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The role of context in the reading of English vowels: Evidence from ‹s› clusters

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Vowel letters are a source of difficulty in reading English words, for they have both long and short pronunciations. In two studies, we examined how vowels are pronounced before different types of medial consonants in the words of English and the degree to which skilled readers follow those vocabulary statistics in their behavior. We found more short vowels before sequences beginning with ‹s› than before those such as ‹pl›, regardless of whether the letter after ‹s› corresponded to a stop consonant (e.g., ‹sp›) or a sonorant (e.g., ‹sl›). These results show that pronunciation of vowels is influenced by the nature and not just the number of following consonants, contrary to the assumptions that commonly underlie phonics instruction. Although the results support a statistical learning view of reading, in that participants showed an implicit use of untaught patterns, participants' pronunciations differed in some ways from those expected, given the vocabulary statistics.

1. Introduction

The English writing system is difficult to learn and use, in part because a letter may have one pronunciation in some words and other pronunciations in other words. This difficulty, sometimes referred to as orthographic depth, is especially prominent for vowels. For example, the letter ‹a› corresponds to different phonemes in *chapter* and *paper*. How do readers cope with such variability? Studies suggest that the context in which a letter appears often provides useful information about its pronunciation and that readers benefit from this information (e.g., Kessler & Treiman, 2001; Siegelman, Kearns, et al., 2020). In the research reported here, we study one type of context effect in spelling-to-sound translation: how the number and type of consonants after a vowel influence its pronunciation. We focus on vowels that are followed by consonant sequences beginning with ‹s›, because, as we will explain, this is a good test case for examining context effects in the English writing system and how they influence readers' behavior.

Many studies of the nature and use of spelling–sound relations in English (e.g., Kessler & Treiman, 2001; Siegelman, Kearns, et al., 2020) have been limited to monosyllables. Our study extends previous work by examining items with more than one syllable. Although some researchers have studied such items (e.g., Jared & Seidenberg, 1990), more work is needed, given the frequency of longer words in English, the importance of these words for understanding complex texts, and the fact that only some types of linguistic structures have been examined.

Learners of English are taught that each vowel letter has two main pronunciations: what educators call a *short* one and a *long* one. The five main vowels have their short sound in *cat, bed*, *big, body*, and *run*, and their long sound in *cake*, *betel*, *bike*, *bony*, and *rude* and *cute*. (Note that these designations are terms of art in phonics; the vowels in the two categories differ in quality, and the former are not always longer in acoustic duration than the latter.) In phonics instruction, students are often taught to consider the number of consonant letters after a vowel in order to choose between the long and the short pronunciations (Kearns, 2020). Specifically, students are directed to first try the short pronunciation of a vowel letter that is followed by two consonant letters, as in *chapter* and *pepper*. If the vowel is followed by a single consonant letter and then another vowel letter, as in *paper*, their first choice should be the long pronunciation. Thus, the view that underlies typical phonics instruction is that the number of consonant letters after the vowel influences its pronunciation.

Kearns's (2020) analyses of the spelling-to-sound correspondences in English disyllabic words confirm the idea from phonics instruction that the number of consonant letters after a vowel is associated with its pronunciation. Specifically, according to his analyses, the first vowel of a VCCV (C = consonant, V = vowel) sequence is more likely to be pronounced as short than is the first vowel of a VCV sequence. However, the results of Treiman et al. (2023) suggest that the ratio of short to long vowels varies not only with the number of following consonant letters, but also with the phonological properties of the consonants for which the letters stand. According to the vocabulary analysis of Treiman and colleagues, long vowels are reasonably common in disyllabic words like *apron*, in which the medial CC sequence corresponds to an obstruent phoneme (e.g., a stop or a fricative) followed by a liquid phoneme. Long vowels are virtually nonexistent when a medial CC sequence corresponds to an obstruent followed by another obstruent.

Treiman et al. (2023) suggested that the higher proportion of long vowels in words such as *apron* than in words such as *captain* is related to the fact that the consonant sequence for which the ‹pr› of *apron* stands may be an onset (initial consonant or consonant cluster of a syllable). If a written word is broken up so as to maximize the onsets of its syllables (Chee et al., 2020; Wiley et al., 2024), then ‹a› is the last letter of *apron*'s first syllable. This syllable does not have a coda (a final consonant), promoting the long pronunciation of the vowel. The consonant sequence to which the ‹pt› of *captain* corresponds cannot be an onset in English. Thus, the first element of this sequence must be in the coda of the first syllable and the second element must be the onset of the second syllable. The first vowel of *captain* may be short because its syllable is closed by a consonant.

The vocabulary analyses of Treiman et al. (2023) show that the ratio of long to short vowels differs not just according to the number of following consonants, but also according to the consonants' phonological properties, but does this affect readers' behavior? Short vowels outnumber long vowels in disyllabic words with medial obstruent + sonorant sequences (e.g., ‹pr›) and words with medial obstruent + obstruent sequences (e.g., ‹pt›), albeit by a smaller margin for the former, and no program of reading instruction that we know of teaches children to consider the type of consonant sequence in selecting between long and short vowels. Thus, we might expect readers to be influenced by the number of medial consonant letters, but not the phonemes to which they correspond. To find out, Treiman et al. (2023) asked university students to pronounce novel disyllabic items with different types of medials. The proportion of long vowels relative to the total number of long or short vowels was significantly higher before CC sequences that correspond to obstruent + sonorant sequences, such as ‹pr›, than before CC sequences that correspond to obstruent + obstruent sequences, such as ‹pt› (26% vs. 6%). For example, participants were more likely to use a long first-syllable vowel in ‹baproc› than in ‹baptoc›. This result suggests that skilled readers have picked up, without explicit instruction, the knowledge that the nature as well as the number of consonants after a vowel influences the vowel's pronunciation. This knowledge may reflect statistical learning: implicit learning about the links between spellings and pronunciations. Statistical learning plays an important role in the learning of reading and spelling, as in the learning of other skills (Siegelman, Rueckl, et al., 2020; Treiman & Kessler, 2022).

