Kučera and Francis (1967), which is of limited extent.

Selection of child word list. We also developed a smaller list of words that the average first grade pupil would be familiar with in print. The selection criterion was based on Zeno et al.'s (1995) count of how often words appeared in reading material targeted at pupils in the first grade and kindergarten. We selected all words that were in the college-age list and for which Zeno et al. report a first-grade *U* value (frequency adjusted for variation in distribution) of 20 words per million or higher. This list contained 914 words, of which 500 were CVC.

Pronunciation scheme. Any analysis of the correspondences between sounds and letters depends crucially on how the pronunciations are represented. The pronunciation standard we strove for was a careful pronunciation as would be used by young people in Michigan. Although there is some sharp differentiation among speakers in the phonetic realization of some of the vowels, especially among some white speakers in the Detroit area, the phonemic contrasts themselves are uniform and representative of speech in the United States as a whole. In cases of doubt we used the first pronunciation given by Flexner (1987). In this accent, words like fern /fɝn/ have three segments, with /ɝ/ being a unitary vowel. Words like bar /bɑr/ were considered to end with a consonantal /r/. In words such as tune and dune, the /j/-less form was used. In words spelled with initial wh and traditionally pronounced with /hw/, we used the now-dominant pronunciation /w/. We treated the vowel of bomb as /ɑ/, the same as the vowel in calm, representing a merger that is almost universal in North American speech. However, we treated /ɔ/ (wrought) and /ɑ/ (rot) as separate vowels, in accord with what is still the practice in much of the Midwestern U.S. Affricates and diphthongs were considered as single phonemes.

One difficult issue is whether words like fire and tower are monosyllabic or disyllabic. We relied on the judgment of the dictionaries, preferring Flexner (1987) in case of conflict. Thus, fire was considered a monosyllable but tower was not. As for the quality of the vowel in these monosyllables, we recorded the pronunciation by which most vowels are lowered before /r/, but not before /l/: thus /ɪr/, not /ir/, in beer; /ʊr/, not /ur/ or /ɔr/, in poor; /ɛr/, not /er/ or /ær/ in bare; /ɔr/, not /or/, in more, horse. This agrees with the procedure of Aronoff and Koch (1996), and is similar to that of Treiman et al. (1995), except that the latter transcribed words like more with an /o/. Hanna et al. (1966), in contrast, treated all r-colored vowels as separate phonemes, giving beer a different vowel from both beet and bit.

Sound–Letter alignment. Pronunciations were associated at the smallest level possible: usually individual phonemes, but with a few unavoidable exceptions as when /ks/ was assigned to x. Although alignment is straightforward for words like cat /kæt/, difficulties arise when digraphs and silent letters are involved. If we did not assign the b of debt to any phoneme, saying only that /d/ is spelled d, /ɛ/ is spelled e, and /t/ is spelled t, we would obtain artificially high estimates of the consistency of relations between sounds and letters. Therefore, we required that phonemes and letters match linearly and that everything be assigned to something. In cases of doubt, a "silent letter" was associated with the unit to the left. In calm /kɑm/, for instance, al was assigned to /ɑ/. Our approach differs from that of Treiman et al. (1995), who assigned w or y to a preceding vowel (as in lawn), but assigned other postvocalic consonant letters to the coda. Our contrary decision was based on the observation that silent letters modify the phoneme to the left much more often than they modify the phoneme to the right. For instance, the difference in pronunciation between calm and cam is in the vowel rather than the final consonant.

The sole exception to the preceding rules was that, when e is not the first vowel letter in the word (excluding from consideration here the digraphs ee and ie), it was given a special status, Silent E. Silent E is special in English because it has several functions, none of which is to directly represent a phoneme; in the terminology of Venezky (1999), it is a marker, not a relational unit. In make it functions to show that the a has the pronunciation /e/, not /æ/. This is perhaps the most familiar use of Silent E, and Hanna et al. (1966, p. 32–33) and Treiman et al. (1995) generalized this and assigned all Silent E's to the vowel. But the letter has additional functions as well. In bathe, it shows that the th represents a voiced phoneme. In peace, it shows that the c is pronounced /s/, not /k/. In house, it shows that the s is not a separate morpheme. In toe, it ensures that the word has at least three letters (a general requirement for nouns, verbs, and adjectives). In borne, it distinguishes the word from born. Unlike other markers, Silent E can serve several of these functions at the same time. A simple assignment of Silent E to any single phoneme in the word could be misleading or incomplete.

We considered Silent E as part of the vowel if the vowel is (otherwise) spelled with a single vowel letter (a, e, i, o, u, or y), provided that single vowel is followed by a single consonant phoneme (hate) or /st/ (haste), or no consonant at all (toe), then the silent e. Normally any intervening consonant must be spelled with a single letter, but we also permitted ch spelling /k/ (ache), gu spelling /g/ (vague), and th spelling /ð/ (bathe). Silent E was considered part of the preceding consonant if that consonant is g or dg spelling /dʒ/ (gorge, badge); g spelling /ʒ/ (beige); c spelling /s/ (farce); s spelling /s/ or /z/ (house); th spelling /ð/ (wreathe); or v, z, or u (have, bronze, league). If neither of those conditions holds, the e was considered part of the preceding consonant (steppe). If both of these conditions hold, then the Silent E was assigned to both the vowel and the consonant. For example, cage /kedʒ/ was aligned c=/k/, a_e=/e/, g_e=/dʒ/.

Computing consistency. Our primary interest is in the consistency of relationships between letters and sounds. For example, what is the consistency of reading the letter c in the onset? If the letter string is always sounded the same way, then the consistency is 1. Otherwise, the consistency is some number between 0 and 1. Consistency was computed by calculating the proportion of the instances of the letter string each distinct sound accounts for, then taking the weighted average across those sounds. For example, the consistency of the onset letter string c is .884, because of the 97 words with onset c, 91 of them (.938) are pronounced with /k/ and 6 of them (.062) are pronounced with /s/. The weighted average of those proportions is $(91 \times .938 + 6 \times .062)/97 = .884$. The consistency of the onset letter strings as a whole is simply the weighted average of those consistencies across all onset letter string types.

We also computed conditional consistencies averaged across all possible onsets, vowels, and codas. For example, to find the conditional consistency of the onset letter string g given the vowel, we computed the (unconditional) consistency of g before each of the vowel letter strings it appears before. The letter g is pronounced /g/ in each of the words where the vowel is au, so the consistency there is 1.0; before the vowel e the consistency is .625, because in 3 words it is pronounced /dʒ/ (gel, gem, gent) and in 1 word it is pronounced /g/ (get): $(3 \times 3/4 + 1 \times 1/4)/4 = .625$. When the weighted average of those consistencies before each vowel is taken, we have the conditional consistency for the onset letter g. Such figures are averaged across all onset letters to get an average figure for onset letter strings in general. We also determined the average permuted conditional consistency, and the significance of any conditional consistency that is higher than that average.

All computations used type frequencies. That is, each word was counted once, regardless of its frequency in text.

Results and Discussion

Tables 1 through 3 show the computed reading consistencies for the adult vocabulary. The results for vowels are presented in Table 1, the results for onsets in Table 2, and the results for codas in Table 3. In each table, the top rows are the most important: They show consistency computed by word-type counts across all words. However, we present the results a total of four ways, varying whether one looks at all monosyllables or only CVC words; and whether one includes words that have postvocalic /r/ or excludes them. The motivation for presenting the results separately for CVCs is to allow comparison with the results of Treiman et al. (1995), which were based only on CVCs. The motivation for presenting results excluding words with postvocalic /r/ is that the conditional effects of postvocalic /r/ are pervasive: Virtually all vowels have special spellings before /r/. Because that condition is widely recognized, it could be thought that any overall conditional effect of codas on vowels is due to /r/. Presenting results for words lacking postvocalic /r/ forestalls such an interpretation.

To summarize the table structures by way of example, the first rows of Table 1 show that when we compute over all words, the consistency by which letter strings map into vowel phonemes is .717. Vowels are less consistent than either onsets (.976) or codas (.982), as shown in Tables 2 and 3, respectively. These figures are in the columns labeled “Unconditional Consistency”. That is short for “consistency that is not conditioned by other elements in the syllable”. Of course all our measures have several implicit conditions; for example, the “unconditional” consistency of the onset consonant can be thought of as the consistency of the consonant, conditioned by the fact that it is in the onset. If the onset is taken into account in pronouncing the vowel, the consistency rises to .807. The improvement over chance is 0.1%, and is not significant. But if the coda is taken into account, consistency rises to .920, which is a significant ($\underline{p} < .001$) improvement over chance of 13.6%. Thus, consideration of the coda provides information that is potentially helpful in pronouncing the vowel. When two parts of the syllable each significantly improve the spelling of the part under consideration, as is the case when /r/ words are excluded in Table 1, an additional row is added (here Coda/Onset) which compares the magnitude of the two improvements by presenting their ratio.

