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Anticipatory Conditioning of Spelling-to-Sound Translation

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Abstract

College students' pronunciations of initial *c* and *g* were examined in English words and nonwords, both monosyllables and polysyllables. Pronunciations were influenced by adjacent context—whether the following letter was *e* or *i*—and by long-distance context—whether the item contained a suffix or spelling pattern characteristic of Latinate words. Pronunciations were also influenced by whether students had studied a language such as French in which *c* and *g* are systematically fronted before those vowels. The findings were not well fit by either a dual-route or a single-route reading model. Although skilled readers were affected by the contextual patterns in the input, they did not use these patterns to the extent that would be expected given the patterns' reliability in the English vocabulary. The results are discussed in terms of the size of the window within which spelling-to-sound translation takes place and the nature of the units that are used.

Keywords: reading, word recognition, spelling-to-sound translation, reading models

Anticipatory Conditioning of Spelling-to-Sound Translation

The English writing system is often viewed as highly irregular. Many letters and letter groups have more than one possible pronunciation, as when *ea* is pronounced as /i/ in *clean*, /ɛ/ in *head*, and /e/ in *steak*. (For an explanation of the phonetic symbols used here, see International Phonetic Association, 1999.) Writing systems with such characteristics, which are often called deep or inconsistent, are thought to be difficult to learn and use (e.g., Katz & Frost, 1992; Ziegler & Goswami, 2005). Analyses of English spelling-to-sound correspondences, however, paint a somewhat more encouraging picture (e.g., Kessler & Treiman, 2001). Although many letters and letter groups have more than one possible pronunciation, the surrounding context may provide a clue to the correct pronunciation. For example, *ea* is more likely to be pronounced as /ɛ/ before *d* than *n* (e.g., *dead* vs. *dean*), and *a* is more likely to be pronounced as /ɑ/ after *w* than *p* (e.g., *wander* vs. *pander*). If readers use context, some words that would otherwise have to be treated as containing exceptional spelling-to-sound correspondences would become more regular.

The English writing system contains information that could help readers, but do people actually use it? Several studies suggest that college-level readers consider consonantal context when translating vowel spellings into pronunciations (e.g., Ashby, Treiman, Kessler, & Rayner, 2006; Treiman, Kessler, & Bick, 2003). For example, students are more likely to pronounce *a* as /ɑ/ in nonwords such as *twamp* than those such as *glamp*. These studies are limited, however, in that the stimuli were monosyllables and the relevant context was always adjacent to the target vowel. In the experiments reported here, we went beyond the previous studies by examining context effects on the pronunciation of the initial consonants *c* and *g*. We examined polysyllables as well as monosyllables, and nonadjacent as well as adjacent context. Before discussing the theoretical issues that our experiments address, we provide some background on the pronunciation of *c* and *g* in English.

The English spelling tradition is derived from the Latin, where *c* always spelled /k/ and *g* always spelled /g/, sounds produced with the back of the tongue. But an anticipatory assimilation occurred as Latin evolved into the Romance languages: Those sounds were pronounced with the front of the tongue before *e*, *i*, or *y*, which spell front vowels in those languages. Because those changes were so consistent, the original spellings *c* and *g* were retained. In Old French, the result was that *c* and *g* were still pronounced /k/ and /g/, except before *e*, *i*, or *y*, in which case they were pronounced /s/ and /dʒ/. English scribes borrowed spelling patterns as well as much vocabulary from Old French, so that the same pattern broadly holds in English today: ***c**ane* /k/, ***g**out* /g/, but ***ce**nt* /s/, ***g**in**ge**r* /dʒ/.

Languages developed different ways of spelling /k/ and /g/ when they exceptionally appeared before front vowels (cf. French *quiche*, *guillotine*). In English, *k* is systematically used to spell /k/ before those letters (e.g., *cat* but ***k**itten*). However, although *gu* is used in a handful of words like *guest*, for the most part English does not add anything to indicate that *g* is pronounced /g/ before the front vowels: *give*, *get*, *leggy*. This may be due to the fact that the sound /dʒ/ is not native to English or to Viking Norse, another Germanic language from which it borrowed heavily, so in the core Germanic vocabulary, /g/ before front vowels is the rule rather than the exception. The upshot is that when one reads English, the pronunciation of *c* is predictable—/s/ before front vowel letters, else /k/. But *g* is more nuanced. It is usually /g/, but before *e*, *i*, or *y*, it can be either /g/ or /dʒ/—normally /g/ in Germanic words like *give*, but /dʒ/ in older French borrowings like *ginger*. Because French tradition influenced how English pronounces loanwords from Latin and Greek, /dʒ/ is also used for those words: e.g., *genius*, *gymnast*.

Thus the pronunciations of *c* and *g* in modern English are influenced by the letter's immediate context—whether it is followed by *e*, *i*, or *y* or some other letter—and by the vocabulary stratum to which the word belongs—whether it is a native word, like *gimmick*, or a word that stems from Old French or the classical languages, like *gigantic* or *cenotaph*. A word's origin may be marked by a suffix, as with the *-ic* of *gigantic*, or by a characteristic spelling pattern, such as the *ph* of *cenotaph*. The present study was designed to determine whether skilled readers' pronunciations of *c* and *g* are influenced by these markers, some of which are adjacent to the target letter (e.g., the first *i* of *gigantic*) and others of which are in a later syllable (e.g., the *-ic* of *gigantic*, the *ph* of *cenotaph*). We did this by asking people to read aloud nonwords as if they were real words of English (Experiments 1, 2, and 4) and by examining their pronunciations of real words (Experiment 3).

Influences of adjacent consonants on vowel pronunciation (e.g., Treiman et al., 2003) may be interpreted in several ways. According to the *large-unit* view, readers treat a letter sequence such as *ead* as a unit, linking it to the phoneme sequence /ɛd/ (e.g., Norris, 1994; Patterson & Morton, 1985). If nonadjacent context affects spelling-to-sound translation, however, a more plausible interpretation would be that people link print and speech at the level of letters and sound—*small units*—but that some of these links are sensitive to a letter's context. According to this small-unit view, the effects of a nonadjacent final *e* on vowel pronunciation are of a piece with the effects of an adjacent *d* on the pronunciation of *ea*: Both the *e* of *gate* and the *d* of *read* cue readers to activate a specific pronunciation of a vowel more highly than they would otherwise. In neither case do readers decode units as wholes.

Long-distance context effects, if found, would also speak to questions about the size of the window within which spelling-to-sound translation takes place. On some views, this window is as big as the word itself. Parallel models of spelling-to-sound translation take this view when they claim that readers consider all parts of a word when translating the letters into sound (e.g., Harm & Seidenberg, 2004; Norris, 1994; Plaut, McClelland, Seidenberg, & Patterson, 1996; Seidenberg & McClelland, 1989). Serial models, in contrast, hold that phonological codes are built up sequentially from left to right. According to one prominent serial model, the dual-route model of Coltheart, Rastle, Perry, Langdon, and Ziegler (2001), this takes place one letter at a time. Because most experimental and modeling work has been limited to monosyllables, little is known about the size of the window for polysyllabic words. Some evidence suggests that French polysyllables are translated into sound one syllable at a time (e.g., Carreiras, Ferrand, Grainger, & Perea, 2005; Ferrand & New, 2003), although a study with English suggests different conclusions (Jared & Seidenberg, 1990).

An additional question is whether readers' sensitivity to context is commensurate with the reliability of contextual patterns in the English vocabulary. Learning to read can be seen as a process of picking up the statistical patterns in the writing system to which the reader is exposed. Given college students' many years of reading experience, one might expect them to have internalized an optimal model of the statistical regularities in their writing system. Brown's (1998) ROAR model—an acronym for *rational, optimal, adaptive reading*—exemplifies this view. Connectionist theories (e.g., Harm & Seidenberg, 2004; Plaut et al., 1996; Seidenberg & McClelland, 1989) are also described as learning the statistics of the input. But what statistics do people or models internalize? In the present study, we asked whether skilled readers use adjacent and nonadjacent context to the extent that would be expected based on the reliability of the contextual patterns in the input. For example, *c* is virtually always pronounced as /s/ in English words when it is followed by *e* and *i*, and so readers who have had extensive experience with the language might be expected to virtually always pronounce it this way. Previous studies, however, suggest that college students are pulled toward the typical context-free pronunciations or spellings of vowels, making less use of context than might be anticipated (Perry, Ziegler, & Coltheart, 2002; Treiman, Kessler, & Bick, 2002; Treiman et al., 2003). We asked here whether the same phenomenon occurs for the initial consonants *c* and *g*.