According to some views, experienced readers have internalized the statistics of their language's spelling-to-sound relationships and mirror them in their behavior (Brown, 1998; Siegelman, Kearns, et al., 2020). In the above-described study of Treiman et al. (2023), however, the behavioral data did not match the vocabulary statistics perfectly. For readers, for example, the proportion of long vowels relative to the total number of long or short vowels was 26% for disyllabic nonwords with medial obstruent + sonorant sequences. In an analysis of disyllabic English words with medial obstruent + sonorant sequences, the proportion of words with long vowels relative to the total number of words with long or short vowels was substantially higher: 44%.

In the present research, we sought to expand our knowledge about the role of context in spelling-to-sound relationships and the degree to which experienced readers' behavior mirrors the statistics of the vocabulary. We did so by examining medials that have not featured in previous studies: those with ‹s› as their first letter. Sequences such as ‹sl› and ‹sp› are like the sequences such as ‹pr› that were studied by Treiman et al. (2023), in that they stand for phoneme sequences that can occur at the beginnings of English words. Reading researchers have, therefore, assumed that sequences like ‹sl› and ‹sp› are onsets (e.g., Chee et al., 2020; Kinoshita, 2000; Wiley et al., 2024). If so, we would expect the vocabulary statistics to show the same proportion of long first vowels in words with medial sequences such as ‹sl› and ‹sp› as in words with medial sequences such as ‹pr›. We would also expect readers to use long vowels as often before sequences such as ‹sl› and ‹sp› as before sequences such as ‹pr›.

However, linguists have noted that consonant clusters beginning with /s/ have some unusual properties in English and other languages, such as Italian (Kaye et al., 1990), raising questions about the behavior of the corresponding orthographic units. One difference between /s/ clusters and other clusters is that, for clusters appearing at the beginnings of words, only those with initial /s/ may have three elements (e.g., /spl/). Another difference is that, in initial clusters that begin with a consonant other than /s/, the second element (e.g., /l/ of /pl/), is always more sonorant or vowel-like than the first element (/p/). Thus, the cluster has a rising sonority profile. But /sp/, /st/, and /sk/ do not have such a profile. Indeed, in some views of sonority, the sonority profile falls from the fricative /s/ to the following stop consonant. According to some linguistic views reviewed by Goad (2011, 2012), /sp/, /st/, and /sk/ are not onsets, whereas clusters such as /sl/ and /sn/, with their rising sonority profiles, are onsets. In other linguistic views, all clusters with initial /s/, regardless of their second element, are represented differently from clusters like /pr/ and /bl/ (Kaye, 1992).

In the research reported here, we ask whether medial sequences beginning with ‹s› are similar to, or different from, obstruent + sonorant sequences with respect to their influence on the pronunciation of a preceding vowel. Our first study considered ‹s›-initial medial sequences as a group, comparing them to medial obstruent + sonorant sequences. The second study distinguished between different types of sequences beginning with ‹s›, including those whose usual pronunciation has a rising sonority profile (e.g., ‹sl›) and those without rising sonority profiles (e.g., ‹sp›).

The first component of each study was a behavioral experiment that examined university students' pronunciations of vowels in disyllabic nonwords. For example, Study 1 included nonwords with medial ‹s› clusters, such as ‹kestep›, and nonwords with medial obstruent + sonorant clusters, such as ‹ketrep›. The study also included, for purposes of comparison, items with single medial consonants, such as ‹kesep› and ‹ketep›. Participants were asked to pronounce each item with emphasis on the first syllable and then select, from two options, the one that better matched their pronunciation of the first vowel. Thus, participants decided whether their pronunciation of the first vowel of ‹kestep› was "ē as in b**ee**t" or "ĕ as in b**e**t." The experiment also included well-known English disyllabic words with long and short vowels in the stressed first syllable. Inclusion of these filler items allowed us to check whether participants understood the task and were paying attention throughout the experimental session.

The second component of each study was a vocabulary analysis. Here, we analyzed the spelling-to-sound relationships in comprehensive lists of English words with the same medials as the items in the behavioral experiment. For example, the vocabulary analysis of Study 1 examined long and short vowels in the first syllables of disyllables with medial ‹s› sequences (e.g., *whisper*, *postal*), medial obstruent + sonorant sequences (e.g., *progress*, *apron*), single medial ‹s› (e.g., *closet*, *resource*), and single medial obstruents (e.g., *widow*, *opal*). Given that people's reading of vowels in disyllables may be affected by their experience with words of more than two syllables as well as by their experience with disyllabic words (Treiman et al., 2023), we also included words with three or more syllables (e.g., *testify*, *nucleus*, *prosecutor*, *stabilizes*) in some of the analyses. Our vocabulary analyses go beyond those of Kearns (2020), who did not distinguish among CC sequences based on the phonemes to which the letters correspond, and Treiman et al. (2023), who did not include words with medial sequences beginning with ‹s›.

To summarize, the goal of the present research was to shed light on the role of context in spelling-to-sound translation by examining use of long and short vowels before medial sequences that begin with ‹s›. This structure provides a good case study for examining the role of context on vowel pronunciation in English and the degree to which skilled readers have internalized statistical patterns in the vocabulary.

2. Study 1

2.1 Method

2.1.1 Behavioral experiment

2.1.1.1 Participants

We analyzed data from 71 undergraduate students at Washington University in St. Louis The students were recruited through the subject pool of the Department of Psychological and Brain Sciences, and they received course credit in return for participation. All of the participants stated that they were native speakers of English, and none reported reading, spelling, or hearing problems. Sixty identified as female and 11 as male. Their mean age was 20.1 years (range: 18–22). Five additional individuals completed the experiment but achieved less than 75% correct on the words that were interspersed with the nonwords. Their data were omitted from the analyses.

2.1.1.2 Stimuli

We constructed 44 quadruplets of items that were not words in American English. Two items in each quadruplet – the ‹s› + consonant item and the obstruent + sonorant item – had medial consonant clusters that occur at the beginnings of well-known English words. The cluster was ‹sk›, ‹sl›, ‹sm›, ‹sn›, ‹sp›, ‹st›, or ‹sw› for the ‹s› + consonant items and ‹bl›, ‹br›, ‹fl›, ‹fr›, ‹gl›, ‹tr›, or ‹tw› for the obstruent + sonorant items. Within a quadruplet, the two items with clusters were the same except for the letters in their medial clusters. For example, one quadruplet included the ‹s› + consonant item ‹keslep› and the obstruent + sonorant item ‹ketrep›. The two other nonwords in each quadruplet – the ‹s› item and the obstruent item – had single medial consonants. These items were derived from the cluster items by omitting the second consonants of the clusters. For example, the sample quadruplet included the ‹s› item ‹kesep› and the obstruent item ‹ketep›.