Adopting a significance level of .05, we can conclude that knowledge of the coda letters substantially increases the consistency of the vowel reading (Table 1). However, knowledge of the onset letters provides little or no help in the reading of the vowel. There is a significant but minuscule improvement of 0.7% if we exclude words with postvocalic /r/, but the increase is not significant in any of the other tests. Knowledge of the vowel letters does increase consistency of the onset reading by a significant but minuscule amount, less than 1% over chance (Table 2); vowels do not significantly improve reading of the coda (Table 3). Knowledge of the onset does not reliably improve the consistency of the coda over chance levels, nor vice versa.

The same analyses were performed over the child vocabulary. The results, although not presented in the main tables, are summarized in Figure 1, with separate diagrams for the adult and child vocabulary. The numbers tell by how much more than chance one syllable part increases the consistency of the adjacent part, in the direction of the arrow (leading from the predictor to the predictee). The only significant effect for children was that codas increase the consistency of vowels by 11.6% over chance ($\underline{p} < .001$). The onset does not help significantly, nor are consonant readings improved when one considers other parts of the syllable. When comparing significance levels, it must be kept in mind that the size of the child word list is less than a third the size of the full adult list: It is not necessarily meaningful that very small effects in the adult list are insignificant in the child word list. What is meaningful is that the general tendencies are the same. The preeminent result in both sets of words is that codas help predict vowels much more than any other part of the syllable helps predict anything else.

The results presented so far are weighted averages across many different onset, vowel, and coda types. That approach gives a good sense of the relative magnitude of the interactions between the various parts of the syllable, and it is relatively succinct. However, it is also helpful to look in the details for patterns that are lost in the aggregate. Those details help us to better understand the source and nature of the patterns. One immediate finding upon closer inspection is that even when parts of the syllable interact, that is not always true for all possible sound or letter string types for those parts. Secondly, many of the interactions fall into patterns that generalize across many vowel and consonant types.

There are 68 different vowel letter strings used in English monosyllables, and 39 of those are completely consistent. Of the 29 that have some inconsistency, 23 are significantly helped by the letter string in the coda. The facts are summarized in Table 4, which lists all the vowels for which the permutation tests show a significant increase in consistency when codas are considered. The default letter string is that which dominates after major conditions have been taken into account. The conditions listed are those that make the default vowel phonemes less likely; we have omitted conditions that make the default more likely. Where possible, we listed conditions that are significant by a 2×2 χ^2 test and affect several words. As an example, the first lines of Table 4 show that a is generally pronounced as /æ/ but that the /ɑ/ pronunciation becomes more common when a is in word-final position or when it is followed by r. Results are similar for children's words, though scaled down because of the smaller number of words. There are 46 distinct vowel spellings in this vocabulary, 23 of which are fully consistent. Of the remaining 23 spellings, 11 are significantly improved by the coda.

Sound change is behind most of the conditionings in Table 4, although readers are typically not aware of this. For example, consider the fact that i, which usually is pronounced /ɪ/ as in bit, is usually pronounced /aɪ/ before nd and ld, as in mind and wild. This is due to a sound change that occurred in Old English: A short /i/ (ancestor of modern /ɪ/) was lengthened to long /iː/ (ancestor of modern /aɪ/) before /nd/ or /ld/. Similarly, in the American accent under consideration, many vowels have changed their pronunciation before /r/, but the spelling has not changed to explicitly reflect that fact. Therefore words like rare have letter strings that in the first instance should represent /rer/; but the sound change means that it is pronounced /rɛr/ instead. The fact that sound change usually affects all words of a particular structure makes reading not nearly as difficult as it might be. For example, because Old English /i/ was lengthened before all /ld/ sequences, and because the spelling reflects the original pronunciation, one only has to look at the following consonants to determine whether current i should be pronounced /ɪ/ or /aɪ/.

In contrast to the 23 vowel letter strings in the adult vocabulary that are read significantly better when one takes the coda into account, only two of the vowel letter strings can be read significantly better when one takes the onset into account. The letter a is significantly helped because when the onset ends in a spelling of /w/ (w, qu), the vowel is interpreted as if an o, i.e., normally /ɑ/ (e.g., squad), but /ɔ/ before r (e.g., warm). This is a sound change: The rounding of the lips needed to form /w/ systematically spread to the adjacent vowel (the phoneme /ɑ/ is the descendant of an earlier rounded vowel). The conditioning is highly significant ($p < .001$). Some examples are present in the child vocabulary, but not in enough words to reach significance. The only other onset conditioning that proves significant in the adult vocabulary ($p = .035$) is due entirely to the curiosity that the only word in which i_e is read /i/ also begins with su (suite). This word is not in the child vocabulary, contributing to the fact that onset conditioning is not significant overall for that vocabulary subset.

The great majority of consonant letter string types have perfectly consistent pronunciations. There are 145 distinct letter strings in codas in the adult vocabulary, and 137 of those are at ceiling. Of the eight with inconsistencies, two are improved by considering the vowel letter string. The coda s can be pronounced /s/ or /z/, but, curiously, is always /s/ after u (e.g., bus, plus); this is the major contributor to a significance of .041. Just as curious is the case of s with a Silent E. Its high significance

(.002) is due to the fact that of the two pronunciations /s/ and /z/, /s/ is overwhelmingly predominant after *r* and *ou* (*nurse, spouse*). The child vocabulary is not extensive enough to make either of these conditionings significant.

Ten out of the 89 onset types have some inconsistencies in the adult vocabulary, and four of these can be significantly aided by considering vowel letter strings. Three of those are due to a French spelling convention that has been adopted in English. In French, *c* corresponds to /s/ before *e, i,* and *y*, and /k/ elsewhere; *g* spells /ʒ/ before those same three letters, and /g/ elsewhere. English has completely adopted the convention (with /dʒ/ instead of /ʒ/), except that it admits a few exceptions where *g* spells /g/ before *e, i, y* (*get, girl*). This accounts for a significant influence by the vowel letter on reading the onset strings *c* (e.g., *cent* vs. *cat*, $p < .001$), *g* (e.g., *gem* vs. *gate*, $p < .001$), and *sc* (e.g., *scent* vs. *scald*, $p = .005$). Perhaps because words with *c* spelling /s/ or *g* spelling /dʒ/ in the onset are loans from French or Latin, they are infrequent in children's reading materials, and none are on our child word list. The remaining case of onset influence in the adult vocabulary is that the reading of the onset *wh* can be significantly ($p = .004$) improved by considering the following vowel: It is normally /w/ (e.g., *what*), but usually /h/ before *o*. Only *who* and *whole* are present in the child vocabulary, which is not enough to achieve significance.

Even though we followed procedures similar to those of Treiman et al. (1995) in computing unconditional consistencies, we have got slightly different results. Whereas the previous researchers found that onsets had a consistency of .94 and codas .92, we got slightly higher numbers of .97 for both syllable positions even when we restricted our purview to CVC words, as they did. Our results for the head and rime as a whole (not mentioned in the tables) were also rather higher than theirs: For the head we got .82 versus their .55; for the rime we got .92 versus their .80. Several factors may have resulted in lower numbers on their part. First, they computed consistency of their word lists based on values derived from larger lists, such as the set of all monosyllables. Larger lists are bound to have more varied phonotactics and orthographics, and hence, less consistency than a small set of CVC words. More importantly, those larger word lists were not controlled for familiarity, and, as we have noted, even their basic list of CVC words contained some material that was inadequately controlled for familiarity. Including words like gneiss will certainly decrease consistency metrics. Second, the treatment of Silent E in Treiman et al. was harder on consistency metrics than was our own treatment. For example, in a word like lunge, we assigned the Silent E to the coda, where Treiman et al. assigned it to the vowel. In our study, the resultant nge is pronounced /ndʒ/ with full consistency; in their study, the resultant ng would appear very inconsistent, being pronounced /ndʒ/ in some words (those with Silent E) and /ŋ/ in some words (those without Silent E, like lung). If we rerun our data, this time always assigning E to the vowel as Treiman et al. did, we arrive at a consistency of .94 for the coda, which is much closer to their figure of .92.

Despite our findings of somewhat higher consistencies overall, the patterns uncovered in this analysis of monosyllables from the standpoint of the reader confirm the basic finding of Treiman et al. (1995). In showing that vowel–coda (rime) units are more consistent than onset–vowel (head) units even though by themselves the codas were no more consistent than onsets, they demonstrated that rimes have a special status in reading. But many questions were left unanswered. Was the special association caused by some differential distribution of the consonant types in the onset and coda? If not, by how much did the increase in consistency exceed the amount that one would expect whenever many-valued categorical variables are juxtaposed? Were the vowel letters helping to predict the coda sounds, were the coda letters helping to predict the vowel sounds, or both? Was the association limited to a few vowels and consonants, or was it broader in scope? Our current study answers these questions. By far the dominant effect is that knowledge of the letters in the codas helps disambiguate the pronunciation of the vowel. That goes far beyond what one would expect from the random combination of vowels and consonants: It is a 13.6% improvement over chance. By contrast, the only other significant conditioning is that vowel letters help predict onset sounds, but at only a 0.8% improvement over chance. We have also shown that the effects are spread out broadly among the various letter strings. Of the 29 ambiguous vowel letter strings, 22 are significantly improved by considering the coda, but only 2 by considering the onset. We have also extended the results of Treiman et al. by showing that they apply not only to CVC words but to monosyllables of other structures.