In addition to examining variation across linguistic contexts in spelling-to-sound translation, we also examined variation across readers. Skilled readers may assign different pronunciations to the same nonwords (e.g., Andrews & Scarratt, 1998; Seidenberg, Plaut, Petersen, McClelland, & McRae, 1994), but little is known about the causes of these differences. In Experiments 2 and 3, we compared people who had studied a language such as French or Spanish—in which the pronunciations of *c* and *g* vary in a highly systematic way as a function of the following letter—to people who had not studied such a language. If differences are found, this would suggest that spelling-to-sound translation in a first language (L1) can be influenced by knowledge of a second language (L2).

Studies of cross-language effects on spelling-to-sound translation, like studies of cross-language effects in other aspects of language processing, have tended to focus on influences of L1 on L2 (e.g., Brysbaert, Van Dyck, & Van de Poel, 1999). Relatively few studies have looked for effects in the opposite direction. One exception is a study by Jared and Kroll (2001), which tested native speakers of English who also knew French. The participants' knowledge of French spelling-to-sound correspondences influenced their oral reading of English words only after the participants had recently read some French words. The results of Van Wijnendaele and Brysbaert (2002) and Brysbaert, Van Wijnendaele, and Duyck (2002) are similar in the sense that exposure to nonwords that looked similar to words of the participants' L2 influenced performance on subsequently presented L1 words. In the present study, we asked whether participants' knowledge of L2 influenced their performance in L1 even when the experimental session did not include L2 words or nonwords that looked like L2 words.

We know of only one prior study that has systematically examined the treatment of *c* by skilled readers of English. Calfee, Venezky, and Chapman (1969) asked college students to pronounce nonwords that contained *ce* or *ci*, finding that /s/ pronunciations occurred about 75% of the time. This rate is lower than expected given that *c* is pronounced as /s/ in almost all English words before these vowels. The results of Calfee et al. suggest that people have some bias to pronounce *c* as /k/, the phoneme with which it is most often associated in English, and that this bias is not completely overcome after years of experience with words such as *cent* and *cinnamon*. However, the Calfee et al. study had relatively few items with *c*, making it difficult to draw strong conclusions, and items with *g* were not included at all.

Several studies have examined spelling-to-sound translation for *c* and *g* in languages other than English. As mentioned earlier, the alternation between two different pronunciations as a function of the following vowel is virtually exceptionless, for *g* as well as *c*, in Romance languages such as French, Italian, and Spanish. Despite this, college students who are native speakers of these languages sometimes misread *g* and *c* in nonwords. Errors are particularly common when a nonword differs minimally from a real word in which the consonant has the other pronunciation. An example for Italian is *deliceto*, which is similar to the real word *delicato*. However, errors on *c* and *g* occur at rates as high as 30% even when this is not the case (Content & Peereman, 1992, and Peereman, 1991, for French; Job, Peressotti, & Cusinato, 1998, for Italian; Sebastián-Gallés, 1991, for Spanish; Martensen, Maris, & Dijkstra, 2003, for Dutch, which has many loanwords showing the alternation for *c*). The findings suggest that skilled readers have a surprising amount of difficulty with context-sensitive patterns in which the pronunciation of a consonant is conditioned by the following vowel, even when the pronunciation is fully predictable in the words of the language.

Experiment 1

This experiment was designed to examine the pronunciation of initial *c* and *g* by skilled readers of English, going beyond the preliminary study by Calfee et al. (1969). We examined people's pronunciations of initial *c* in monosyllabic nonwords with different vowels, comparing their patterns of performance to the English vocabulary statistics. We also examined skilled readers' pronunciations of initial *g* before different vowels. Because the alternation as a function of the following vowel is much less consistent for *g* than for *c*, Experiment 1 gives us the opportunity to examine people's use of adjacent context in a situation in which context provides an almost perfect cue to pronunciation and a situation in which context is less useful.

Method

Participants. Twenty Washington University students participated in exchange for course credit. None of the participants in this or the following experiments reported any serious speech, hearing, or reading problems. All had been exposed to spoken English since birth, and all had learned English as their first written language. Most of the Experiment 1 participants, as is typical for this population of college students, had some reading and speaking knowledge of a Romance language, usually Spanish or French.

Stimuli. There were 25 nonwords that began with *c* and 25 with *g*. For each initial consonant, there were nonwords with each of the vowels *a*, *e*, *i*, *o*, and *u* before each of the final consonant clusters *rsh*, *lth*, *nve*, *lsh*, and *pth*. We chose these finals because they do not form real words with any of these combinations of initial consonant and vowel. Fifty additional monosyllabic nonwords with a variety of spelling patterns served as fillers. The filler items in this and the other experiments did not contain the graphemes *c* or *g*; nor *s*, *k*, or *j*, letters that often spell the same sounds as *c* and *g*. Hardly any of the Experiment 1 nonwords with *e* or *i* differed by only one letter from a real word pronounced with initial /k/ or /g/ (e.g., a nonword like *girm*, which could be influenced by *girl*). Thus, these are not the kinds of nonwords that have been reported to cause particular difficulty in the studies with Romance languages that were discussed earlier.

The stimuli were divided into five lists. Each list had five items with initial *c* and five items with initial *g*, two with each vowel, as well as ten fillers. No vowel–final combination was repeated within a list. Three different random orders were prepared for each list. Each participant was presented with all five lists in a randomly chosen order. One of the three orders of each list was randomly selected for each participant.

Procedure. The participant was presented with the first list of nonwords and was asked to pronounce each nonword the way that he or she thought it would be read if it were an ordinary English word. Responses were tape recorded. The participant then answered a series of questions about his or her background, knowledge of foreign languages, and other topics. These questions took about five minutes. The second nonword list was then presented, followed by a filler task that took approximately five minutes. This procedure continued until all five lists had been presented. A short questionnaire was administered at the end of this and the other experiments involving nonwords. It asked participants how they had determined the pronunciations of *c* and *g*. The results of these final questionnaires will be mentioned in the General Discussion.

Results and Discussion

Pronunciations were transcribed by a phonetically trained experimenter. The initial consonants of the nonwords with initial *c* and *g* were scored as front (/s/ for *c*-initial nonwords and /dʒ/ for *g*-initial nonwords), back (/k/ for *c*-initial nonwords and /g/ for *g*-initial nonwords), or neither. This last category, which included unusual pronunciations such as /tʃ/ for *c*, was extremely uncommon. In this experiment and the following ones, 0.1% or less of all responses fell into the “neither” category. Table 1 shows, for the various types of nonwords, the proportion of front responses relative to the total number of front and back pronunciations.

Analyses of variance (ANOVAs) were performed using the factors of initial consonant (*c* vs. *g*) and vowel (*a*, *e*, *i*, *o*, *u*). There was a main effect of initial consonant ($F_1(1, 19) = 178.74$; $F_2(1, 4) = 107.96$; min $F'(1, 10) = 67.31$; $p < .001$ for all), such that participants produced more front pronunciations for *c* than *g*. A main effect of vowel was also found ($F_1(4, 76) = 234.79$; $F_2(4, 16) = 37.53$; min $F'(4, 21) = 32.36$; $p < .001$ for all), along with an interaction between initial consonant and vowel ($F_1(4, 76) = 156.89$; $F_2(4, 16) = 63.42$; min $F'(4, 31) = 45.16$; $p < .001$ for all). For both *c* and *g*, participants produced more front pronunciations before *e* and *i* than before *a*, *o*, and *u*. This effect was larger for *c* than for *g*; front pronunciations of *g* were infrequent even before *e* and *i*. For nonwords with initial *g*, the trend for more front responses before *e* than *i* was significant by subjects ($p < .001$) but not by items.

To aid in the interpretation of the results, we examined the pronunciations of *c* and *g* in the words of the English Lexicon Project (ELP; Balota et al., in press). The words in the ELP were selected so as to be generally familiar to Washington University students, and so statistics using this vocabulary should provide a good indication of the patterns to which our participants are exposed. We derived statistics on links from spellings to sounds because, although Stone, Vanhoy, and Van Orden (1997) suggested that ambiguity in the links from sounds to spellings affects readers' performance, later studies have found little support for this idea (e.g., Kessler, Treiman, & Mullennix, in press; Massaro & Jesse, 2005). The pronunciations of *c* and *g* in most words of the ELP are unambiguous. Exceptionally, *Celt* and *Celtic* may be pronounced with either /k/ or /s/. A poll of 44 students from the same population as in Experiment 1 showed 61% /s/ pronunciations for *Celt* and 68% for *Celtic*. The vocabulary statistics were adjusted to reflect these percentages, such that *Celt* for example counted as 61% of an /s/ word. Table 2 shows data on the pronunciations of the graphemes *c* and *g* when they occur in word-initial position and in any position. Because people's pronunciations of initial *c* and *g* in monosyllabic nonwords are likely to be most influenced by their experience with initial *c* and *g* in monosyllabic real words, we discuss the results for word-initial position first. Among the relatively few monosyllabic English words with initial *ce* and *ci*, /s/ pronunciations are virtually exceptionless. This is true whether each word is weighted equally (type count) or whether the words are weighted by the frequencies that are provided in the ELP database (token count). Front pronunciations are less common for *ge* and *gi* than for *ce* and *ci*, both by types and by tokens. The rates of front pronunciations for *ge* and *gi* are especially low by tokens, since some very common words such as *get* and *give* have back pronunciations. For initial *g*, front pronunciations are more common before *e* than before *i*. The patterns are the same in the statistics that include *c* and *g* in all positions of monosyllables.