The experimental nonwords all began with a single consonant, counting ‹y› as a consonant, followed by ‹a›, ‹e›, ‹i›, ‹o›, or ‹u›. The medial consonant or cluster was followed by a vowel–consonant sequence or a single vowel letter or digraph, counting ‹y› as a vowel here. We did not use nonwords with a single final ‹e› (e.g., ‹kete›) because they are likely to be pronounced as monosyllabic rather than disyllabic. None of the nonwords began with a sequence that commonly corresponds to a prefix, such as ‹re›.

We chose 20 well-known disyllabic English words with first-syllable stress as fillers. There were four words with each of ‹a›, ‹e›, ‹i›, ‹o›, and ‹u› in the first syllable, two with a long pronunciation of the vowel and two with a short pronunciation. Another 10 disyllabic words with first-syllable stress were used in the practice phase of the experiment. There were two practice words with each of ‹a›, ‹e›, ‹i›, ‹o›, and ‹u› in the first syllable, one with a long pronunciation of this vowel and the other with a short pronunciation. None of the filler words or practice words had a medial ‹s›.

We created two response options for each vowel, one exemplifying the long pronunciation and one exemplifying the short pronunciation. The options were presented with real-word examples, and the letters in the examples that corresponded to vowels were bolded. The options were as follows: ā as in b**ai**t, ă as in b**a**t; ē as in b**ee**t, ĕ as in b**e**t; ī as in s**igh**t, ĭ as in s**i**t; ō as in s**oa**k, ŏ as in s**o**ck; ū as in b**oo**t; ŭ as in b**u**t. We used the same options for the practice items, nonwords, and words.

To keep the experiment a manageable length, we constructed two lists of items, each of which included the items from 22 quadruplets of nonwords and all 20 words. The nonwords in the two lists may be found in the Appendix.

2.1.1.3 Procedure

The experiment was delivered online as a Qualtrics survey (https://www.qualtrics.com). Participants were automatically assigned to one of the two item lists in such a way as to balance the number of participants between them. Participants were instructed to complete the experiment individually by accessing their assigned URL. After they clicked the survey link, participants were provided with an information sheet and were asked if they agreed to participate. Those who agreed were informed that they would see a "real word or a made-up word" and were asked to pronounce it aloud with emphasis on the first vowel. They were told that their task was to decide on the pronunciation of the first vowel by choosing between two spelling options; these options were presented one above the other. Participants were instructed that, when an item was a made-up word, they should pick the option that better represented how they would pronounce the first vowel given the spelling of the made-up word. When an item was a real word, they should pick the option that corresponded to how they pronounced the first vowel of the word. Participants were told that they would see one item at a time and could take as much time as they needed to make their decision.

Participants were first presented with the practice items. After they provided an answer to each practice item, they saw a screen that showed the correct answer. The practice items were presented in the same order for all participants, and the two response choices for each item were also in the same order for all participants. We chose this order to avoid sequences of three or more trials for which the correct answer was in the same position (top or bottom). After completing the practice trials, participants were presented with a sequence of trials comprising the nonwords and the words from their assigned list. This sequence was shuffled by a computer's (pseudo)random number generator to determine the order of presentation. This shuffling was done afresh for each participant. The order of the two choices for each experimental item was also shuffled for each participant.

After completing all the items, participants were presented with a short questionnaire about their gender, age, language background, and any reading, spelling, hearing, or speech disabilities they may have had. They were then provided with a debriefing statement. The procedure lasted approximately 25 minutes.

2.1.2 Vocabulary analysis

We selected from the Unisyn lexicon version 1.3 (http://www.cstr.ed.ac.uk/projects/unisyn), which has 119,200 words, those 68,210 words that began with a spelling pattern that was similar to that of the experimental nonwords. Specifically, we chose words with the following spelling elements, in order:

- zero or more initial consonant letters, or the single letter ‹y›
- single ‹a›, ‹e›, ‹i›, ‹o›, or ‹u›
- a consonant letter or sequence of two consonant letters that was similar to those in the experimental stimuli in a way that we describe below
- any sequence starting with a vowel letter or ‹y›

We also filtered words by their pronunciation, using the General American pronunciations generated in Unisyn. Our vocabulary analysis included the 7,308 words for which the pronunciation had the following elements, in order:

- any sequence of zero or more consonants
- a stressed long or short vowel
- a consonant or consonant sequence that straightforwardly matches any one of the medial consonants or consonant clusters of interest
- an unstressed vowel, followed optionally by other phonemes without a primary stress

We treated syllabic consonants as if they contain a schwa vowel, allowing for the inclusion of words like *tiger*. We did not restrict the number of syllables, but rather report the results for words of different lengths in 2.2. For heterographic homophones, we included all spelling–pronunciation combinations as separate entries. Our computations were based on the token counts reported by Unisyn. To better model people's perception of frequencies, we transformed the raw token count of each word by adding 1 and then taking the binary logarithm: $\log_2(f + 1)$. The counts we report in our analyses are based on summing these transformed token counts across the relevant words. When the text mentions the number of words without taking their frequency into consideration, we use the term *types*.