Importantly, the same general results apply when we consider words that young children are likely to encounter. In fact, the rime advantage is more pronounced in that the only significant effect is that coda letters help in reading vowels. While the difference in significance levels between children and adults is partly due to the smaller size of the child word list, some of it reflects differences in the vocabulary of younger children. Young children's vocabulary seems to lack significant onset–vowel interactions because of an underrepresentation of Latinate vocabulary, where c and g have special values before e, i and y. For beginning readers, therefore, the rime superiority is not just predominant, it is exclusive. Learners' exposure to onset–vowel interactions is both smaller than and begins later than their exposure to vowel–coda interactions.

In this paper we have used type-based measures. A word like of is counted no more nor less heavily than a word like love, despite the large difference in frequency: About half of all words in text that end in /v/ are instances of the word of. We have taken this approach because it corresponds to the logic of the English orthographic system. A word type is meant to have a unique correct spelling that does not vary across the multiple instances that a word appears in text. It is much more useful to think of the f:/v/ correspondence in of as something that occurs in a single word type than as something that applies to half of the instances of word tokens (words in text) that end in /v/. Under the latter view, one would just as readily spell love with an f half of the time. Because children are taught early in their education that words have single correct spellings, this type-based analysis is not just logical, but plausibly corresponds to how they in practice think about reading and spelling as well. Nevertheless it is reasonable to ask how our analyses of letter-to-sound correspondences would change if one were to take a frequency-weighted (i.e., token-based) approach. We ran such analyses, repeating each word by a count derived by rounding to the nearest integer the natural log of 2 plus the frequency of the word in Zeno et al. (1995). Consistencies and conditional consistencies are almost always comparable but a little bit lower than type-based measures. For example, the token-based measures for reading vowels in the child vocabulary are .647 for overall consistency (vs. .668 by types); .798 for conditional consistency given the onset (vs. .806), and .903 (vs. .911) given the coda. Such figures reassure us that our analysis is compatible with a token-based approach, but also suggest that it is indeed wise to direct children toward a type-based approach to reading. On the other hand, the numbers change quite a bit when we ask how much better than chance those token-based consistencies are. Randomly rearranging the parts of the syllables across word tokens gives a much lower chance consistency: Dropping the assumption that the orthography of a word is stable causes the chance consistencies to plummet. Accordingly, the estimate of the significance of the conditioning (the degree to which measured consistency is greater than chance consistency) is greatly increased vis-à-vis type-based calculations. Because of ceiling effects, that means that some of the ratios between improvements over chance, such as the relative influence of the coda over the onset, are smaller. Nevertheless, the effects all go in the same direction as reported for types. These token-based data, as well as additional data not presented here, can be viewed on the Web site referenced in the author note.

Spelling

As mentioned earlier, much less work has been done on analyzing English orthography from the standpoint of the speller than from the standpoint of the reader. Our goal in this part of the work was to provide a quantitative analysis of sound-to-letter correspondences for English monosyllables, asking which parts of the syllable most strongly condition the spelling of other parts.

Method

The same word inventories, spellings, pronunciations, and alignments were used as in the analyses of reading. Consistency was computed over individual sound types, to see how consistently the letter strings spell them. The analyses were the same as in the case of reading.

Results and Discussion

Tables 5 through 7 show the spelling consistencies for the adult vocabulary. To take an example of how these tables are read, the first rows of Table 5 show that when we compute over all words, the consistency by which letters spell the vowels is .529. This is substantially lower than the spelling consistency for onsets (.910) and codas (.821), shown in Tables 6 and 7, respectively, and it is also lower than the reading consistency for vowels. If the onset is taken into account, the consistency rises to .649, which is a significant ($p <$ .001) improvement of 2.2% over chance. If the coda is taken into account, consistency rises to .737, which is also a significant ($p < .001$) improvement over chance, though to a much larger degree, 16.8%. Knowledge of the coda improves consistency 7.619 times as much as does knowledge of the onset.

To summarize the significant results in Tables 5 through 7, the consistency of the vowel spelling is aided by knowledge of both the onset sounds and the coda sounds. However, the latter is much more influential than the former (Table 5). Conversely, knowledge of the vowel phoneme significantly improves the spelling consistency of the onset (Table 6) and of the coda (Table 7), though by much more in the latter case: 9%, versus 1% for the onset. Knowledge of the onset does not improve the spelling consistency of the coda over chance levels, nor vice versa. Substantially the same results apply whether we include or exclude words with postvocalic /r/ and look at all monosyllables or only the CVC ones. As the lower two diagrams in Figure 1 show, the picture for the child vocabulary is very similar to that of the adult vocabulary, except that the effect of onset on vowel does not reach significance.

When one examines the details of how consonant sounds affect the spelling consistency of vowel sounds, one is immediately struck by a disparity between onsets and codas: Whereas 14 of the 15 vowel types in the adult vocabulary are affected by the coda, all at $p \leq .001$ (Table 8), only 4 of the vowels are significantly affected by the onset. Very similar results obtain for the child word list: 13 of the 15 vowel types are spelled significantly more accurately if the coda is taken into account, but only one is affected by the onset.

In Table 8, one can detect two broad classes of ways in which vowel spellings are influenced by codas. The first is purely graphical. These are cases where the same phoneme is spelled different ways for visual reasons, leading to conditions that usually do not affect reading consistency. One pervasive consideration is that several vowels are spelled differently when they are word-final. For the most part, this is due to a reluctance to use i or u at the end of words: y and w are used instead. Another condition that might best be explained graphically is the use of o where u is expected, as in love. Such spellings are probably due to a strong reluctance to write u before v (which was originally the same letter), and a weaker reluctance to write it before the graphically similar n or m: Sequences like uv, un could be confusing in certain medieval scripts (Jespersen, 1909–1949, vol. 3, as cited in Venezky, 1970). The same consideration might explain the prevalence of aw and ow instead of au and ou before n.

The other great class of conditions are the results of sound changes. To some extent these are the simple inverse of the changes listed for reading in Table 4: Even as in reading i takes on a special pronunciation /aɪ/ before ld, in spelling /aɪ/ takes on a special spelling, i (without Silent E), before /ld/. Some differences between the contents of the tables stem from the fact that relative importance may change when viewed from the different directions. There is, however, one major asymmetry between reading and spelling that not only makes the tables irreversible but also makes spelling significantly harder. As mentioned above, sound changes usually affect all words that have a particular structure. Therefore, because the orthography basically represents the earlier pronunciation, one can unambiguously read off the current pronunciation from the spelling. But there is no guarantee that sound change will result in a structure that no other word already has, and so the fact that the orthography represents the earlier pronunciation can sometimes hinder spelling. For example, /o/ has become /ɔ/ before /r/, as in hoarse. In reading, one readily decodes that oa is /ɔ/ before /r/. But since there were already words with /ɔ/ before /r/ (such as horse), the pronunciation offers no clue as to what the original pronunciation, hence the letter strings, should be. For such reasons the consistency of spelling is on average much lower than the consistency of reading.

The sound change which had perhaps the greatest effect on the English spelling system was that which led to the use of Silent E at the end of words (Venezky, 1999, p. 100). Vowels lengthened in open syllables, that is, at the end of the word or if followed by no more than a single consonant before the next vowel. Subsequently, the pattern CV after a vowel could serve as a sign of length, and that remained true even after final schwas, spelled e, became silent. Final e came to be employed as a marker of vowel length, provided only a single consonant or st intervened between it and the vowel. We highlighted the importance of this pattern by running a separate analysis to see how much the spelling of the vowel could be improved by taking into consideration nothing but the number of consonants that followed it. The improvement is a considerable 11.2% over chance, and is significant at $p < .001$. That can be compared to the overall 16.8% improvement that obtains when all the information in the coda is taken into account.

The influence of onset sounds on vowel spelling is much smaller than that of codas. Only four of the vowels in the adult word list are significantly conditioned by the onsets. There do not seem to be any cases where vowels are spelled differently when they stand at the absolute beginning of the word, as was the case for i/y, u/w at the end of words. There does seem to be one clear case of graphic conditioning, however: The prevalence of wo for expected wu (as in work, contributing to a significance of $p < .001$ for /ɝ/) is probably a graphical avoidance, much like avoiding uv. There are two clear cases of conditioned sound change. The use of /ɑ/ instead of /æ/ after /w/ ($p < .001$) is a simple phonetic change. More complicated is the distribution of oo and u_e, eu, ew as spellings of /u/. The latter set is used for almost all cases of /ju/, as found in huge, feud, few. The /j/ has however disappeared after dental and alveolar consonants, without change in spelling: blue, dew. Therefore the presence of a preceding /j/, or of dental/alveolar consonants, can be a significant clue to the correct spelling of /u/ ($p < .001$). The fourth and last case where the onset makes a significant contribution to the consistency of vowel spelling, and the only one that applies to the child subset ($p = .029$ for children, $p < .001$ for adults), is the fact that /ʌ/ is improved by considering the onset in a few words. Unlike the case with codas, very little of the improvement due to onsets can be attributed to the size of consonant clusters. The improvement over chance, although significant ($p < .001$), is a tiny 0.7%.