Comparing the behavioral results in Table 1 with the vocabulary statistics in Table 2, it appears that readers' pronunciations of initial *c* and *g* follow the vocabulary statistics in some ways but not others. People's tendency to use more front pronunciations for *c* than for *g* reflects the patterns in the monosyllabic words they have experienced, as does their tendency to use front pronunciations of *g* more often before *e* than *i*. For *ge* and *gi*, adults' rate of front pronunciations is much lower than anticipated from the type-based statistics for these vowel contexts but fairly similar to that anticipated on the basis of monosyllabic tokens. For *ce* and *ci*, adults produce front pronunciations less often than expected based on types or tokens. That is, even though the pronunciation of *c* in English is almost perfectly predicted by the following vowel (the only exceptions being *Celt* and *Celtic*, for people who pronounce them with /k/), skilled readers do not invariably follow the pattern when pronouncing nonwords. Instead, they sometimes pronounce *c* before *e* and *i* with the /k/ that is the typical pronunciation of *c* in other contexts. The results thus suggest that skilled readers do not adjust their pronunciations of initial *c* on the basis of context as much as might be expected given the reliability of the pattern in the input. Similar phenomena have been found for a number of context-conditioned vowels (Treiman et al., 2002, 2003).

As described in the Introduction, words that stem from French and the classical languages are especially likely to show the alternation between front and back pronunciations of *c* and *g* as a function of the following vowel. When a polysyllabic word has a suffix, that suffix may provide a clue to the origin of the word. Suffixes such as -*ic* and -*oid* mark a word as Latinate,[1] in contrast with those such as -*ful* and -*ness*. In Experiment 2, we designed monosyllabic nonword stems and presented these in their bare form (e.g., *geb*), as bisyllables with a native suffix (e.g., *gebful*), or as bisyllables with a Latinate suffix (e.g., *gebic*). We asked whether skilled readers are more likely to use front pronunciations in the Latinate suffix condition than in the native suffix condition or the monosyllabic condition. If such a difference is found, it would suggest that context effects extend beyond the type of context studied in Experiment 1—adjacent context. Long-distance anticipatory effects would speak against the view that spelling-to-sound translation necessarily proceeds from left to right across the word, either letter by letter (e.g., Coltheart et al., 2001) or syllable by syllable (e.g., Carreiras et al., 2005; Ferrand & New, 2003).

Another goal of Experiment 2 was to examine individual differences in spelling-to-sound translation. As described earlier, *c* and *g* are consistently pronounced differently before *e* and *i* than before other vowels in certain languages, most notably Romance languages. If experience with such languages influences performance in English, we might find differences in the pronunciation of initial *c* and *g* between people who have studied such a language, which we will call a *promoting* language, and those who have not. We cannot test this hypothesis using the data of Experiment 1 because the large majority of the participants in that experiment had studied a Romance language, typically Spanish or French, which promotes the alternation. In Experiment 2 we encouraged participation by individuals who had studied a variety of foreign languages, not only Spanish or French.

Experiment 2

Method

Participants. The participants were 40 students from the same population as Experiment 1; none had participated in the earlier experiment. The sign-up materials encouraged participation by students who had studied languages other than French and Spanish.

Stimuli. Stimuli with initial *c* and *g* were constructed in triplets. Each triplet included a monosyllabic nonword, a bisyllabic nonword that that was made up of this same letter sequence followed by a native suffix, and a bisyllabic nonword with this same stem followed by a Latinate suffix. We chose suffixes such as -*ent* (Latinate) and -*est* (native) that clearly fell into one or the other category. There were six suffixes of each type. The two types of suffixes were equated for length and, when possible, consonant–vowel structure. We had six triplets beginning with each of *ce*, *ci*, *gi*, and *ge*, and three triplets with each of *ca*, *co*, *cu*, *ga*, *go*, and *gu*, for a total of 126 critical stimuli. The make-up of the critical stimuli is detailed in the Appendix. An equal number of filler stimuli were constructed. These were monosyllabic and bisyllabic nonwords with a variety of structures.

The critical stimuli were divided into three lists such that one member of each triplet occurred on each list. Each list contained an equal number of *c* and *g* items with each initial consonant–vowel combination. The fillers were evenly divided among the three lists. The stimuli in each list were arranged in three different random orders. Each participant was presented with all three lists, their order randomly chosen for each participant. One of the three orders of each list was randomly selected for each participant.

Procedure. The procedure was similar to that of Experiment 1, except that the filler tasks between each list lasted approximately 15 minutes.

Results and Discussion

The pronunciations were transcribed and scored as in Experiment 1. Table 3 shows the proportion of front responses relative to the total number of front and back responses for the nonwords with initial *c* and *g*. Front pronunciations were extremely uncommon for nonwords with *a*, *o*, and *u*, and so the results for the stimuli with these vowels were pooled in Table 3 and the following analyses.

ANOVAs were carried out using the factors of initial consonant (*c* vs. *g*), vowel (*e* vs. *i* vs. *a*, *o*, and *u*), and structure (monosyllable vs. native bisyllable vs. Latinate bisyllable). There was a main effect of initial consonant ($F_1(1, 39) = 439.37$; $F_2(1, 36) = 934.78$; min $F'(1, 68) = 298.89$; $p < .001$ for all), such that readers produced more front pronunciations for *c* than *g*. A main effect of vowel was also observed ($F_1(2, 78) = 381.05$; $F_2 (2, 36) = 503.11$; min $F'(2, 107) = 216.83$; $p < .001$ for all), together with an interaction between initial consonant and vowel ($F_1(2, 78) = 328.58$; $F_2(2, 36) = 256.21$; min $F'(2, 89) = 143.96$; $p < .001$ for all). For both *c* and *g*, participants produced more front pronunciations before *e* and *i* than before the control vowels *a*, *o*, and *u*. This effect was larger for *c* than for *g*, where front pronunciations were in the minority even before *e* and *i*. For nonwords with initial *g*, there were significantly more front pronunciations before *e* than *i*, both by subjects and by items. For nonwords with initial *c*, the difference between *e* and *i* was not significant either by subjects or by items. The ANOVAs also showed a main effect of structure ($F_1(2, 78) = 12.94$, $p < .001$; $F_2(2, 72) = 8.65$, $p < .001$; min $F'(2, 142) = 5.18$, $p = .007$). Bisyllables with Latinate endings yielded significantly more front responses than bisyllables with native endings or monosyllables. The latter two types of items did not differ reliably from one another. The main effect of structure was modulated by an interaction with vowel ($F_1(4, 156) = 3.72$, $p = .006$; $F_2(4, 72) = 2.62$, $p = .042$; min $F'(4, 170) = 1.54$, $p = .19$). The pattern just described held when the vowel was *e* or *i*, but it did not hold for back vowels, where front responses were extremely uncommon regardless of structure. The interaction between structure and consonant was not significant either by subjects or by items.

The results for monosyllables replicate those of Experiment 1. Specifically, the rate of front pronunciations for initial *c* and *g* was affected by the identity of the consonant—more front pronunciations for *c* than *g*—and the identity of following vowel—more front pronunciations before *e* and *i* than other vowels. For *g*, there were more front pronunciations before *e* than *i*. The difference between *ge* and *gi* was significant by both subjects and items, supporting the trend that was observed in Experiment 1.

The results for bisyllables show that the nature of the second syllable influences spelling-to-sound translation for a word-initial consonant. Skilled readers were more likely to produce front pronunciations of the initial consonant in nonwords such as *gebic*, with a Latinate suffix, than in nonwords such as *gebful*, with a native suffix, or in monosyllabic nonwords. The effect was relatively small, but it was statistically significant and it held for both *g* and *c*. Context effects are thus not limited to immediate context. How the first letter of a bisyllabic nonword is translated may be influenced by the letters at the end of the nonword—as many as seven letters away for our stimuli. Such long-distance effects suggest that spelling-to-sound translation does not necessarily proceed one letter or even one syllable at a time.