We filtered the words into those that represented one of the four kinds of medials in the experiment. The ‹s› + consonant category included words that had medial ‹sk›, ‹sl›, ‹sm›, ‹sn›, ‹sp›, ‹st›, or ‹sw›, for example *aspen* and *tastier*. This category comprised 3,164 disyllabic tokens, using the frequency-adjusted weighting described above (524 types), and a total of 5,232 polysyllabic words (1,107 types). The obstruent + sonorant category included words with medial ‹bl›, ‹br›, ‹cl›, ‹cr›, ‹dr›, ‹dw›, ‹fl›, ‹fr›, ‹gl›, ‹gr›, ‹kl›, ‹kr›, ‹pl›, ‹pr›, ‹tr›, or ‹tw›, such as *apron* and *metrical* (disyllables: 1,963 tokens, 383 types; polysyllables: 4,210 tokens, 1,155 types). The ‹s› category consisted of words with a single medial ‹s›, such as *nasal* and *fuselage* (disyllables: 1,456 tokens, 205 types; polysyllables: 2,865 tokens, 527 types). Finally, the obstruent category included words with a medial letter that corresponds to an obstruent: ‹b›, ‹d›, ‹f›, ‹g›, ‹j›, ‹k›, ‹p›, ‹q›, ‹t›, or ‹v›, such as *natal* and *aviary* (disyllables: 10,442 tokens, 1,671 types; polysyllables: 21,682 tokens, 4.519 types). We did not include words with medial ‹c› and ‹z› in this category, because their pronunciations overlap with those of ‹s›.

2.2 Results

2.2.1 Behavioral experiment

Participants chose the correct response on 98% of the word trials. They chose long vowels on 31% of the nonword trials (1,957) and short vowels on the other 69% (4,291). The left column of data in **Table 1** shows the mean percentage of long vowels for nonwords with each type of medial sequence. There appear to be substantially fewer long vowel responses for ‹s› + consonant clusters than for obstruent + sonorant clusters, but only a small difference between ‹s› and other consonants when they occurred as singletons.

Table 1: Percentage of long vowels in first syllable in behavioral experiment and vocabulary analysis of Study 1.

Medial	**Behavioral data**		**Vocabulary analysis**	
			Disyllables	**All words of two or more syllables**
	M	***SD***	%	%
‹s› + consonant	19	12	10	7
Obstruent + sonorant	28	12	40	42
‹s›	38	14	82	58
Obstruent	40	14	70	54

We tested the results statistically by running a mixed-model logistic regression analysis using the lme4 package in R (Bates et al., 2015). The dependent variable was whether the first vowel was long, and cluster versus single and ‹s› versus non-‹s› were the fixed factors. The model had random intercepts for participants and item quadruplets. There was a main effect of cluster, such that participants were less likely to choose long vowels when the medial was a cluster than when it was a single consonant ($b = -0.81$, $SE = 0.09$, $p < .001$). This main effect was qualified by an interaction with ‹s› versus non-‹s› ($b = -0.55$, $SE = 0.14$, $p < .001$). Follow-up tests showed that, in the case of clusters, there were significantly fewer long vowel responses when the cluster began with ‹s› than when it did not ($p < .001$). For medial singletons, the trend toward fewer long vowels before ‹s› than before other consonants was not statistically reliable ($p = .06$).

2.2.2 Vocabulary analysis

The columns marked "Vocabulary analysis" in **Table 1** show the percentage of long vowels for each type of item in disyllabic words and all words of more than two syllables, weighting words by their frequency of occurrence in the manner described earlier. Although the percentages in corresponding cells differ substantially in magnitude from the behavioral ones – the square root of the mean of the squared differences is 28 percentage points using the vocabulary statistics for disyllables and 15 using the vocabulary statistics for all words of two or more syllables – relevant differences between item types (rowwise) are in the same direction. Specifically, both the behavioral and the vocabulary data show more long vowels before single consonants than before clusters, and both show fewer long vowels before clusters starting with ‹s› than before clusters starting with other obstruents. In general, the vocabulary statistics have many more long vowels before single medials than the behavioral statistics show; this difference is especially large when we only consider two-syllable words.[1]

2.3 Discussion

The behavioral results for items with medial obstruents and items with obstruent + sonorant clusters are similar to those of Treiman et al. (2023): more long vowels for items with single medial obstruents than for items with medial obstruent + sonorant clusters. The data for the present study come from participants' choices between two pronunciations, whereas, participants in Treiman et al. (2023) read nonwords aloud and their pronunciations were scored by trained judges. Despite the difference in tasks, the results for these types of items were quite similar –

[1] In the review process, we were asked whether a long vowel in a base word has a confounding effect on the vowel of a longer word derived from it. For example, do more ‹s› + consonant words like *postal* (based on *post*) have long vowels than do words like *costal* (not based on an independent English word)? To explore this issue, we reran the vocabulary statistics including only those words that Unisyn indicated were not derived from an independent word. The overall percentage of long vowels was lower, but the focal pattern was the same, with more long vowels before single consonants than before clusters and fewer long vowels before clusters starting with ‹s› than before clusters starting with other obstruents. Full details of this post hoc analysis are in the supplementary materials at https://osf.io/by5gn/.

40% and 28% long vowels for items with medial obstruents and items with medial obstruent + sonorant clusters, respectively, in this experiment, and 43% and 26% combined across the three experiments of Treiman et al. (2023).

Of most interest here are the two types of items that were not studied by Treiman et al. (2023): those with medial clusters that start with ‹s› and those with single medial ‹s›. These sequences are like ‹pr› and ‹p›, respectively, in the number of letters they contain. They are also distributionally similar, in that they are found at the beginnings of English words. For these reasons, reading researchers have generally treated them alike, as onsets (Chee et al., 2020; Kinoshita, 2000; Wiley et al., 2024). However, our results show that people are much less likely to use long vowels before clusters beginning with ‹s› than before clusters such as ‹pr›. In the words of English, too, vowels are also less likely to be pronounced as long before ‹s› clusters than before obstruent + sonorant clusters. The different results for ‹s› clusters than for obstruent + sonorant clusters appear to reflect a property of ‹s› when it is followed by another consonant, rather than a property of ‹s› itself, for we did not see a consistent pattern of fewer long vowels before items with single medial ‹s› than before other single medial obstruents. Thus, the choice between the long and short pronunciation of a vowel letter, both in the English vocabulary and in the behavior of skilled readers, is influenced not just by whether the vowel letter is followed by one or two consonant letters but also by the phonological sequence to which the consonant letters correspond.