As for the spelling of the consonants, the consistency of the coda is helped quite a bit by taking the vowel into account (9% increase over chance). This applies, however, only to single-consonant codas. Of the 72 multiple-consonant coda clusters in the adult vocabulary, 56 are at ceiling and the other 16 are not significantly helped by the vowel. If we look at the 21 single-consonant codas, only two of them are completely consistent; of the remaining 19, 11 are significantly affected by the vowel. For children's words, 40 of 52 distinct codas are at ceiling, and 5 of the remaining 12 are significantly improved by considering the vowel.

One fact accounts for the high increase in conditional consistency for many of the codas, and this at $\underline{p} < .001$. The phonemes /dʒ/, /tʃ/, /f/, /k/, /l/, /s/, /z/ are all spelled with more letters when they are the sole consonant in the coda and follow a single vowel letter (e.g., stuff, rock) than otherwise, i.e., when clustered in the coda (e.g., loft, silk) or when the vowel is spelled with two letters, including Silent E (e.g., loaf, lake). Because some vowels are almost always spelled with one letter and others are almost always spelled with two, it follows that the identity of the vowel would strongly condition the spelling of those consonants, but only when they are alone in the coda. The foregoing considerations apply also to children's vocabulary: /tʃ/ is significant at $\underline{p} = .007$, and /k/, /l/, /s/, /z/ at $\underline{p} < .001$. For the adult vocabulary, an equally significant condition is for /g/, which is spelled gu if and only if followed by a Silent E, which is part of the spelling of certain vowel phonemes, e.g., plague because /e/ is spelled a_e. A few other conditionings are less significant and much less regular. The coda /ʃ/ is conditioned at $\underline{p} = .002$ because it is more often spelled ch after long vowels, as in quiche: Long vowel plus /ʃ/ is common in French loan words, but not in native English words. A moderate significance level for /t/ ($\underline{p} = .029$) comes entirely from the coincidence that three of the four words in tt are preceded by /ʌ/. The phoneme /v/ has .021 simply because rev is the only word with both an /ɛ/ and a final v.

Only four of the 63 distinct onset types have their spelling significantly assisted by the vowel in the adult word list (41 are at ceiling). For /h/, the fact that it is sometimes spelled wh (who, whole) is enough to establish significance at $\underline{p} = .038$, though not for the child subset. A sound change deleted postconsonantal /w/ before round vowels, so the earlier spelling for /hw/ can now stand for /h/ in that environment. The other three interactions are all the result of the aforementioned French spelling convention that has been adopted in English. The phoneme /k/ is normally spelled k before e, i, and y, but c otherwise; that also goes for the /k/ in the cluster /sk/; /g/ is often spelled gu before e, i, and y, but g otherwise; all at $p \leq .001$. The first of these (/k/) is the only onset whose spelling is significantly helped by the vowel in the children's word subset ($p \leq .001$).

The general picture that obtains for spelling is summarized in the lower half of Figure 1. Each of the three syllable parts can be spelled better if one takes into account the sounds in any of the other adjacent parts. Similarly, each syllable part has certain sounds that are spelled significantly better when an adjacent syllable part is taken into account. But the magnitudes of the effects differ greatly, depending on whether one is looking at the onset or the coda. Improvements between the vowel and the coda are about seven times the size of corresponding improvements between the vowel and the onset. Furthermore, many more individual coda sounds than onset sounds are affected by the vowel, and many more vowel sounds are affected by codas than by onsets. These results hold equally well for CVC words and for monosyllables in general. And they hold for the child vocabulary as well as for the adult vocabulary, although some of the numbers for children are smaller because of the smaller size of the data set.

These results are not directly comparable to those of Treiman et al. (1995), because those researchers only looked at reading. However, Peereman and Content (1998), using the same methods as Treiman et al., reported that the rime did not show any advantage over the head in English monosyllables. The contrast with our results, which show that the vowel–coda pairing is seven times as strong as the onset–vowel pairing, could not be more striking. The difference is readily attributable to different methodologies.[2] Peereman and Content report only unconditional consistencies. But differences in those consistencies may be due to several factors. In their case, a low consistency for the rime was surely due to the fact that the coda itself had a much lower consistency than the onset. We argue that our new method of comparing conditional consistencies, especially after chance increases are factored out, furnishes a more direct answer to the question of how strongly one part of the syllable influences the spelling of another part.

Token-based analyses were also performed. They give comparable results to these type-based analyses, subject to the special conditions mentioned above in the Results and Discussion of the section on reading. Detailed results are available on our Web site.

General Discussion

The earliest work on the statistics of sound-spelling correspondence in reading and spelling (e.g., Hanna et al., 1966) assumed a context-free, phoneme-level processing model. But there are so many irregularities at that level that researchers began looking for broader models. Recent work such as that of Treiman et al. (1995) and the aforementioned analysis of Peereman and Content (1998) took a statistical approach tacitly retaining the assumption that processing is context free, but adding the idea that it potentially takes place on higher levels, such as over entire rimes or heads. We agree that broadening the domain of analysis is a major step in the right direction, but there are certain problems with keeping the statistical model context free. Apparent paradoxes arise. For example, if the greater consistency of rimes over vowels means that one processes at the level of rimes, does the greater consistency of codas over rimes mean that, at the same time, one processes at the level of codas, which are parts of rimes? The implication that rimes are processed as indivisible units seems implausible, and we in fact doubt that researchers who stress the role of rimes really intend that implication of their approach. That would mean, for example, that a person reading cat would have to take at = /æt/ as a unit and would gain no benefit from the fact that a spells /æ/ and t spells /t/ in so many other rimes. What we find a more plausible model is one that fundamentally operates on the phonemic level, but can take into account the context in which each phoneme is found. It is such a context-sensitive, phoneme-level model that we have based our new statistical methodology on.

Conditional consistency provides more information than past techniques, because it allows direct comparison of context-free consistency (e.g., vowels considered alone) with context-dependent consistency (e.g., vowels given the coda). It also allows one to consider directionality, distinguishing whether vowels help codas, vice versa, or both. But conditional consistency still suffers from the fact that improvements invariably happen when stochastic variables with many categorical values are juxtaposed in a finite data set. The introduction of permutation tests of significance allows one to factor out increases that are due to chance, and make observations that are more specific to the English spelling system itself.

One such finding is that spelling and reading are not symmetrical. Spelling is always harder: Each part of the syllable is less consistent in spelling than it is in reading, even when information from another part of the syllable is used as a predictor. At the same time, spelling is always helped when one takes into account the sounds in an adjacent part of the syllable. In reading, the conditioning is much more restricted. The only certain improvement is that coda letters help in reading vowels. Vowel letters do help in reading onsets, but not for young children.

Despite these differences, reading and spelling have much in common. The onset is not significantly associated with the coda in either case. Only adjacent syllable parts influence each other significantly. Vowels are by far the most inconsistent syllable part in both directions, and the part that gains the most from considering other parts of the syllable. One can look at this latter fact purely statistically: The vowel simply has more room for improvement. On the other hand, the vowel got to its current state of inconsistency for a reason. As illustrated from our consideration of individual string types, the vowel was affected by sound changes much more than the consonants were.

Another generalization that holds for both reading and spelling is that items tend to be helped more by the syllable part to their right than by the syllable part to their left. That holds absolutely for reading, where left-to-right influences (onset helping vowel, vowel helping coda) are not even significant. In spelling, codas improve vowel spelling about twice as much as the opposite. The only questionable part of the generalization is interactions between onset and vowel in spelling. It holds for the child vocabulary, where only the right-to-left influence (vowel improves onset) is significant. In the adult vocabulary, however, the onset does improve the vowel more than the other way around.

Perhaps the most important generalization is that effects between the parts of the rime (vowel and coda) are stronger than effects between the parts of the head (onset and vowel). There are four different ways of comparing rime effects to head effects. One way is to follow the arrows in Figure 1 from left to right: Does the onset help predict the vowel more or less than the vowel helps predict the coda? In reading, neither effect is significant, but in spelling, the rime-internal effect (vowel predicts coda) is four times as strong as the head-internal effect (onset predicts vowel). Another approach is to look at the arrows from right to left. In reading, the coda predicts the vowel (rime) 17 times as much as the vowel improves the onset (head); and for the children's vocabulary, the head effect is not even significant. The other two ways of comparing head and rime are vowel-centered. First, one can ask whether the onset influences the vowel (head effect) more or less than the coda influences the vowel (rime effect). In reading, there is no contest: The coda greatly assists in reading vowels, but the influence of the onset is not significant. In spelling, a similar situation exists for the child vocabulary, and for the adults, the rime effect is 7.6 times as strong as the head effect. Finally, one can go in the opposite direction and ask whether the vowel influences the onset (head) more or less than it does the coda. Again, in spelling, the rime dominates: The vowel's effect on the coda is 7.3 times as strong as the onset's in the adult vocabulary. In reading, the rime effect is not significant: Knowledge of the vowel letters does not help in reading the coda. But for the adult vocabulary, it does help to a very small extent in reading the onset. This constitutes the one exception to the rule that rime-internal effects are stronger than head-internal effects. For adult reading, the right-to-left generalization discussed above seems to dominate the rime advantage effect.