To aid in the interpretation of the behavioral data, we examined the pronunciations of words in the ELP that contained the grapheme *c* or *g* and one of the suffixes used in this experiment. The results are shown in Table 2. Front pronunciations of *c* before *e* and *i* are virtually the rule for real words, whether the suffix is native or Latinate and whether the *c* is at the beginning of the word or elsewhere. *Celtic*, for those who pronounce it with /k/, is the only exception. The pronunciation of *g* before *e* and *i* varies substantially with the type of suffix. Words with a native suffix, such as *gelding* and *girlish*, sometimes have the back pronunciation. Back pronunciations are more common when the vocabulary statistics are calculated by tokens than by types. Words with a Latinate suffix, such as *genetic*, always have the front pronunciation.

Even though the Latinate suffixes used in Experiment 2 guarantee a front pronunciation of *g* before *e* and *i* in the words of the ELP, our participants used front pronunciations less than 20% of the time, averaging over *e* and *i*, when a Latinate suffix was present. That is, although a Latinate suffix significantly increased skilled readers' use of front pronunciations, it had a much weaker effect than the vocabulary statistics would suggest. In addition, although participants produced mostly front pronunciations of *ce* and *ci* for nonwords with Latinate suffixes, their rate of front pronunciations for such items was lower than anticipated based on the vocabulary statistics. These results support the conclusion drawn from Experiment 1: Skilled readers adjust their pronunciations of initial *c* and *g* according to context, but not as much as expected given the strength of the context effects in the words to which they have been exposed. People are drawn to the typical context-free pronunciations of *c* and *g* (/k/ and /g/, respectively), and this appears to constrain their use of other factors.

People's tendency to produce more front pronunciations for *g* before *e* than *i* in the initial positions of nonwords mirrors the pattern seen in the initial positions of real words. The difference between *ge* and *gi* is reversed in the vocabulary statistics based on all positions of polysyllabic words with native suffixes, probably reflecting the front pronunciations of *gi* in the many words like *raging*. This is the one case in which the vocabulary statistics vary markedly with word position, and people's pronunciations of initial *gi* and *ge* in nonwords seem to reflect primarily their experiences with *gi* and *ge* in the same positions in real words.

The participants in Experiment 2 had studied between zero and four languages other than English. We classified the participants in terms of whether or not the other written language(s) they had studied would promote fronted pronunciations of both *c* and *g* before *e* and *i* that differ from the back pronunciations used before other vowels. For example, French promotes the alternation in that *c* is pronounced in French as /s/ before *e* and *i* but as /k/ elsewhere; *g* also is pronounced differently in the two contexts. Other Romance languages, such as Spanish, promote the alternation as well. Latin as taught in U.S. schools works against the alternation, because *c* is always pronounced /k/ and *g* is always pronounced /g/, regardless of the following vowel. A language such as Arabic is neutral. We grouped neutral and inhibiting languages in our analyses because relatively few participants had studied only an inhibiting language. Participants were dropped from this analysis if they knew a language that could not be neatly classified or if they had studied two or more languages that fell into different categories, such as both French and Latin. Table 4 shows the proportion of front pronunciations of *c* and *g* before *e* and *i*, pooling over stimulus structure, for participants whose other language(s) fell into the promoting ($n = 14$) and nonpromoting ($n = 19$) categories. For both *c* and *g*, the proportion of front pronunciations was higher for participants who had studied a language that promoted the alternation than for participants who had not studied such a language. This was reflected in a main effect of language background ($F_1(1, 31) = 5.79$, $p = .022$; $F_2(1, 22) = 32.63$, $p < .001$; min $F'(1, 41) = 4.92$, $p = .03$). As expected on the basis of the previous analyses, the main effect of consonant was also significant ($F_1(1, 31) = 418.66$; $F_2(1, 22) = 537.39$; min $F'(1, 53) = 235. 33$; $p < .001$ for all). The participants who had studied a promoting language did not have a high degree of skill in this language: Over half of them had begun their study of that language only in high school, and none were studying the language as their college major. The results thus suggest that even a relatively small amount of experience with a language in which the pronunciations of *c* and *g* vary systematically as a function of the following vowels promotes use of this pattern for English. That is, knowledge of a second language can influence reading in a first language.

The apparent effects of L2 knowledge on L1 spelling-to-sound mapping are surprising. Previous studies have found such effects only with participants who, prior to being tested with L1 stimuli, saw L2 words or nonwords with spelling patterns found in L2 but not L1 (Brysbaert et al., 2002; Jared & Kroll, 2001; Van Wijnendaele & Brysbaert, 2002). In the present study, L2 knowledge had not been primed via such manipulations. Moreover, most of our participants were not all that skilled in their L2. Perhaps the effects that we found occurred because participants answered questions about the language(s) they had studied after the first of the three blocks of the experiment, activating their L2 knowledge. If so, then differences between participants with promoting and nonpromoting languages might appear on the second block of trials, immediately after the questionnaire had been presented, but not on the first block. The difference between the groups in front pronunciations of *c* and *g* before *e* and *i* was about 2% larger in the second block of trials than in the first, but the critical interaction did not approach significance either by subjects or by items. An effect of L2 on spelling-to-sound translation in L1 was thus apparent even before people had been asked about their history of language study. We sought additional evidence in Experiment 3 by selecting participants in such a way that they did not know that their experience with other language(s) was at all relevant to the study and by not asking questions about knowledge of other languages during the experiment.

Another possible explanation for the effect of language background found in Experiment 2 was that the stimuli were nonwords. The participants were asked to pronounce the nonwords as if they were ordinary English words, but those who knew another language might have treated the nonwords as belonging to that other language. To address this issue, we used real word stimuli in Experiment 3. If participants with promoting and nonpromoting L2s perform differently even with real English words, this would support the idea that experience with other languages affects spelling-to-sound translation in English.

In addition to re-examining the effects of L2 knowledge on L1 reading, Experiment 3 sought further evidence for the surprising and theoretically important long-distance context effects found in Experiment 2. One category of words in Experiment 3 began with *g* followed by *e*, *i*, or *y* and had /dʒ/ as the correct pronunciation. Of these, half had an ending that is typically associated with Latinate words, such as the *-id* of *gelid*. The other half, such as *genip*, did not have a Latinate ending. These and the other words in Experiment 3 were uncommon, and we expected our participants to have difficulty pronouncing them. We asked whether front pronunciations, which are correct pronunciations for the *g* items in this category, were more common for words with Latin-type endings. A second category of words with initial *ge*, *gi*, and *gy* had /g/ as the correct pronunciation. We expected front pronunciations to be more common for the Latinate items of this type, such as *gilsonite*, than for the non-Latinate items, such as *gemsbok*. In other words, readers should make more errors on the Latinate items in this case. We also included words with initial *ce*, *ci*, and *cy* pronounced with /s/. Correct front pronunciations should be more common when such words bear Latin-like endings, as with *cicatrix*, than when they do not, as with *cittern*. A fourth category of words would have had initial *ce*, *ci*, or *cy* pronounced with /k/, but English has no such words other than *Celt* and its relatives. The results of the pilot study described earlier—68% front pronunciations for *Celtic*, as compared to 61% for *Celt*—are consistent with the idea that a Latinate suffix encourages front pronunciations in this case.

Experiment 3

Method

Participants. The participants in the main study were 34 students from the same population as Experiment 1. Half of them had studied one or more Romance languages in which *c* and *g* have fronted pronunciations before *e*, *i*, and *y*. None of these participants had studied a language that works against the alternation. The other half of the participants had not studied a language that promotes the alternation. The participants were selected on the basis of a screening questionnaire, typically given several weeks before the experiment, which included questions about language background and a variety of other topics. Participants whose responses qualified them for the study were invited to take part. They did not know why they had been selected. Because of this, together with the time that had elapsed between the screening questionnaire and the experiment itself, the participants could not know that their experiences with other languages were relevant to the study. An additional 27 students from the same population served in a pilot study that was used to select stimuli for the main study. None of the students had participated in other experiments in this series.

Stimuli. We began by selecting 106 words that could potentially be suitable for the experiment. These included virtually all of the English words we could find that fit the criteria. A pilot study was carried out to select the best-equated subsets of these words for the main experiment. The participants in the pilot study completed a familiarity rating task followed by a definition task. For the former, the participants rated each word on a scale of 1 to 5. A rating of 1 meant "I'm very sure I haven't seen this word before," 2 corresponded to "I'm pretty sure I haven't seen this word before," 3 was "I'm not sure if I've seen this word before or not," 4 was "I'm pretty sure I've seen this word before," and 5 was "I'm very sure I've seen this word before." In the definition task, participants were shown three possible definitions for each word and chose the one they thought was correct. The words were arranged in three different random orders, and approximately one third of the pilot subjects were assigned to each order. The experimenter explained that all the items were real English words but that many were rare.