Our participants' behavior was influenced by both the number and the quality of the medial consonants, supporting the view that they have picked up patterns in the vocabulary, even untaught ones (Siegelman, Rueckl, et al., 2020; Treiman & Kessler, 2022). The agreement between the behavioral data and the vocabulary statistics was closer when we calculated the vocabulary statistics over all words of more than two syllables than over just disyllables, suggesting that people's reading of disyllables is affected by their experience with longer words as well as by their experience of disyllables. However, our results do not support the idea that experienced readers' behavior perfectly mirrors the statistics of the vocabulary to which they are exposed (pace Brown, 1998; Siegelman, Kearns, et al., 2020). For example, people used fewer long vowels before single medial consonants and before obstruent + sonorant sequences than anticipated, based on the vocabulary statistics, even as calculated over all words of more than two syllables. We reserve further discussion of this finding until after Study 2.

A limitation of Study 1 is that we did not differentiate between different types of ‹s› clusters. As reviewed by Goad (2011), some linguists have suggested that the corresponding clusters in spoken language are represented differently as a function of whether they have a rising sonority profile, as with the /s/ + sonorant clusters /sl/, /sm/, /sn/, and /sw/, or a non-rising sonority profile, as with the /s/ + stop clusters /sk/, /sp/, and /st/. Post hoc inspection of the behavioral data from the present study shows a long vowel proportion of 18% for ‹s› + sonorant clusters and 22% for ‹s› + obstruent clusters, both below the 28% observed for obstruent + sonorant clusters. However, we cannot draw strong conclusions, because the items with the two types of ‹s› clusters also differed in other ways, including in the identity of the first-syllable vowel and the final vowel or vowel–consonant sequence. Our main goal in Study 2 was to make a better-controlled comparison between ‹s› clusters that differ in the sonority profiles of the corresponding phonological sequences, asking whether ‹s› + sonorant and ‹s› + obstruent clusters differ from one another in the vocabulary statistics and in readers' behavior.

A second goal of Study 2 was to examine a type of medial sequence that was not included in Study 1: ‹ss›, which almost always spells single /s/ in English words. For consonants that correspond to obstruents other than /s/, Treiman et al. (2023) found many fewer long vowels before double-letter spellings than before single-letter spellings in the vocabulary statistics and the behavioral data. We asked whether we would see the same influence of consonant number for ‹ss› and ‹s›.

3. Study 2

3.1 Method

3.1.1 Behavioral experiment

3.1.1.1 Participants

We analyzed data from 75 undergraduate students at Washington University in St. Louis. The students were recruited as in Experiment 1, and no student participated in both experiments. The students whose data were included stated that they were native speakers of English. None of them reported reading, spelling, or hearing disabilities. Of the 74 participants who responded to a question about their gender, 60 identified as female, 13 as male, and 1 as nonbinary. Their mean age was 20.1 years (range: 18–22). We excluded data from one additional individual who was not a native speaker of English and one who reported that they had a language-related disability. Another three individuals achieved less than 75% correct on the words that were interspersed with the nonwords. Their data were also dropped from the analyses.

3.1.1.2 Stimuli

We constructed 44 quadruplets of items that were nonwords in American English. The nonwords in a quadruplet differed only in the medial consonant or consonant cluster. For example, one quadruplet consisted of ‹casub›, with a single medial ‹s›; ‹caswub›, with a letter corresponding to a sonorant consonant (‹l›, ‹m›, or ‹w›) after the medial ‹s›; ‹caspub›, with a letter corresponding to an obstruent, specifically, a stop (‹k›, ‹p›, or ‹t›), after the ‹s›; and ‹cassub›, with medial ‹ss›. The nonwords were similar in their other characteristics to those of the behavioral experiment in Study 1. We constructed two lists of items, as shown in the Appendix. Each list included the items from 22 quadruplets of nonwords and 20 words, the same ones as in Study 1. The practice items and the response options were the same as in Study 1.

3.1.1.3 Procedure

The procedure was the same as in Study 1.

3.1.2 Vocabulary analysis

The vocabulary analysis was conducted as in Study 1, filtering the words into the four categories used for the present experiment. The ‹s› + sonorant category included medial ‹sl›, ‹sm›, ‹sn›, and ‹sw› (disyllables: 308 tokens, 63 types; polysyllables: 443 tokens, 110 types), the ‹s› + obstruent category included ‹sk›, ‹sp›, and ‹st› (disyllables: 2,856 tokens, 461 types; polysyllables: 4,789 tokens, 997 types), the ‹ss› category included ‹ss› (1,584 types, 267 tokens; polysyllables: 2,287 tokens, 460 types), and the ‹s› category included single medial ‹s› (as in Study 1: 1,456 tokens, 205 types for disyllables; 2,865 tokens, 527 types for polysyllables).

3.2 Results

3.2.1 Behavioral experiment

Participants chose the correct response on 99% of the words. On the nonword trials, they chose long vowels on 25% of the trials (1,633) and short vowels on 75% (4,967). The left columns of data in **Table 2** show, for nonwords with each type of medial, the mean and standard deviation of the percentage of long choices. We conducted a mixed-model logistic regression analysis in R, using the lme4 package (Bates et al., 2015). The dependent variable was whether the first vowel was long, and medial type was a fixed factor with ‹s› + sonorant as the reference level. The model had random intercepts for participants and item quadruplets. Compared to ‹s› + sonorant, ‹ss› did not elicit a significantly different number of long vowels ($p = .303$), nor did ‹s› + obstruent ($p = .155$). But single ‹s› elicited significantly more long vowels ($p < .001$).[2]

[2] A reviewer asked whether ‹sl› and ‹sw›, which have true complex onset parallels, e.g., ‹pl› and ‹tw›, pattern together, in contrast to ‹sm› patterning with ‹s› + stop, which do not. A breakdown of the data for individual clusters, presented in the supplementary materials, did not support this idea.

Table 2: Percentage of long vowels in first syllable in behavioral experiment and vocabulary analysis for Study 2.