Despite that one exception, the big picture is clearly discernible in Figure 1. The largest improvements in conditional consistency are always between the vowel and the coda. The fact that vowel–coda associations are so much larger than those between the vowel and onset reinforces a series of findings that the vowel and coda share a special relationship, which is often formalized as saying that they form a separate intrasyllabic constituent called the rime (e.g., Fudge, 1969, 1987; Pike & Pike, 1947; Selkirk, 1982; Treiman & Kessler, 1995). From a historical standpoint, these associations surely originated from the fact that vowels changed more than consonants, and vowel changes were conditioned more by codas than by onsets; all while the spellings of individual words remained conservative.

If we count all the vowel changes that are listed by Wełna (1978) beginning with the fifteenth century, when the spelling system began to crystallize, we find that of those changes whose descriptions mention the conditioning effect of an adjacent consonant, 22 mention only the coda; 1 mentions only the onset; and 2 mention both jointly.

One might wonder whether the potentially controversial decisions we made in sound-letter alignment may have been responsible for our findings of particularly strong conditionings between the vowel and coda. It will be recalled, for example, that we assigned "silent" postvocalic letters to the vowel, even when they are drawn from the set of consonant letters. Thus f-au-n, f-aw-n, t-al-k, c-al-m, s-ig-n, f-igh-t, d-eb-t were all treated the same, whereas much previous work would have produced parses such as d-e-bt and s-i-gn and t-a-lk and perhaps even f-a-wn. Another controversial decision was to assign final Silent E to the final consonant phoneme in some situations, e.g., b-a-dge, h-ou-se, whereas previous researchers would always assign Silent E to the vowel. In both cases, our decision tends to increase consistency overall for the individual units in comparison to the older practices: Postvocalic silent letters modify the sound of the vowel much more than they do that of the coda, and Silent E after multiple vowel or coda letters does not modify the sound of the vowel. It increases consistency, for example, if one does not have to include ou_e in the set of potential spellings for /ɑʊ/. At the same time, our decision lowers the measured conditional effect of the coda on vowel consistency, and vice versa. This happens because the associated elements in question (e.g., igh in fight, se in house) are already grouped into the same part of the syllable. For example, in the scenario parsing f-igh-t, a reader looking at the vowel letters knows that igh spells /aɪ/, which is the end of the story; considering the t does not help. But in the alternative parse f-i-ght, the reader knows that i has an inconsistent reading, but always spells /aɪ/ before coda ght; that parse would have resulted in a greater rise in conditional consistency for the vowel given the coda. Of course not every single word using our parsing would give higher unconditioned consistency and lower vowel–coda conditional consistency in all cases in all processing directions, but we believe our decisions taken as a whole do tend strongly in that direction. In other words, whenever there was a potential controversy in how the word letter strings should be parsed into onset–vowel–coda, we favored the alignment that would bias against our research finding that there are particularly strong conditional consistency effects between the vowel and the coda. Adopting the alternative codings would have strengthened our findings.

An understanding of English letter-to-phoneme and phoneme-to-letter relationships sets the stage for an understanding of how readers and spellers deal with the English writing system. Findings of massive irregularities and inconsistencies at the level of individual phonemes have lent support to the idea that English orthography is particularly deep (Frost, 1992), and that accessing the pronunciation of a written word cannot therefore proceed in a straightforward fashion. Such irregularity is one piece of evidence that leads some theorists to conclude that readers of English primarily process words by retrieving their pronunciations from a lexical entry that is addressed directly by the whole spelling. Our demonstration of fairly high conditional consistencies in letter-to-phoneme mappings increases the plausibility of theories that assign a greater role to assembled (rule-based) routes for construction of a word's pronunciation: With relative efficiency, a reader may be able to assemble a small set of candidate pronunciations without having to access any mental lexicon. Of course it would be premature to judge the issue on statistical grounds alone; further research is required to establish under what conditions readers actually make use of conditional consistency. A good deal of research is already beginning to show that adults are particularly sensitive to conditional regularities involving vowels and final consonants (e.g., Andrews & Scarratt, 1998; Taraban & McClelland, 1987; Treiman et al., 1995; Treiman, Goswami, & Bruck, 1990; Treiman & Zukowski, 1988). Hopefully the measures we have introduced will facilitate further research in that area. If, as we suspect, readers do prove to be sensitive to a letter's environment, several lines of research that rely on measures of spelling regularity or consistency may need to be revisited. Investigation into the cognitive processing of reading often measures the accuracy or response time of tasks such as lexical decision or naming as a function of the complexity of the word's letter-to-sound mapping; or attempts are made to hold the complexity constant, so that other factors can be measured. Another type of consistency measure that is employed in recent research on reading is the consistency of sound-to-letter mappings (feedback consistency, Stone, Vanhoy, & Van Orden, 1997). Misleading results are possible if researchers use consistency metrics based on individual units rather than on conditional consistencies. For example, <u>c</u> as an onset has an inconsistent pronunciation, with /s/ being a minority pronunciation; therefore a word like <u>cent</u> may appear to have a low consistency by unconditional measures. But the conditional consistency of <u>c</u> given the vowel letter <u>e</u> is a perfect 1.0. If readers are indeed sensitive to these kinds of conditional consistencies, there is a danger that experiments disregarding that sensitivity will tend to misclassify conditionally consistent words as inconsistent. At best such misclassification would add noise to the experiment; at worst, the fact that the bias uniformly points in one direction could lead to false findings.

The present findings show that adults' use of intra-rime context in reading is well founded given the nature of the English writing system. A variety of models can explain this general pattern, including models with a built-in sensitivity to orthographic and phonological rimes (e.g., Patterson & Morton, 1985; Zorzi, Houghton, & Butterworth, 1998), models that develop such a sensitivity from their exposure to patterns in the English writing system (e.g., Plaut, McClelland, Seidenberg, & Patterson, 1996; Seidenberg & McClelland, 1989), and models that, like that of Coltheart, Curtis, Atkins, and Haller (1993), permit lexical neighbors to influence pronunciations. The models make different predictions on certain specific points, however. For example, the Seidenberg and McClelland model appears to predict that effects of lexical neighbors will depend on the combined frequencies of those neighbors (token count) rather than on the number of such neighbors (type count; Jared, McRae, & Seidenberg, 1990). Models also differ on whether they expect adults to be sensitive to regularities involving interactions between onsets and vowels. The regression analyses of Treiman et al. (1995) revealed no significant sensitivity to onset–vowel patterns among adults. However, the present results show that these patterns are weak, so adults may be only weakly sensitive to those patterns or may not generalize them beyond the few pairs of sounds or letters to which they apply. The measures of letter-to-sound consistency developed here should be useful in designing studies to further investigate these issues (see Balota & Spieler, 1998; Spieler & Balota, 1997, for examples of such item-level analyses).

Children as well as adults appear to be especially sensitive to vowel–coda associations in reading (e.g., Bowey & Hansen, 1994; Treiman et al., 1990; Treiman et al., 1995). The present findings suggest that the reading vocabulary that young children encounter is sufficient for the induction of these patterns. Prereaders' ability to segment spoken syllables into onsets and rimes, that is, keeping the vowel with the coda (e.g., Kirtley, Bryant, Maclean, & Bradley, 1989; Treiman & Zukowski, 1991), may pave the way for particular sensitivity to associations obtaining between the vowel and coda in print. Children's tendency to associate vowels with codas may be further promoted, in turn, by their exposure to the patterns in the writing system itself.

As compared to the large body of research on word reading processes in adults and children, relatively few studies have examined spelling. It is not even clear whether adults' spelling of known words involves recall of their sounds and generation of letter strings to encode those sounds. Some investigators (e.g., Burt & Fury, in press) have argued that adults rely exclusively on learned word-specific knowledge to spell known words. Detailed data about the distribution of sound-to-letter correspondences will be vital in sorting out the relative contribution of whole-word memorization and phonological encoding to spelling. Some research has assumed that adults use sound-to-letter rules that are not sensitive to context (Barry & Seymour, 1988; Kreiner, 1992, 1996; Kreiner & Gough, 1990). Indeed, Barry and Seymour argued that, although rime units may play an important role in reading, they are unlikely to do so in spelling. However, other evidence suggests that adults sometimes use the identity of the coda to help specify the spelling of a vowel (Treiman & Zukowski, 1988). A similar debate about the necessity of context-sensitive spelling rules has arisen in the case of children. Some investigators (Marsh, Friedman, Welch, & Desberg, 1980; Nation & Hulme, 1996) have claimed that young children use links from phonemes to letter strings that are not sensitive to context. Other researchers (e.g., Goswami, 1988; Varnhagen, Boechler, & Steffler, 1999) have emphasized the effects of context on vowel spelling, with Goswami arguing that rime context is particularly important. The present results suggest that both young children and adults could potentially benefit from links between sounds and spellings that are sensitive to context. This is especially true within the rime, but it could help elsewhere as well in certain cases. Additional work will be required to find out if and when spellers actually benefit from context-sensitive links.