Based on the results of the pilot study, we chose 96 words as the critical items for the main experiment, 16 in each of the six cells. Words were classified as Latinate if the end of the word corresponded to a reasonably well-known Latin, Greek, or French ending, regardless of the true etymology of the word or the ending. We selected the words so that the cells were as well matched as possible on several covariables that could affect performance—rated familiarity and definition accuracy from the pilot study, number of letters, and objective frequency. For the last of these variables, we used the log of the number of Web pages that contained the word according to a Yahoo Advanced Web Search (2004). This was expected to give more reliable information than standard frequency counts. A rare word may have a zero frequency in standard frequency counts, but differences among such words may be picked up by examining the vastly larger Web. ANOVAs for each of the preceding variables were carried out using the factors of correct pronunciation (/s/, /dʒ/, /ɡ/) and word type (native, Latinate). No significant effects were found in any of the analyses. Averaging over all of the words chosen for the experiment, the mean length was 7.0 letters, the mean proportion of correct responses on the definition task was 50%, and the mean familiarity rating was 2.2. Thus, although participants said that they had not seen many of the words, they performed above the level expected by chance (33%) on the definition task, an outcome that is in line with previous reports (e.g., Whitmore, Shore, & Smith, 2004).

Each participant read aloud 168 filler words in addition to the 96 critical words. The fillers were words of more than one syllable that were expected to be familiar to our participants. Approximately half the participants saw fillers of Latinate origin, and the other half had fillers of native origin. The two types of fillers were similar in length (mean of 7.1

letters, averaging over the two types of fillers) and frequency (mean frequency of 61 tokens per million according to the ELP frequency counts).

The critical words and fillers were randomly intermixed for presentation, with the constraint that the few critical words that shared a stem were separated by at least 10 other words. Three different random orders were prepared, and approximately equal numbers of participants were assigned to each random order.

Procedure. The participants were asked to pronounce each word aloud to the best of their ability, and their pronunciations were tape recorded. The participants were told that all of the items were real English words but that some of them were quite uncommon.

Results and Discussion

The pronunciations were transcribed and scored as in the previous experiments. Table 5 shows the proportion of front pronunciations relative to the total number of front and back pronunciations for the various categories of words. The results are shown separately for those participants who had studied a language that promotes fronted pronunciations of *c* and *g* before certain vowels and those who had not studied such a language. The data were analyzed by subjects only. As the experiment used almost all of the English words that fit the criteria, it is inappropriate to test whether the results would be expected to generalize to other items.

An ANOVA was carried out using the factors of correct pronunciation (/s/, /dʒ/, /g/), word type (native, Latinate), participant language background (promoting, nonpromoting), and filler type (native, Latinate). We found a main effect of correct pronunciation ($F_1(2, 60) = 1019.32$, $p < .001$). Front pronunciations were most common for the words with initial *c* pronounced as /s/, and intermediate in frequency for the words with initial *g* pronounced as /dʒ/. Such pronunciations were least common for the *g*-initial words for which the back pronunciation was correct. There was also a main effect of word type ($F_1(1, 30) = 60.59$, p

$< .001$). The rate of front pronunciations was higher for Latinate type words than for non-Latinate words, as found in Experiment 2. Word type interacted with correct pronunciation ($F_1(2, 60) = 9.01$, $p < .001$). The difference between native and Latinate words was smaller for *c*-initial words, where front pronunciations were close to ceiling, than for *g*-initial words. In addition, there was a main effect for participant language background ($F_1(1, 30) = 6.44$, $p = .017$). Participants who had studied a language that promoted the alternation produced more front pronunciations before *e*, *i*, and *y* than participants who had not studied such a language. Language background interacted with correct pronunciation (F_1 $(2, 60) = 3.47$, $p = .037$). This effect occurred because the effect of language background was smaller for *c*-initial words, where front pronunciations were close to ceiling for both groups of participants, than for *g*-initial words. We found no significant effects as a function of filler type.

The results of this experiment show that similar effects occur in the reading of uncommon real words as in the reading of nonwords. With real words, as with nonwords, *c* is more likely to receive a fronted pronunciation before *e*, *i*, or *y* than *g* is. Indeed, the participants in this study almost always chose /s/ pronunciations for real words that began with *ce*, *ci*, or *cy*. With real words, as with nonwords, front pronunciations are more common for items with Latin-type suffixes than for other items. That is, letters later in a word affect how the first letter is pronounced. With real words, as with nonwords, people who have studied a Romance language are more likely to pronounce initial *ge*, *gi*, and *gy* with /dʒ/ than people who have not studied a Romance language. This occurs even when participants' other languages are not used or mentioned in the experiment. As in the previous experiment with nonwords, high levels of skill in another language are not required for knowledge of that language to affect the reading of English. In the current study, a minority of the students who had studied a Romance language were continuing their study of that language in college. Eight of the 17 students who had studied a Romance language had begun the study of this language only in high school, while the other 9 had begun earlier. Given the relatively low quality of language instruction in most U.S. schools, we can infer that participants' knowledge of their L2 was not uniformly high.

Together, the results of Experiments 2 and 3 indicate that the presence of certain Latinate suffixes promotes front pronunciations of initial *c* or *g* before *e*, *i*, and *y*. The suffixes are not adjacent to the *c* or *g*; indeed, they are in a different syllable. The results thus show that elements that appear later in a word can influence spelling-to-sound translation for an initial consonant. In Experiment 4, we tested the effects of nonadjacent context in another way. We designed two types of nonwords: those that had letter patterns that are often found among Latinate words and those that contained native spelling patterns. The critical spelling patterns in Experiment 4 were not suffixes. For example, *ph* is found in words of Latinate origin but is not a meaningful unit. The spelling pattern *ff* is native, not found at the end of Latin words. If the presence of a Latinate spelling pattern such *ph* triggers a front pronunciation, we would expect to see a higher rate of /s/ pronunciations in nonwords such as *ceph* than in nonwords such as *ceff.* The nonwords of interest in Experiment 4 all had a vowel that promoted front pronunciations of *c* and *g*; the vowel was immediately after the *c* or *g* and the critical spelling pattern was later in the word. If the two conditions differ in the rate of front pronunciations, this would suggest that the presence of certain spelling patterns combines with the effect of the vowel letter to raise the rate of front pronunciations. Context effects need not involve adjacent letters, and they need not involve meaningful suffixes.

Experiment 4

Method

Participants. The participants were 18 students from the same population as Experiment

1. Two had participated in Experiment 3; the rest had not participated in any of the other experiments. We did not select participants for language background in this experiment, as few of the students in our population have never studied a Romance language. The large majority of the Experiment 4 participants, therefore, had studied a promoting language. Half of the participants were assigned to the *c* condition and half to the *g* condition.

Stimuli. We selected letters and letter groups that are typical of native words and those that are typical of words of Latinate origin, picking pairs of spelling patterns that were as similar as possible in length and consonant–vowel status. Some pairs of spellings, such as *ff* (native) and *ph* (Latinate), had the same pronunciations. Few such pairs exist, however, and so in most cases, as with *oy* (native) and *os* (Latinate), the spellings had different pronunciations. For the *c* condition, the pairs of spelling patterns were incorporated into nonwords that begin with *ce* or *ci*, such as *ceff* and *ceph*. The stimuli for the *g* condition were similar to those of the *c* condition except that they began with *ge* or *gi*. The nonwords with native and Latinate spelling patterns were equated for length. There were 18 pairs of stimuli in each condition, as the Appendix shows. There were also 72 filler nonwords.

Two lists were constructed for each condition such that the nonwords in a pair were assigned to different lists. The 18 critical nonwords in each list were mixed with 36 fillers. For each list, three different random orders were constructed. Half of the participants in each condition did List 1 in the first session followed by List 2 in the second session, and half had the reverse order. One version of each list was randomly chosen for each participant.

Procedure. The two sessions for each participant took place at least one day apart, with an average of four days between the sessions. In each session, the participant was presented with the list of nonwords and was asked to pronounce each nonword the way that he or she thought it would be read if it were an ordinary English word. Responses were tape recorded.