Medial	Behavioral data		Vocabulary analysis	
			Disyllables	All words of two or more syllables
	M	*SD*	%	%
‹s› + sonorant	19	11	0	0
‹s› + obstruent	18	11	11	7
‹ss›	21	12	2	2
‹s›	41	16	82	58

3.2.2 Vocabulary analysis

The columns in **Table 2** marked "Vocabulary analysis" show the percentage of pronunciations with long vowels in the first syllable for each type of item, weighting words by their frequencies in the way mentioned earlier. Comparing the vocabulary data to the behavioral data, we see a root mean square difference of 25 percentage points when using the vocabulary statistics for disyllables and 17 when using those for all words of more than one syllable. The proportion of long vowels is lower for all types of sequences that begin with ‹s› than before single ‹s› in both the vocabulary data and the behavioral data, but the two datasets differ in that the vocabulary data show a higher proportion of long vowels for ‹s› + obstruent sequences than for other ‹s› sequences, whereas the behavioral data do not. Closer inspection of the vocabulary data reveals that the difference between ‹s› + obstruent sequences and other ‹s› sequences mostly reflects the use of long vowels before ‹st› in words such as *postal*, which derive from single-morpheme words with long vowels before ‹st›.[3] Long vowels are extremely rare before ‹sk› and ‹sp›. Another difference between the two datasets is that the vocabulary data show many more long vowels before single ‹s› than the behavioral data show, as also observed in Study 1.

3.3 Discussion

This study went beyond Study 1 by distinguishing between two types of medial sequences that begin with ‹s›: those that correspond to phonological sequences with rising sonority profiles (e.g., ‹sl›) and those that correspond to phonological sequences with non-rising sonority profiles (e.g.,

[3] In a reanalysis using only words not listed as being derived from independent words, the percentage of long vowels for ‹s› + obstruent sequences fell to 4% for disyllables and 3% for all words of more than two syllables.

‹sp›). It was important to make this comparison, because some linguists have postulated that /s/ clusters with rising sonority profiles are onsets, just like clusters such as /pl/, but that /s/ clusters with non-rising sonority profiles are represented differently (for discussion, see Goad, 2011; 2012; Kaye, 1992). In other linguistic views, clusters with initial /s/ are structured differently than clusters without initial /s/, regardless of their sonority profile. We found that sequences corresponding to /s/ clusters with rising sonority profiles and sequences corresponding to /s/ clusters without rising sonority profiles behaved alike in both the vocabulary analysis and the behavioral study. The present behavioral results align with those from experiments using syllabification tasks. In those studies, participants often place the /s/ of items with medial /s/ clusters in the first syllable, both for clusters with rising sonority profiles (e.g., /sl/) and clusters without rising sonority profiles (e.g., /sp/; Eddington et al., 2013; Redford & Randall, 2005; Treiman et al., 1992).

Study 2 went beyond Study 1 not only by distinguishing between ‹s› clusters that differ in their phonological sonority profiles, but also by including ‹ss› sequences. This sequence represents a single phoneme, as ‹s› does, but we found it to have a dramatically different effect on the pronunciation of a preceding vowel. In both the behavioral experiment and the vocabulary analysis, there were many fewer long vowels before ‹ss› than before ‹s›. Treiman et al. (2023) found the same results when comparing single and double versions of other consonant letters. When controlling for phonology, therefore, the number of letters that follows a vowel has a strong influence on whether the vowel is long or short.

4. General discussion

The English writing system is complex, to the point that some have suggested that “it is almost impossible to predict the actual pronunciation” of a letter string (Domahs et al., 2014, p. 68). However, studies with English monosyllables paint a more positive view, showing that the context in which a letter occurs can help to specify its pronunciation and that skilled readers take advantage of these effects (e.g., Kessler & Treiman, 2001; Siegelman, Kearns, et al., 2020). The goal of the present research was to expand our knowledge of context effects for items of more than one syllable, which have been underrepresented in previous research. We focused on two-syllable items with different types of medial CC sequences – a good test case for learning about the English writing system itself, how readers translate from spelling to sound, and the degree to which skilled readers have picked up patterns in the vocabulary without explicit instruction.

Educators who follow a phonics approach often assume that a vowel is generally pronounced as long if it is followed by a single consonant and then another vowel letter and that it is generally pronounced as short if it is followed by two consonant letters (Kearns, 2020). The results of our vocabulary analysis confirm that the ratio of long to short vowels in English words is affected by the number of following consonants. For example, long vowels are more common than short vowels when they occur before ‹s› followed by another vowel letter, but long vowels virtually never occur before ‹ss›. However, our results also show that the number of medial consonant letters is not the only systematic influence on the use of long and short vowels. The ratio of long to short vowels, rather than being the same for all types of medial consonant sequences, is affected by the characteristics of the phonemes that the consonant letters represent. Long vowels are fairly common, although not in the majority, before sequences that correspond to an obstruent followed by a sonorant (e.g., ‹pl›). Long vowels are much less common before medial sequences that begin with ‹s›, regardless of whether the following consonant corresponds to a sonorant (e.g., ‹sl›) or a stop (e.g., ‹sp›). Thus, English spelling-to-sound relations are more predictable than is often believed.

Our behavioral results are not consistent with the idea that readers rely on the rules of phonics, either because they were taught to do so as children or because they have induced them on their own. Users of phonics rules would not be expected to produce more long vowels before sequences such as ‹sp› and ‹sl› than before sequences such as ‹pr›, but our participants used fewer long vowels in the former case than the latter case. Users of phonics rules would be expected to produce primarily long vowels before single medial consonants, but our participants did not.

Another view within reading research is that readers break up written words so as to maximize the codas of their syllables (Taft, 1979; Taft & Álvarez, 2014). If so, the first orthographic syllable of all the items in our behavioral studies would end with at least one consonant letter. If readers tend to use a long pronunciation for a vowel in a syllable that is closed by a consonant, there is no reason to expect long vowel use to vary across types of items, as it did in our studies. Thus, the idea that readers form syllables via coda maximization is not supported.

A more common view in reading research is that readers form syllables by maximizing onsets and that sequences such as ‹sp› and ‹sl› are onsets, just like sequences such as ‹pr› (e.g., Wiley et al., 2024). If so, readers should have shown the same pattern of responses for items with medial sequences such as ‹sp› and ‹sl› as for items with medial sequences such as ‹pl›. For both types of items, they should place the consonant cluster at the beginning of the second syllable and pronounce the first vowel, which is in an open syllable, as long. However, our participants were much less likely to use long vowels before ‹s› clusters than before clusters such as ‹pl›.