The current research was carried out exclusively on monosyllables. It is difficult to gauge how strongly these results would extend to polysyllabic words. As we mentioned above, part of the problem is definitional: There is little agreement on which syllable intervocalic consonants belong to. Even if the definitional problem is finessed, there would be many factors interfering with a clear analysis. The most important is that most polysyllables are polymorphemic. Because English has a strong tendency to apply a constant spelling to the phonological variants of a morpheme (compare <u>photograph</u> /ˈfodəgraf/, <u>photography</u> /fəˈtɑgrəfi/), we would not want to compute statistics over a word list that repeated the same morphemes. The results would essentially encode information about the relative frequency of different morphemes. One less problematic possibility is to analyze only the monomorphemic polysyllables, such as <u>apple</u>, <u>cavil</u>, <u>garage</u>, and <u>catamaran</u>. That would be a worthwhile study, although it would cover only a small fraction of all polysyllabic words. Under the assumption that the consonant following a stressed vowel forms a rime with that vowel, we would expect to find patterns similar to those we have found for the monosyllables. We know that there is a coordination between the pronunciation of the first vowel and the spelling of the intervocalic (coda) consonant in pairs like <u>Bible</u>, <u>nibble</u>; and that the same onset–vowel conditioning applies in the polysyllable <u>water</u> as in the monosyllable <u>what</u>. We suspect however that there may be some overall attenuation of conditioned influence between vowel and coda. The rule for doubling intervocalic consonants to distinguish long and short vowels in polysyllables is not nearly as regular as the rule for using Silent E in monosyllables (e.g., apple, but chapel). And historically, the influence of a consonant on the preceding vowel is often weaker when the consonant is intervocalic. For example, while in all, tall, etc., the ll conditions a special reading for the vowel (/ɔ/ instead of /æ/), that is not true in words like alley. At the moment, these observations await quantitative verification.

Cross-language studies are another important area for future research. The work reported here is restricted to English, but similar studies with other languages could help to quantify the differences among various writing systems and shed light on similarities and differences in processing. For example, readers of English may use intrasyllabic context to a greater extent than readers of Dutch, because Dutch is more regular than English at the level of single letters and phonemes (Martensen, Maris, & Dijkstra, in press). Heretofore, differences in complexity between alphabetic orthographies for various languages have mostly been characterized in terms of orthographic depth. Languages with high context-free correspondences on the level of individual letters and phonemes are characterized as shallow, and others, including English, are considered deep. The measures we have introduced can help quantify these impressions. In addition, these new measures help us to distinguish several different aspects of orthographic complexity that have previously been lumped together into one omnibus characterization. An orthography that appears complex when one looks at it with context-free measures may appear much more regular when one applies context-sensitive measures. A researcher studying processing in different languages is helped somewhat by the general information that the orthography is deep, but may be helped much more by knowing in what part of the syllable the inconsistencies lie and which other parts of the syllable contribute most to disambiguating the inconsistencies.

More generally, the present work demonstrates the importance of large-scale lexical studies as a basis for psycholinguistic research. This is critical not only in the study of reading and spelling but also in the study of phonology (e.g., Kessler & Treiman, 1997), language acquisition (e.g., MacWhinney & Snow, 1990), and other areas. Many researchers agree that statistical information plays an important role in language acquisition and processing (e.g., Seidenberg, 1997). To understand what sensitivity to statistical information is able to account for, and what it is not able to account for, we must have a detailed understanding of the patterns in the language itself. This is now easier than before, due to better availability of large language databases and better ways to process them efficiently. Such studies can serve as a foundation for studies of language processing in the area of reading and spelling, and in other areas of psycholinguistics.

References

Andrews, S., & Scarratt, D. R. (1998). Rule and analogy mechanisms in reading nonwords: Hough dou peapel rede gnew wirds? *Journal of Experimental Psychology: Human Perception and Performance, 24,* 1052–1086.

Aronoff, M., & Koch, Eric. (1996). Context-sensitive regularities in English vowel spelling. *Reading and Writing: An Interdisciplinary Journal, 8,* 251–265.

Balota, D. A., & Spieler, D. H. (1998). The utility of item-level analyses in model evaluation: A reply to Seidenberg and Plaut. *Psychological Science, 9,* 238–240.

Barry, C., & Seymour, P. H. K. (1988). Lexical priming and sound-to-spelling contingency effects in nonword spelling. *Quarterly Journal of Experimental Psychology, 40A,* 5–40.

Berndt, R. S., Reggia, J. A., & Mitchum, C. C. (1987). Empirically derived probabilities for grapheme-to-phoneme correspondences in English. *Behavior Research Methods, Instruments, & Computers, 19,* 1–9.

Bowey, J. A., & Hansen, J. (1994). The development of orthographic rimes as units of word recognition. *Journal of Experimental Child Psychology, 58,* 465–488.

Burt, J. S., & Fury, M. B. (in press). Spelling in adults: The role of reading skills and experience. *Reading and Writing: An Interdisciplinary Journal.*

Centre for Lexical Information. (1987). CELEX lexical database. Available: http://www.kun.nl/celex/index.html.

Coltheart, M., Curtis, B., Atkins, P., & Haller, M. (1993). Models of reading aloud: Dual-route and parallel-distributed-processing approaches. *Psychological Review, 100,* 589–608.

Cummings, D. W. (1988). American English spelling: An informal description. Baltimore: Johns Hopkins University Press.

Flexner, S. B. (Ed.). (1987). Random House dictionary. 2nd ed. New York: Random House.

Francis, W. N., & Kučera, H. (1982). Frequency analysis of English usage: Lexicon and grammar. Boston: Houghton Mifflin.

Frost, R. (1992). Orthography and phonology: The psychological reality of orthographic depth. In M. Noonan, P. Downing, & S. Lima (Eds.), The linguistics of literacy (pp. 255–274). Amsterdam: Benjamins.

Frost, R. (1998). Toward a strong phonological theory of visual word recognition: True issues and false trails. Psychological Bulletin, 123, 71–99.

Fudge, E. (1969). Syllables. Journal of Linguistics, 5, 253–287.

Fudge, E. (1987). Branching structure within the syllable. Journal of Linguistics, 23, 359–377.

Good, P. (1995). Permutation tests. 2nd corrected printing. New York: Springer.

Goswami, U. (1988). Children's use of analogy in learning to spell. British Journal of Developmental Psychology, 6, 21–33.

Hanna, P. R., Hanna, Jean S., Hodges, R. E., & Rudorf, E. H., Jr. (1966). Phoneme–grapheme correspondences as cues to spelling improvement. Washington, DC: U. S. Department of Health, Education, and Welfare.

Harm, M. W., & Seidenberg, M. S. (1999.) Phonology, reading acquisition, and dyslexia: Insights from connectionist models. Psychological Review, 106, 491–528.

International Phonetic Association. (1996). Reproduction of The International Phonetic Alphabet. [On-line]. Available: http://www2.arts.gla.ac.uk/IPA/ipachart.html.

International Phonetic Association. (1999). Handbook of the International Phonetic Association: A guide to the use of the International Phonetic Alphabet. Cambridge, Eng.: Cambridge University Press.

Jared, D., McRae, K., & Seidenberg, M. S. (1990). The basis of consistency effects in word naming. Journal of Memory and Language, 29, 687–715.

Jespersen, O. H. (1909–1949). A modern English grammar on historical principles. Heidelberg: Winter.

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

Kirtley, C., Bryant, P., Maclean, M., & Bradley, L. (1989). Rhyme, rime, and the onset of reading. Journal of Experimental Child Psychology, 48, 224–245.

Kreiner, D. S. (1992). Reaction time measures of spelling: Testing a two-strategy model of skilled spelling. Journal of Experimental Psychology: Learning, Memory, and Cognition, 18, 765–776.

Kreiner, D. S. (1996). Effects of word familiarity and phoneme–grapheme polygraphy on oral spelling time and accuracy. Psychological Record, 46, 49–70.

Kreiner, D. S., & Gough, P. B. (1990). Two ideas about spelling: Rules and word-specific memory. Journal of Memory and Language, 29, 103–118.

Kučera, H., & Francis, W. N. (1967). Computational analysis of present-day American English. Providence, RI: Brown University Press.

MacWhinney, B., & Snow, C. (1990). The Child Language Data Exchange System: An update. Journal of Child Language, 17, 457–472.

Marsh, G., Friedman, M., Welch, V., & Desberg, P. (1980). The development of strategies in spelling. In U. Frith (Ed.), Cognitive processes in spelling (pp. 339–353). London: Academic Press.

Martensen, H., Maris, E., & Dijkstra, T. (in press). When does inconsistency hurt?: On the relation between phonological-consistency and the reliability of sublexical units. Memory & Cognition.