Results and Discussion

The pronunciations were transcribed and scored as in Experiment 1. Table 6 shows the proportion of front responses for the initial consonants relative to the total number of front and back responses. The data were analyzed using the factors of initial consonant (*c* vs. *g*) and spelling pattern (native vs. Latinate). A main effect of initial consonant was observed ($F_1(1, 16) = 20.65$, $p < .001$; $F_2(1, 17) = 222.99$, $p < .001$; min $F'(1, 33) = 10.88$, $p = .002$). As shown in Table 6, and consistent with the results of the previous experiments, readers were more likely to use front pronunciations for *ci* and *ce* than for *gi* and *ge*. A new result was the main effect of spelling pattern ($F_2(1, 16) = 10.19$, $p = .006$; $F_2(1, 17) = 14.58$, $p = .001$; min $F'(1, 32) = 6.00$, $p = .02$). Participants were more likely to pronounce *c* as /s/ and *g* as /dʒ/ when the nonword contained a Latinate spelling pattern such as *pt* than when it contained a native spelling pattern such as *ft*. This result held when we restricted the analyses to pairs of nonwords whose final portions were pronounced alike. For example, all nine of the participants in the *g* condition pronounced *geck* and *gec* with the same vowel and final consonant, but two of them pronounced the initial *g* of *gec* as /dʒ/, whereas none pronounced the initial *g* of *geck* as /dʒ/. The difference between native and Latinate spelling patterns appeared to be smaller for the nonwords with initial *c*, where front responses were close to ceiling, than for the nonwords with initial *g*. However, the interaction between initial consonant and spelling pattern was not significant by subjects or by items.

The results confirm that letters that are not adjacent to a target letter may influence the spelling-to-sound translation of that target. Front pronunciations of *c* and *g* are especially likely when the letter that immediately follows the consonant promotes a fronted pronunciation and when a letter pattern later in the word also promotes such a pronunciation. Long-distance context effects are driven not just by morphological endings, as in Experiment 3, but by spelling patterns that are not associated with specific meanings. For example, the *ph* of *gileph*, which is not a suffix, increases the rate of front pronunciations. This happens, presumably, because *ph* tends to appear in words of Latinate origin and because such words, more often than native ones, have fronted pronunciations of *g*.

Human–Model Comparisons

Several computational models of single-word reading have been developed that purport to pronounce words and nonwords as people do. Current models are largely limited to single-syllable items (e.g., Coltheart et al., 2001; Harm & Seidenberg, 2004; Plaut et al., 1996; but see Ans, Carbonnel, & Valdois, 1998 and Kello, in press, for initial modeling work that includes longer words). We compared the pronunciations produced by two influential computational models to the pronunciations that our participants produced for the monosyllables of Experiments 1 and 2. Table 7 presents the results, the top part of the table showing the results for humans pooled over the monosyllables of these two experiments and the bottom part showing the results for the models.

One model that we looked at, the DRC (Coltheart et al., 2001) includes context-sensitive rules that translate *c* into /s/ before *e*, *i* and *y*, and into /k/ otherwise. The DRC rules further specify that *g* followed by *e* is pronounced as /dʒ/ but that *g* followed by any other vowel is /g/. The monosyllabic nonwords were run through the publicly available version of the DRC (http://www.maccs.mq.edu.au/~max/DRC/), and the results were as expected given the preceding description of the rules. That is, the model always used the front pronunciation for *ce*, *ci*, and *ge* and always used the back pronunciation for *gi*. Although human readers often produced front pronunciations for *ce* and *ci*, they did not always do so. Indeed, a number of participants produced /s/ for some of these items and /k/ for others. For humans, moreover, front pronunciations were in a distinct minority for *ge*. Across the 60 participants in

Experiments 1 and 2, only one showed a consistent pattern of /dʒ/ pronunciations on the *ge*-initial monosyllabic nonwords that fit the DRC rule that *ge* is pronounced as /dʒ/. The current DRC model, with its all-or-none patterns of performance, does not agree with human behavior.

A second model that we examined was a slightly modified version of the Harm and Seidenberg (2004) model, described in more detail by Treiman, Kessler, Zevin, Bick, and Davis (2006). This single-route connectionist model contains sets of input units, hidden units, and output units. It is trained on a large corpus of monosyllabic English words, adjusting its weights on each trial in light of the pronunciation that is presented for the word. Fifteen runs of the model were tested, and we averaged the results across the runs. As Table 7 shows, the model produced very few front pronunciations for *c* and *g* before *e* and *i*, many fewer than people. This occurred even though the trained model's performance captured certain other patterns shown by skilled readers (e.g., Treiman et al., 2006). The model's poor performance on nonwords with initial *c* and *g* before *e* and *i* is surprising given that connectionist models are described as picking up the spelling-to-sound patterns in the input. The results may reflect, in part, the small number of monosyllabic English words with initial *c* and *g* before front vowels. The model does not have experience with longer words to draw on, but people do.

Thus, neither of the two currently popular models accounts at all well for skilled readers' pronunciations of initial *c* and *g* in monosyllables. And neither model attempts to deal with items of more than one syllable. Some investigators (e.g., Besner, 1999) have suggested that present models do a good job with nonwords, having overcome the problems encountered by earlier models. However the results of the present human–model comparisons, together with those of Treiman et al. (2003), suggest that current models remain inadequate in this regard. The DRC model's performance on the types of nonwords studied here might be improved by increasing the influence of the lexical route. Such a change might have negative consequences for other aspects of the model's performance, however, causing it to give real-word pronunciations to nonwords that look very similar to real words. Modifications of the input and output representations might improve the performance of connectionist models, as might training on isolated grapheme–phoneme correspondences (e.g., Hutzler, Ziegler, Perry, Wimmer, & Zorzi, 2004). However, connectionist modelers may need to tackle the issue of spelling-to-sound translation for longer words in order to provide a good account even of monosyllables.

General Discussion

Studies of English spelling-to-sound correspondences paint a gloomy picture: Many letters and letter groups, even those at the beginnings of words, may be pronounced in more than one way (e.g., Berndt, Reggia, & Mitchum, 1987; Borgwaldt, Hellwig, & De Groot, 2005; Gontijo, Gontijo, & Shillcock, 2003). For example, *g* is pronounced as /g/ about 64% of the time in the corpus of words studied by Berndt et al., with /dʒ/ pronunciations occurring about 35% of the time. But this study, like a number of others, does not provide quantitative information on how a letter's context may constrain its pronunciation. Many such influences exist, one of which is that *g* is more likely to take on the pronunciation /dʒ/ when it is followed by *e* or *i* than by some other letter. Not only adjacent context but also broader context is important. When a word appears to be Latinate, as may be marked by a suffix or a characteristic spelling pattern, *g* is more likely to be pronounced as /dʒ/ than it is otherwise. The lexical statistics that we calculated in the present study show sizable context effects for *c* and *g*. Indeed, *g* is highly likely to be /dʒ/ if the following vowel is *e* or *i* and if the word is Latinate. Once such patterns are taken into account, the English writing system is not as inconsistent as typically believed.

Do skilled readers of English take advantage of context to decrease the uncertainty in spelling-to-sound translation? When children are taught to read, they are usually told that *c* corresponds to /k/ and that *g* corresponds to /g/. Children are more likely to endorse these back pronunciations as what these letters “say” than to endorse the front pronunciations (Hardy, Smythe, Stennett, & Wilson, 1972). Experience with words such as *cent*, *ginger*, and *geographic*, however, gives children an opportunity to observe how adjacent vowels and Latinate suffixes and spelling patterns condition the pronunciations of *c* and *g*. Teachers may explicitly point out the influence of the following vowel as a part of phonics instruction, but the effects of vocabulary stratum are rarely acknowledged. If we view learning to read as a process of picking up the statistical patterns in the writing system, however, we would expect people to internalize untaught as well as taught patterns given sufficient exposure to the correct pronunciations of words that exemplify the patterns. College students, with their many years of reading experience, might be expected to mirror the contextual effects in the vocabulary almost perfectly.

Our behavioral results show that, although skilled readers’ pronunciations of initial *c* and *g* are influenced by both adjacent and nonadjacent context, these influences are not as large as would be expected given the reliability of the context effects in the words of English. For example, college students’ rate of /dʒ/ pronunciations for nonwords beginning with *ge* and *gi* and ending with Latinate suffixes was substantially lower than the rate of /dʒ/ pronunciations for comparable words in the English vocabulary. As another example, skilled readers sometimes pronounced initial *c* as /k/ before *e* and *i* even though virtually all English words with *c* before *e* and *i* have the /s/ pronunciation. The typical context-free pronunciations of *c* and *g*—/k/ and /g/, respectively—appear to constrain the performance of even skilled readers, serving as default pronunciations. Similar phenomena have been observed with vowels, both for reading and spelling (Perry et al., 2002; Treiman et al., 2002, 2003).