As the preceding discussion shows, current theories of orthographic parsing and syllabification in reading do not account well for our results, including the difference in vowel pronunciation that we found between ‹s› clusters and obstruent + sonorant clusters. One linguistic interpretation of our results is consistent with Goad's (2012) analysis of /s/-initial clusters. Goad showed that a variety of unique properties of such clusters, especially apparent violations of sonority sequencing, can be explained by theorizing that the /s/ belongs to the preceding syllable. That would mean that items like ‹feslum› and ‹feskum› syllabify as ‹fes.lum› and ‹fes.kum›. If readers are sensitive to that syllabification, and if they have a general tendency to choose short vowels more in closed syllables than in open syllables, it is understandable that they usually read these items with short first-syllable vowels. Another linguistic interpretation of our results is that /s/ before a consonant is especially susceptible to ambisyllabicity, being simultaneously a coda of the syllable to its left, thus favoring short vowels, and an onset of the syllable to its right, as expected by the maximal onset principle (Gussenhoven, 1986; Kahn, 1976). We thank a reviewer for the interesting suggestion that all consonants after stressed vowels could be ambisyllabic, but with a graded level of attraction to the two syllables. Differences in degree of ambisyllabicity would be compatible with the graded nature of our experimental data.

With regard to spelling-to-sound translation, our results support the idea that readers are sensitive to subtle statistical patterns, including those that are not explicitly taught. However, the behavior of experienced readers in this and other studies (e.g., Treiman et al., 2021) does not mirror the statistical patterns of the writing system to the extent expected by many statistical learning theories of reading (Brown, 1998; Siegelman, Kearns, et al., 2020). For example, most English disyllabic words with medial VCV sequences have a long pronunciation of the first vowel, meaning that people could maximize their chances of correctly pronouncing a new disyllabic word if they used a long vowel in this context. But our results show that people often use short vowels when pronouncing novel disyllabic items of this sort. There are several possible reasons, not mutually exclusive, for readers' frequent use of short vowels. One reason may be that readers attend to both context-free and context-sensitive mappings and to different levels of contexts. For example, people may learn about the frequency of the ‹a› to /æ/ mapping irrespective of context and about its frequency in various contexts: before a consonant in all types of words and in words of specific lengths and before a CV in all types of words and in words of specific lengths. When trying to compute a pronunciation for the novel item ‹catab›, people could attend to any or all of those contexts, with competing or interacting results. A second reason for readers' frequent use of short vowels in VCV contexts may be that they read some nonwords as compound words like *login* that have the root boundary and, therefore, a syllable boundary after the medial consonant. A third reason for adults' frequent use of short vowels may lie in how they were taught the alphabet as children. U.S. children are typically taught that each letter has a name and a sound, the latter being how it is pronounced in words. The sound that is taught for vowel letters is the short pronunciation, and this early focus on short pronunciations may influence reading throughout life.

We turn now to models that are intended to simulate how readers translate spellings to sounds. Such models have played an important role in discussions of reading, because constructing a model forces us to consider in detail the workings of the reading process and because modeling can shed light on how reading develops and how it can go wrong. One way to test models is to ask whether they produce the same pronunciations for specific items that human readers do. Many models of spelling-to-sound translation work only for monosyllables

(Chang et al., 2019; Coltheart et al., 2001; Harm & Seidenberg, 2004), but one model that produces pronunciations for disyllables is that of Rastle and Coltheart (2000), which we refer to as RC00. Built into this model are a set of all-or-none rules that determine whether the first vowel of a disyllable receives stress and, if stressed, whether it is short or long. Specifically, nonwords have first-syllable stress unless they have a defined stress-repelling prefix or stress-attracting suffix. When the first syllable is stressed, the pronunciation of its vowel is determined based on the vowel letter and specific characteristics of the following letters. For the stimuli in our behavioral studies, this amounts to pronouncing ‹a›, ‹o›, or ‹u› as long if the consonant that comes after the vowel is immediately followed by ‹e› or final ‹y› and as short otherwise. **Table 3** shows that the RC00 model is compatible with our participants' behavior in assigning fewer long vowels to items with two-letter medials than to items with single-letter medials (cf. **Tables 1** and **2**) and in treating the different types of ‹s› clusters in Study 2 the same. But the number of long vowels is much lower in all categories than the number produced by our participants – the root mean square difference between RC00 and the behavioral data across the eight categories is 26 percentage points in Study 1 and 21 in Study 2 – with most categories showing no long vowels at all. This model also did a poor job of accounting for behavioral data on vowel length in previous studies (Treiman & Kessler, 2023; Treiman et al., 2023).

Table 3: Percent of nonword items pronounced with long vowels by the computational models RC00 (Rastle & Coltheart, 2000) and CDP++ (Perry et al., 2010).

Medial	**RC00**	**CDP++**
Study 1		
‹s› + consonant	0	19
Obstruent + sonorant	0	32
‹s›	11	44
Obstruent	11	41
Study 2		
‹s› + sonorant	0	21
‹s› + obstruent	0	7
‹ss›	0	0
‹s›	16	32

The second main model that computes pronunciations for disyllables is the CDP++ model of Perry et al. (2010). This model can be seen as an instantiation of a statistical learning view, in that it includes a network that learns about the connections between spellings and pronunciations. The model is first trained on the simple phonics rules (e.g., ‹l› to /l/, ‹a› to /æ/) that are often taught to young children, and then with a large set of monosyllabic and disyllabic English words and their pronunciations. When we ran our nonword stimuli through the CDP++ program for Windows, we found that this model fit the behavioral data quite a bit better than RC00 did. The overall root mean square difference was only 4 percentage points in Study 1 and 13 points in Study 2. Like RC00, CDP++ reflected the behavioral pattern of using fewer long vowels before two-letter medials than before one-letter medials; unlike RC00, it also agreed with participants in using fewer long vowels when a medial cluster began with ‹s›. However, the CDP++ model showed pronounced differences between the types of two-letter ‹s› medials in Study 2, using more long vowels before ‹s› + sonorant clusters. In contrast, our participants treated all the ‹s› clusters roughly the same.