Metsala, J. L. (1997). An examination of word frequency and neighborhood density in the development of spoken-word recognition. Memory & Cognition, 25, 47–56.

Milton, R. (1992). CUV2. [On-line]. Available: ftp://svr-ftp.eng.cam.ac.uk/pub/comp.speech/dictionaries/CUVOALD.tar.gz

Nation, K., & Hulme, C. (1996). The automatic activation of sound–letter knowledge: An alternative interpretation of analogy and priming effects in early spelling development. Journal of Experimental Child Psychology, 63, 416-435.

Nusbaum, H. C., Pisoni, D. B., & Davis, C. K. (1984). Sizing up the Hoosier mental lexicon: Measuring the familiarity of 20,000 words. (Research on Speech Perception Progress Report, 10). Bloomington: Indiana University.

Patterson, K. E., & Morton, J. C. (1985). From orthography to phonology: An attempt at an old interpretation. In K. E. Patterson, J. C. Marshall, & M. Coltheart (Eds.), Surface dyslexia: Neuropsychological and cognitive studies of phonological reading (pp. 335-359). Hillsdale, NJ: Erlbaum.

Peereman, R., & Content, A. (1998). Quantitative analyses of orthography to phonology mapping in English and French. [On-line]. Available: http://homepages.vub.ac.be/∼acontent/OPMapping.html.

Pike, K., & Pike, E. (1947). Immediate constituents of Maztec syllables. International Journal of American Linguistics, 13, 78–91.

Plaut, D. C., McClelland, J. L., Seidenberg, M. S., & Patterson, K. (1996). Understanding normal and impaired word reading: Computational principles in quasi-regular domains. Psychological Review, 103, 56–115.

Rastle, K., & Coltheart, M. (2000). Lexical and nonlexical print-to-sound translation of disyllabic words and nonwords. Journal of Memory and Language, 42, 342–364, doi:10.1006/jmla.1999.2687.

Seidenberg, M. S. (1997). Language acquisition and use: Learning and applying probabilistic constraints. Science, 275, 1599–1603.

Seidenberg, M. S., & McClelland, J. L. (1989). A distributed, developmental model of word recognition and naming. Psychological Review, 96, 523–568.

Sejnowski, T. J., & Rosenberg, C. R. (1988). NetTalk corpus. [On-line]. Available: ftp://svr-ftp.eng.cam.ac.uk/pub/comp.speech/dictionaries/nettalk.data.gz

Selkirk, E. (1982). Syllables. In H. van der Hulst & N. Smith (Eds.), The structure of phonological representations (vol. 2, pp. 337–383). Dordrecht, Netherlands: Foris.

Spieler, D. H., & Balota, D. A. (1997). Bringing computational models of word naming down to the item level. Psychological Science, 8, 411–416.

Stanback, M. L. (1992). Syllable and rime patterns for teaching reading: Analysis of a frequency-based vocabulary of 17,602 words. Annals of Dyslexia, 42, 196–221.

Stone, G. O., Vanhoy, M. D., & Van Orden, G. C. (1997). Perception is a two-way street: Feedforward and feedback phonology in visual word recognition. Journal of Memory and Language, 36, 337–359, doi:10.1006/jmla.1996.2487.

Taraban, R., & McClelland, J. L. (1987). Conspiracy effects in word pronunciation. Journal of Memory and Language, 26, 608–631.

Treiman, R., & Danis, C. (1988). Syllabification of intervocalic consonants. Journal of Memory and Language, 27, 87–104.

Treiman, R., Goswami, U., & Bruck, M. (1990). Not all nonwords are alike: Implications for reading development and theory. Memory & Cognition, 18, 559–567.

Treiman, R., & Kessler, B. (1995). In defense of an onset-rhyme syllable structure for English. Language and Speech, 38, 127–142.

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

Treiman, R., & Zukowski, A. (1988). Units in reading and spelling. Journal of Memory and Language, 27, 466–477.

Treiman, R., & Zukowski, A. (1991). Levels of phonological awareness. In S. A. Brady & D. P. Shankweiler (Eds.), Phonological processes in literacy (pp. 67–83). Hillsdale, NJ: Erlbaum.

Varnhagen, C. K., Boechler, P. M., & Steffler, D. J. (1999). Phonological and orthographic influences on children's vowel spelling. Scientific Studies of Reading, 3, 363–379.

Venezky, R. L. (1970). The structure of English orthography. The Hague: Mouton.

Venezky, R. L. (1999). The American way of spelling: The structure and origins of American English orthography. New York: Guilford.

Ward, G. (1993). Moby Pronunciator II. [On-line]. Available: ftp://svr-ftp.eng.cam.ac.uk/pub/comp.speech/dictionaries/moby/

Weide, R. L. (Ed.). (1995). The Carnegie Mellon pronouncing dictionary: cmudict.0.4. [On-line]. Available: ftp://svr-ftp.eng.cam.ac.uk/pub/comp.speech/dictionaries/cmudict/

Wełna, Jerzy. (1978). A diachronic grammar of English. Part 1: Phonology. Warszawa: Państwowe Wydawnictwo Naukowe.

Wilson, M. (1987). MRC psycholinguistic database: Machine usable dictionary. Version 2.00. [On-line]. Available: ftp://ota.ox.ac.uk/pub/ota/public/dicts/1054/mrc2.dct

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

Ziegler, J. C., Stone, G. O., & Jacobs, A. M. (1997). What is the pronunciation for -ough and the spelling for /u/?: A database for computing feedforward and feedback consistency in English. Behavior Research Methods, Instruments & Computers, 29, 600–618.

Zorzi, M., Houghton, G., & Butterworth, B. (1998). Two routes or one in reading aloud?: A connectionist dual-process model. Journal of Experimental Psychology: Human Perception and Performance, 24, 1131–1161.

Author Note

Brett Kessler and Rebecca Treiman, Department of Psychology, Wayne State University.

This research was supported by National Science Foundation Grant 9807736. We are grateful to Howard Nusbaum and David Pisoni for sharing their word familiarity data files with us, and to Jamie Metsala for sharing her age-of-acquisition measurements. We also thank John Mullennix for help with the data, and Ram Frost and two anonymous reviewers for helpful comments on an earlier draft. A full list of words used in the study, a list of the subjectively deleted words, and data on letter-to-sound and sound-to-letter correspondences for each segment may be found at http://www.science.wayne.edu/ psych/faculty/treiman.html. Correspondence concerning this article should be addressed to Brett Kessler, Department of Psychology, Wayne State University, 71 W. Warren Ave., Detroit MI 48202. Email: BrettKessler@ACM.org.

Footnotes

[1]The authors also compute the information statistic H. That is essentially equivalent to the other consistency metric but for a $\log_2$ transform.

[2]Peereman and Content report a head consistency of .74 and a rime consistency of .67. If we attempt to replicate their methodology on our data, we get .67 and .73, respectively. This agrees with their main point, that the two values are similar, but it does reverse their relative ranking. The discrepancy may have to do with different alignment algorithms, which Peereman and Content do not explain, or with the fact that their word list is 28% larger than ours. Possibly their word list included inflected words, where the spelling of inflectional /s/, /z/ (-s), /d/ and /t/ (-ed) is especially inconsistent with the spelling those sounds have when they are not inflectional morphemes.

Table 1

Reading Consistency of the Vowel in Adult Words

Include /-r/[1]	Unconditional Consistency	Conditional Consistency				
		Given	Attested	Permuted[2]	Improvement[3]	*p*
		All Monosyllables				
Yes	.717					
		Onset	.807	.806	0.001	.501
		Coda	.920	.810	0.136	.000
No	.809					
		Onset	.882	.876	0.007	.013
		Coda	.925	.872	0.061	.000
		Coda / Onset			8.874	
		CVC Words Only				
Yes	.757					
		Onset	.830	.837	-0.008	.934
		Coda	.926	.843	0.098	.000
No	.841					
		Onset	.898	.895	0.003	.214
		Coda	.932	.898	0.038	.000

[1]Whether words with postvocalic /r/ were included.

[2]Average conditional consistency across 10,000 permutations randomly reassigning the vowel between words.

[3]Increase of attested conditional consistency over permuted conditional consistency, as a proportion of the latter. Significance test is one-tailed and asymmetric.

Table 2

Reading Consistency of the Onset in Adult Words

Include /-r/	Unconditional Consistency	Conditional Consistency Given	Attested	Permuted	Improvement	p
		All Monosyllables				
Yes	.976					
		Vowel	.993	.985	0.008	.000
		Coda	.988	.989	-0.001	.976
No	.977					
		Vowel	.993	.987	0.006	.000
		Coda	.988	.990	-0.002	.929
		CVC Words Only				
Yes	.966					
		Vowel	.991	.981	0.010	.000
		Coda	.980	.982	-0.002	.835
No	.968					
		Vowel	.990	.982	0.008	.000
		Coda	.981	.983	-0.002	.927

Note. See notes for Table 1. Permutation test reassigns onsets.