These results suggest that, although skilled readers are sensitive to the statistics of the input, they do not perfectly mirror all of its context-based patterns. People's tendency to abstract and to simplify leads them to place a fair amount of weight on simple, context-free associations between letters and phonemes; it means that they do not use context to the extent that Brown's ROAR (1998) model would lead us to expect. This tendency to seek general patterns may be strengthened by the fact that children are often taught such patterns as that *ea* corresponds to /i/ and are told that words that do not follow the patterns must be individually memorized. Even without such teaching, though, we suspect that humans' tendency to simplify and abstract would lead them to privilege context-free spelling-to-sound correspondences. Although people put a good deal of weight on simple spelling-to-sound links, they do not form rules as categorical as those of the DRC model (Coltheart et al., 2001). The nonlexical route of this model translates all examples of *ea* to /i/ and all examples of *g* before *e* to /dʒ/, but people do not behave in this all-or-none fashion. A middle ground is thus needed in debates about rules versus statistical learning: Language users do not necessarily rely on categorical rules, but neither do they fully match the variability in the input.

Although the college students in our studies did not use the following context to the extent that might be expected given the reliability of the contextual effects in the input, they did show significant anticipatory effects. Students' pronunciations of initial *c* and *g* were influenced not only by the following vowel but also by spelling patterns and suffixes that occurred later in the item, even in another syllable. Several studies have previously reported long-distance anticipatory effects in the case of English stress (Kelly, Morris, & Verrekia, 1998; Rastle & Coltheart, 2000). In the former study, for example, spelling patterns at the ends of disyllabic words affected whether readers stressed the first syllable. Our findings go beyond the previous ones by showing that long-distance effects occur in the assignment of phonemes to letters. These effects are not confined to units in the same syllable or to units that do not themselves have a sound, as is the case with final *e*. Such anticipatory effects suggest that spelling-to-sound translation takes place within a larger window than the letter or the syllable. At least some of the time, people consider the end of a disyllabic word before pronouncing the beginning. The results are more compatible with parallel theories of spelling-to-sound translation than with serial ones, although serial theories could potentially handle the findings if evidence could be found for an initial stage of context-free spelling-to-sound translation that was followed by use of context.

We did not collect data on how long it took for our participants to begin pronouncing the stimuli, unlike many previous studies. Reaction times as measured by voice keys vary as a function of the initial phoneme and the following vowel (e.g., Kessler, Treiman, & Mullennix, 2002), making it difficult to compare results for stimuli that are pronounced in different ways. Our study also differed from many previous ones in that we did not ask participants to respond as quickly as they could. We rarely observed participants pausing to puzzle over alternative possibilities, however: They treated the task as a reading task rather than a problem-solving task, and they produced fluent pronunciations. Anticipatory effects seem to occur under a range of instructional conditions, as most of the experiments cited above that showed such effects in the case of stress mentioned speed of response in the instructions (Kelly et al., 1998; Rastle & Coltheart, 2000). In any case, it is by no means clear that the situation to which we wish to generalize—how readers translate from spelling to sound when they encounter printed items whose pronunciations they have not previously memorized—is better captured by experiments in which people are asked to pronounce nonwords as quickly as they can rather than by experiments in which speed of response is not mentioned.

When we see influences of adjacent context, as when *ea* is more likely to be pronounced as /ɛ/ before *d* than before *n* (e.g., Treiman et al., 2003), one potential explanation is that readers use units that are larger than single graphemes and single phonemes. In the example, they translate *ead* to /ɛd/. As discussed in the Introduction, many theorists have adopted such an explanation, postulating that spelling-to-sound translation involves larger units such as rimes in additional to smaller units (e.g., Norris, 1994; Patterson & Morton, 1985). The few English-language studies that have examined words of more than one syllable have implicitly adopted this view, assuming that only letters that are adjacent to a target letter can influence pronunciation of the target (Chateau & Jared, 2003). A more likely possibility, in our view, is that people link print and speech at the level of letters and phonemes but that these links are sensitive to context. It is difficult to distinguish the large-unit and small-unit view in the case of adjacent context—the type of context that has been examined in most previous studies. In the long-distance case, however, an explanation in terms of literal large unit units becomes implausible. The present demonstration of long-distance context effect thus supports the idea that readers of English translate print to speech at the level of phonemes and that some of the mappings are sensitive to context.

Although college students' pronunciations of *c* and *g* are influenced by context, the students appear to have little conscious awareness of these influences. The participants in Experiments 1 and 2 were asked at the end of the experiment whether they knew any rules or patterns for pronouncing *c* and *g* and, if so, what they were. The large majority of participants could not describe any pattern, or else said that these letters have two possible pronunciations but could not describe any factors that make one pronunciation more likely than the other. Only a small proportion of participants (18% or 11/60 for *c* and 3% or 2/60 for *g*, pooling across Experiments 1 and 2) described how the pronunciation of the consonant is influenced by the following vowel. None of the participants in Experiment 2 mentioned any effects that could be interpreted as reflecting vocabulary stratum or type of suffix. At the end of Experiment 4, we explicitly told the participants that *c* and *g* have two pronunciations and asked them to describe any rules or patterns that could help readers choose between the pronunciations. Three of the nine participants in the *c* condition and two of the nine participants in the *g* condition stated that the following vowel could help. No participant mentioned vocabulary stratum or type of spelling pattern. These results suggest that, without special training, many adults would not be in a position to point out these patterns of English to children learning to read. The effects of vocabulary stratum are even less accessible than the effects of the following vowel, consistent with the observation that the former are less likely to be taught in school.

In addition to examining how spelling-to-sound translation varies across linguistic contexts, our study also examined how spelling-to-sound translation varies across readers. Previous researchers (e.g., Baron & Strawson, 1976) have suggested that skilled readers differ from one another in their tendency to use general rules to assign sounds to spellings, and computational modelers have recently become interested in simulating individual variability (Zevin & Seidenberg, 2006). However, little is known about the sources of individual differences. Our results suggest that exposure to a second language is one factor that affects spelling-to-sound translation in a first language. Specifically, people who have studied languages such as French or Spanish, in which *c* and *g* are consistently pronounced differently before certain vowels, are more likely to produce fronted pronunciations of these consonants when reading English words and nonwords. These effects are notable because they suggest that knowledge of a second language can influence performance in a first. Moreover, contrary to the suggestions from some previous studies (Bijeljac-Babic, Biardeau, & Grainger, 1997; Jared & Kroll, 2001), cross-language influences do not necessarily require high levels of fluency in the second language. The influences of second language knowledge that we observed could reflect carryovers in the learning of statistical patterns, explicit teaching, or both. Teachers of French, for example, are likely to point out the different pronunciations of *g* before different vowels even to beginning learners. Such instruction may sensitize learners to the similar patterns that exist in English.

Phonology plays an important role in reading, even for skilled readers who are reading silently (e.g., Frost, 1998). Given this, it is important to understand how readers translate the spellings of words into sounds. Our understanding of this process is currently limited by the fact that most experimental and modeling work, especially in English, has been confined to monosyllables that contain a single morpheme. Studies of more complex items are essential lest we lock ourselves into theories that do not generalize. The present study is a step in this direction.

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Appendix

Stimuli for Experiment 2

The monosyllabic stimulus in each triad is presented first, followed in parentheses by the suffix for the native condition and then the suffix for the Latinate condition

c: *ceb* (-*ful*, -*ic*), *cebe* (-*ness*, -*ment*), *celb* (-*ish*, -*ent*), *cerm (-ing*, -*oid*), *certh* (-*est*, -*ine*), *cesp* (-*en*, -*ous*); *cibe* (-*ness*, -*oid*; *e* of *cibe* was dropped when -*oid* was added), *cilb* (-*ing*, *-ic),* *cipe* (-*ful*, -*ment*), *cirm* (-*est*, -*ent*), *cirth* (-*en*, -*ine*), *cisp* (-*ish*, -*ous*); *cabe* (-*ness*, -*ment*), *caft* (-*ing*, -*ous*), *casp* (-*ish*, -*ic*), *corm* (-*ful*, -*ent*), *corth* (-*en*, -*oid*), *cosp* (-*ish*, *-ent), cug* (-*ness*, -*ment*), *culb* (-*ing*, -*ine*), *curm* (-*est*, -*ous*)

g: *geb* (-*ful*, -*ic*), *genth* (-*ing*, -*oid*), *gep* (-*ness*, -*ous*), *gerf* (-*en*, -*ment*), *gern* (-*est*, -*ent*), *gesp* (-*ish*, -*ine*); *gilm* (-*en*, -*ous*), *gilp* (-*est*, -*ent*), *gime* (-*ful*, -*ment*), *girb* (-*ing*, -*ine*), *girf* (-*ness*, -*ic*), *gisp* (-*ish*, -*oid*); *gant* (-*ish*, -*ment*), *garf* (-*en*, -*ent*), *gart* (-*ing*, -*ine*), *gome* (-*ful*, -*ment*), *gonth* (-*est*, -*ous*), *gosp* (-*ing*, -*oid*), *gub* (-*ful*, -*ous*), *gulb* (-*ness*, -*ic*), *gurch* (-*ness*, -*ent*)