The fact that the CDP++ model accounts reasonably well for our behavioral results is consistent with the idea that adults' reading of vowels is shaped by how they are taught the alphabet as children and by the statistics that they pick up by relating the spellings that they see in texts to words' pronunciations. However, the CDP++ model needs further development, so as to capture the details of adults' reading behavior. In future research comparing the behavior of models to that of human readers, it will be important to match for dialect. The RC00 and CDP++ models were meant for speakers of dialects other than the General American dialect spoken by our participants. We do not expect that differences should be substantial for our sets of items, which were designed to avoid major dialect differences, such as divergent treatments of ‹r›, but future studies will need to address this issue.

In future research, it will also be important to examine other linguistic factors that may influence the choice between long and short vowels. These include the identity of the vowel itself and that of the word ending. These factors have been studied for words with single medial consonants (Berg, 2016; Treiman & Kessler, 2023), and research is needed to determine whether these effects extend to words with two medial consonants. Also, it will be important to compare, within the same experiment, a task in which participants judge whether their own pronunciation of a specified vowel is long or short and a task in which their readings of nonwords are scored by phonetically trained judges.

Research on the role of context in vowel pronunciation is important, not only because of its implications for our understanding of the English writing system and the processes involved in reading, but also because of its implications for teaching. Some educational approaches, such as the idea that children should memorize the spellings of at least some words as phonically unanalyzable wholes or that they should use the pictures accompanying a text to guess words' pronunciations, are based on the idea that English is highly irregular in its spelling-to-sound relationships (see Castles et al., 2018). Our results suggest that English is more predictable than often thought, but that we cannot rely on people to pick up all its patterns on their own.

5. Conclusion

In English, a letter may have one pronunciation in some words and another pronunciation in other words. Are there clues in the writing system about when one to use one pronunciation over the other, or must readers guess at random? In the present study, we addressed this question by examining long and short pronunciations of vowels in words of more than one syllable. The results of our vocabulary analyses show that the choice between long and short pronunciations depends on whether the vowel comes before a single consonant or a consonant sequence and, in the case of a consonant sequence, whether the sequence begins with ‹s›. The difference between sequences like ‹sl› and ‹pl› supports linguists' views that /s/ clusters have unique properties, but not psychologists' views that clusters like ‹sl› are orthographic onsets in the same way as clusters like ‹pl›. In behavioral studies, we found that adult readers are sensitive to the statistical patterns uncovered in the vocabulary analyses, even those that are not taught as a part of phonics instruction. However, adults' behavior does not perfectly mirror the statistics of the vocabulary.

Appendix

Nonwords in Behavioral Study 1

List A: basev batev baswev batwev; basuf babuf basmuf babluf; cisa ciba cisla cibla; cusux cugux cuslux cuglux; dusod dutod duslod dutwod; dusup dutup dusnup dutrup; fesob fegob feskob feglob; gisid gifid gislid gifrid; hesi hebi heski hebli; hesil hebil heskil hebril; jesav jegav jeslav jeglav; kasif kabif kaslif kabrif; pasub pafub paslub paflub; rosu rofu roswu rofru; tesec tefec tesmec tefrec; tusof tutof tuspof tutrof; vosic vobic voslic voblic; vusug vutug vustug vutwug; wosay wobay wospay woblay; yisem yitem yismem yitrem; zisy zify zisly zifly; zoson zoton zospon zotron

List B: B. daset dabet daspet dabret; fesom fetom feslom fetwom; fosen foten fosnen fotren; gesin gefin geswin gefrin; gisab gifab gistab giflab; jisel jibel jismel jibrel; kesep ketep keslep ketrep; liseg ligeg lismeg ligleg; musaz mutaz musmaz mutwaz; muso mubo muspo mublo; nasap natap nasnap natrap; nisoc nifoc niskoc nifroc; puseb pubeb pusleb publeb; rasef rabef raslef rabref; rosim rofim roslim roflim; susud sufud susnud suflud; vosop votop vostop votrop; wasaf wagaf waskaf waglaf; yasam yagam yaskam yaglam; yesib yebib yestib yeblib; yosov yogov yoslov yoglov; zisum zitum ziswum zitwum

Nonwords in Behavioral Study 2

List A: casop cassop caslop caspop; cesef cessef ceslef cestef; fisem fissem fiswem fiskem; foso fosso fosmo fosto; huser husser huswer husper; joser josser josmer josper; keseb kesseb kesweb kespeb; lisud lissud lismud liskud; lusek lussek luswek luskek; nasic nassic naswic naskic; nesom nessom neslom nespom; nusa nussa nusma nuspa; rasib rassib raswib rastib; tasin tassin taswin taspin; tesav tessav teswav teskav; vosic vossic voslic vospic; wisav wissav wismav wistav; wisy wissy wisly wisty; wosu wossu woslu wostu; zesim zessim zeslim zeskim; zisof zissof zismof zistof; zusaf zussaf zuslaf zuspaf

List B: casub cassub caswub caspub; dasif dassif dasmif daspif; dasud dassud daswud daskud; dusep dussep duslep duspep; fesum fessum feslum feskum; fosux fossux foswux fostux; goseb gosseb gosmeb gospeb; husob hussob huslob hustob; jesib jessib jeslib jeskib; jusob jussob juswob justob; kesu kessu keswu kesku; kosif kossif koslif koskif; lusev lussev lusmev luskev; nusab nussab nusmab nuskab; rasef rassef rasmef rastef; rison risson rismon riston; tasuf tassuf tasluf taspuf; tesel tessel teswel tespel; viso visso vismo visko; vosaz vossaz voslaz vostaz; yisaf yissaf yiswaf yistaf; yiset yisset yismet yistet

Data accessibility statement

Data and analysis scripts for the studies are available at https://osf.io/by5gn/.

Ethics and consent

Ethical approval for the behavioral experiments was granted by the Institutional Review Board at Washington University in St. Louis; Reference numbers 202102148 and 202101025).

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Competing interests

The authors have no competing interests to declare.

Author Contributions

Rebecca Treiman: Conceptualization, Methodology, Writing – original draft preparation, Funding acquisition. Brett Kessler: Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing – reviewing and editing, Funding acquisition.

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