Table 3

Reading Consistency of the Coda in Adult Words

Include /-r/	Unconditional Consistency	Conditional Consistency				
		Given	Attested	Permuted	Improvement	*p*
		All Monosyllables				
Yes	.982					
		Onset	.992	.993	-0.001	.832
		Vowel	.992	.990	0.002	.097
No	.980					
		Onset	.991	.992	-0.001	.893
		Vowel	.991	.989	0.002	.131
		CVC Words Only				
Yes	.972					
		Onset	.987	.986	0.001	.545
		Vowel	.986	.986	0.000	.419
No	.970					
		Onset	.986	.985	0.001	.546
		Vowel	.985	.985	0.000	.401

Note. See notes for Table 1. Permutation test reassigns codas.

Table 4

Vowel Letter Strings for Which the Reading is Significantly Conditioned by the Coda

	Significance		Default		Conditioned		
Spell	Adult	Child	Sound	Example	Sound	Coda	Example
a	.000	.000	/æ/	act	/ɑ/	Empty	spa
						r	card
					/e/	nge	change
					/ɔ/	l	bald
a_e	.000	.001	/e/	bake	/ɛ/	r	rare
ai	.000	.000	/e/	chain	/ɛ/	r	chair
al	.000	n.s.	/ɔ/	chalk	/a/	f, v	calf
					/ɑ/	m	calm
au	.010	Ceiling[a]	/ɔ/	cause	/o/	ve, che	mauve
ay	.039	n.s.	/e/	say	/ɛ/	s	says
e	.000	.000	/ɛ/	neck	/i/	Empty	she
e_e	.011	n.s.	/i/	gene	/ɪ/	r	sphere
ea	.000	.000	/i/	beach	/ɪ/	r	beard
					/ɛ/	d	thread
ee	.000	n.s.	/i/	cheek	/ɪ/	r	steer
i	.000	.000	/ɪ/	bit	/aɪ/	nd, ld	mind
ie	.017	n.s.	/i/	priest	/aɪ/	Empty	tie
					/ɪ/	r	fierce
o	.000	.000	/ɑ/	clock	/o/	l	old

(table continues)

	Significance		Default		Conditioned		
Spell	Adult	Child	Sound	Example	Sound	Coda	Example
						Empty	go
					/ɔ/	r	corn
						g, ng	dog
						ss, st, f, th	boss
					/u/	Empty	who
o_e	.000	.001	/o/	cope	/ɔ/	r	core
oa	.000	n.s.	/o/	coat	/ɔ/	r	coarse
oo	.000	.003	/u/	boot	/ʊ/	k, r	book
ou	.000	.001	/ɑʊ/	cloud	/ʌ/	gh	tough
					/u/	p	group
ough	.004	n.s.	/o/	dough	/ɔ/	t	bought
ow	.009	n.s.	/ɑʊ/	crowd	/o/	Empty	grow
u	.014	.038	/ʌ/	bug	/ʊ/	ll, sh	bull
u_e	.000	n.s.	/u/	dune	/ʊ/	r	pure
y	.000	Ceiling[a]	/ɪ/	gym	/aɪ/	Empty	shy

Note. Significance tells whether coda affects vowel reading more than if codas were randomly reassigned. Coda strings are letters that immediately follow the vowel; other letters may follow the ones specified.

[a]Consistency = 1.0, no room for improvement.

Table 5

Spelling Consistency of the Vowel in Adult Words

Include	Unconditional	Conditional Consistency				
/-r/	Consistency	Given	Attested	Permuted	Improvement	p
		All Monosyllables				
Yes	.529					
		Onset	.649	.635	0.022	.000
		Coda	.737	.631	0.168	.000
		Coda / Onset			7.619	
No	.585					
		Onset	.705	.689	0.023	.000
		Coda	.748	.671	0.115	.000
		Coda / Onset			4.942	
		CVC Words Only				
Yes	.559					
		Onset	.663	.652	0.017	.023
		Coda	.719	.646	0.113	.000
		Coda / Onset			6.698	
No	.619					
		Onset	.724	.706	0.025	.001
		Coda	.740	.698	0.060	.000
		Coda / Onset			2.360	

Note. See notes for Table 1.

Table 6

Spelling Consistency of the Onset in Adult Words

Include /-r/	Unconditional Consistency	Conditional Consistency				
		Given	Attested	Permuted	Improvement	*p*
All Monosyllables						
Yes	.910					
		Vowel	.937	.926	0.012	.000
		Coda	.942	.944	-0.002	.851
No	.908					
		Vowel	.938	.926	0.013	.000
		Coda	.939	.942	-0.003	.899
CVC Words Only						
Yes	.873					
		Vowel	.914	.899	0.017	.000
		Coda	.909	.906	0.003	.170
No	.870					
		Vowel	.915	.897	0.020	.000
		Coda	.906	.903	0.003	.193

Note. See notes for Table 1. Permutation test reassigns onsets.

Table 7

Spelling Consistency of the Coda in Adult Words

Include /-r/	Unconditional Consistency	Conditional Consistency Given	Attested	Permuted	Improvement	p
		All Monosyllables				
Yes	.821					
		Onset	.882	.889	-0.008	.997
		Vowel	.925	.850	0.088	.000
No	.809					
		Onset	.873	.880	-0.008	.996
		Vowel	.923	.838	0.101	.000
		CVC Words Only				
Yes	.760					
		Onset	.818	.822	-0.005	.832
		Vowel	.910	.806	0.129	.000
No	.743					
		Onset	.806	.810	-0.005	.837
		Vowel	.905	.793	0.141	.000

Note. See notes for Table 1. Permutation test reassigns codas.

Table 8

Vowel Sounds for Which the Spelling is Significantly Conditioned by the Coda

	Significance		Default		Conditioned		
Sound	Adult	Child	Spell	Example	Spell	Coda	Example
/æ/	.000	.001	a	bat	al	/f/, /v/	calf
/aɪ/	.000	.000	i_e	bride	i	/ld/, /nd/	wild
					igh	/t/	night
					y	Empty	try
/ɑ/	.000	.000	o	dot	a	/r/	bark
					al	/m/	calm
/ɑʊ/	.000	.000	ou	count	ow	Empty	cow
						/n/, /l/, /z/	crown
/e/	.000	.000	a_e	ape	ai	/l/, /n/, /θ/	fail
					ay	Empty	day
/ɛ/	.000	.000	e	bell	a_e	/r/	care
					ai	/r/	chair
					ea	/d/, /θ/, /lθ/	bread
/i/	.000	.001	ea	beach	ee	Empty	tree
						/d/, /p/	feed
					ie	/f/, /dʒ/, C + /d/	brief
/ɪ/	.000	.000	i	bit	ea	/r/	near
					ee	/r/	deer
/o/	.000	.000	o_e	bone	o	/l/	gold

(table continues)

	Significance		Default		Conditioned		
Sound	Adult	Child	Spell	Example	Spell	Coda	Example
					oa	2 C	boast
						/f/, /t/, /θ/, /tʃ/	loaf
					ow	Empty	glow
/ɔ/	.000	.000	au	flaunt	a	/l/	salt
					al	/k/	talk
					augh	/t/	caught
					aw	/n/, /k/	lawn
						Empty	law
					o	Non-Final /r/	fork
						/s/, /θ/, /f/	frost
						/g/, /ŋ/	dog
					o_e	Empty /r/	shore
					ough	/t/	thought
/ɔɪ/	.000	n.s.	oi	coin	oy	Empty	toy
/u/	.000	.004	oo	cool	ew	Empty	new
/ʊ/	.000	.001	oo	good	u	/l/, /s/, /ʃ/, /tʃ/	full
					u_e	/r/	pure
/ʌ/	.000	.025	u	bug	o	/v/, /n/	love

Note. Significance tells whether coda affects vowel spelling more than if codas were randomly reassigned. Coda strings are sounds that immediately follow the vowel; other sounds may follow the ones specified.

Figure Caption

Figure 1. Percentage improvement over chance levels when one part of the syllable (pointed to by arrow) is read or spelled while taking into account the identity of another part of the syllable (from which the arrow points).

$$\text{Onset} \quad \underset{0.8\%}{\overset{\text{n.s.}}{\rightleftarrows}} \quad \text{Vowel} \quad \underset{13.6\%}{\overset{\text{n.s.}}{\rightleftarrows}} \quad \text{Coda}$$

Reading, Adult Words

$$\text{Onset} \quad \underset{\text{n.s.}}{\overset{\text{n.s.}}{\rightleftarrows}} \quad \text{Vowel} \quad \underset{11.6\%}{\overset{\text{n.s.}}{\rightleftarrows}} \quad \text{Coda}$$

Reading, Child Words

$$\text{Onset} \quad \underset{1.2\%}{\overset{2.2\%}{\rightleftarrows}} \quad \text{Vowel} \quad \underset{16.8\%}{\overset{8.8\%}{\rightleftarrows}} \quad \text{Coda}$$

Spelling, Adult Words

$$\text{Onset} \quad \underset{1.2\%}{\overset{\text{n.s.}}{\rightleftarrows}} \quad \text{Vowel} \quad \underset{14.3\%}{\overset{7.5\%}{\rightleftarrows}} \quad \text{Coda}$$

Spelling, Child Words