Stimuli for Experiment 3

c with correct pronunciation /s/, non-Latinate endings: *cedarn*, *censer*, *centner*, *ceplike*, *Ceptaz*, *Ceram*, *cerecloth*, *cesspipe*, *cimbalom*, *cinch*, *cinchless*, *cinnabar*, *cistern*, *cittern*, *cymaise*, *cyme*

c with correct pronunciation /s/, Latinate endings: *ceiba*, *celature*, *centas*, *cerastium*, *cerement*, *cereus*, *ceriman*, *cerise*, *cerium*, *ciborium*, *cicatrix*, *cimetidine*, *cincture*, *citrine*, *cyclas*, *cynosure* *g* with correct pronunciation /dʒ/, non-Latinate endings: *genip*, *gentoo*, *gerbil*, *gerfalcon*, *germander*, *gibing*, *giereagle*, *gillyflower*, *gimcrack*, *ginseng*, *gistless*, *gymel*, *gyproom*, *gypster*, *gyrfalcon*, *gyve*

g with correct pronunciation /dʒ/, Latinate endings: *gelid*, *gelsemium*, *gemmulation*, *genial*, *geniculate*, *gentian*, *gentry*, *gerent*, *giardia*, *gibbet*, *gingival*, *gitalin*, *gypon*, *gypseous*, *gyrene*, *gyrose*

g with correct pronunciation /g/, non-Latinate endings: *Gehinnom*, *gelding*, *gemsbok*, *gettering*, *gewgaw*, *gilder*, *gilgul*, *gilguy*, *gillie*, *gilling*, *gilthead*, *gingham*, *girding*, *girth*, *girtline*, *gizzard*

g with correct pronunciation /g/, Latinate endings: *Gehenna*, *gehlenite*, *gelignite*, *genro*, *geta*, *gibbon*, *gibbosity*, *gibbous*, *gibbsite*, *Gibeonite*, *Gideon*, *gilsonite*, *Gimzo*, *Ginza*, *ginzo*, *Giza*

Stimuli for Experiment 4

c, native: *ceff*, *ceck*, *cift*, *civesh*, *cewib*, *cebosh*, *ciskulting*, *ceruking*, *cireak*, *cedging*, *cewilse*, *citch*, *cief*, *ceib*, *cimlaip*, *cinrey*, *cildoy*, *cedight*

c, Latinate: *ceph*, *cec*, *cipt*, *civects*, *cequib*, *ceborrh*, *cisualting*, *ceruving*, *cirec*, *cenxing*, *cevilse*, *cicts*, *cife*, *cebe*, *cimlape*, *cinrae*, *cildos*, *cedite*

g, native: *gileff*, *geck*, *geft*, *gesh*, *gewib*, *gebosh*, *giskulting*, *geruking*, *gireak*, *gedging*, *gewilse*, *gitch*, *gief*, *geib*, *gimlaip*, *ginrey*, *gildoy*, *gedight*

g, Latinate: *gileph*, *gec*, *gept*, *gects*, *gequib*, *geborrh*, *gisualting*, *geruving*, *girec*, *genxing*, *gevilse*, *gicts*, *gife*, *gebe*, *gimlape*, *ginrae*, *gildos*, *gedite*

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Footnote

[1] Greek-derived elements are here considered Latinate because they entered the language in transliterations that followed Latin orthographic patterns.

Table 1

Mean (and Standard Deviation) Proportion of Front Pronunciations Relative to Total Number of Front and Back Pronunciations in Experiment 1

Initial consonant	Vowel				
	e	*i*	*a*	*o*	*u*
c	.84 (.24)	.87 (.24)	.00 (.00)	.00 (.00)	.01 (.04)
g	.16 (.10)	.04 (.08)	.00 (.00)	.00 (.00)	.00 (.00)

Table 2

Proportion of Front Pronunciations Relative to Total Number of Front and Back Pronunciations by Type (Results by Token in Parentheses; Number of Words in Brackets) for Words of English Lexicon Project

Position	Consonant	Structure	Vowel		
			e	*i*	*a, o, u*
Initial	*c*	Monosyllabic	.92 (1.00) [5]	1.00 (1.00) [3]	.00 (.00) [105]
		Polysyllabic, native suffix	1.00 (1.00) [8]	1.00 (1.00) [5]	.00 (.00) [214]
		Polysyllabic, Latinate suffix	.96 (.85) [9]	1.00 (1.00) [5]	.00 (.00) [219]
	g	Monosyllabic	.67 (.07) [9]	.25 (.01) [12]	.00 (.00) [73]
		Polysyllabic, native suffix	.57 (.03) [7]	.25 (.01) [8]	.00 (.00) [40]
		Polysyllabic, Latinate suffix	1.00 (1.00) [25]	1.00 (1.00) [1]	.00 (.00) [22]
Any	*c*	Monosyllabic	.99 (1.00) [36]	1.00 (1.00) [3]	.00 (.00) [261]
		Polysyllabic, native suffix	1.00 (1.00) [42]	1.00 (1.00) [96]	.00 (.00) [312]
		Polysyllabic, Latinate suffix	1.00 (1.00) [85]	1.00 (1.00) [57]	.00 (.00) [424]
	g	Monosyllabic	.84 (.10) [37]	.28 (.01) [18]	.00 (.00) [107]
		Polysyllabic, native suffix	.41 (.17) [27]	.82 (.46) [78]	.00 (.00) [75]
		Polysyllabic, Latinate suffix	1.00 (1.00) [85]	1.00 (1.00) [45]	.00 (.00) [53]

Note. Latinate and native suffixes are those used in Experiment 2.

Table 3

Mean (and Standard Deviation) Proportion of Front Pronunciations Relative to Total Number of Front and Back Pronunciations in Experiment 2

Initial consonant	Structure	Vowel		
		e	*i*	*a, o, u*
c	Monosyllabic	.89 (.24)	.85 (.23)	.01 (.03)
	Native suffix	.87 (.26)	.87 (.22)	.01 (.04)
	Latinate suffix	.91 (.17)	.90 (.20)	.02 (.04)
g	Monosyllabic	.17 (.24)	.12 (.17)	.00 (.02)
	Native suffix	.15 (.18)	.08 (.14)	.00 (.02)
	Latinate suffix	.24 (.26)	.13 (.18)	.00 (.00)

Table 4

Mean (and Standard Deviation) Proportion of Front Pronunciations Before e and i Relative to Total Number of Front and Back Pronunciations as a Function of Participants' Knowledge of Other Languages

Initial consonant	Other language(s) promotes alternation	Other languages(s) does not promote alternation
c	.97 (.04)	.86 (.20)
g	.22 (.15)	.13 (.17)

Table 5

Mean (and Standard Deviation) Proportion of Front Pronunciations Relative to Total Number of Front and Back Pronunciations in Experiment 3 as a Function of Word Type and Participant Language Background

Correct pronunciation of initial consonant	Word type	Participant language background	
		Other language(s) promotes alternation	Other language(s) does not promote alternation
/s/ for *c*	native	.99 (.02)	.97 (.05)
	Latinate	.99 (.03)	.99 (.04)
/dʒ/ for *g*	native	.65 (.20)	.53 (.13)
	Latinate	.75 (.10)	.67 (.12)
/g/ for *g*	native	.14 (.14)	.09 (.08)
	Latinate	.29 (.17)	.17 (.11)

Table 6

Mean (and Standard Deviation) Proportion of Front Pronunciations Relative to Total Number of Front and Back Pronunciations for Nonwords in Experiment 4 with Native and Latinate Spelling Patterns

Initial consonant	Native	Latinate
c	.89 (.17)	.96 (.07)
g	.31 (.33)	.43 (.37)

Table 7

Proportion of Front Pronunciations Relative to Total Number of Front and Back Pronunciations (Proportion Unusual Pronunciations in Parentheses) for Monosyllables of Experiments 1 and 2 For Humans and Models

	Initial consonant	Vowel				
		e	*i*	*a*	*o*	*u*
Humans	*c*	.87 (.00)	.86 (.00)	.00 (.01)	.00 (.00)	.02 (.00)
	g	.17 (.00)	.08 (.00)	.00 (.00)	.00 (.00)	.00 (.00)
DRC model	*c*	1.00 (.00)	1.00 (.00)	.00 (.00)	.00 (.00)	.00 (.00)
	g	1.00 (.00)	.00 (.00)	.00 (.00)	.00 (.00)	.00 (.00)
Connectionist model	*c*	.02 (.29)	.00 (.01)	.00 (.00)	.00 (.00)	.00 (.00)
	g	.03 (.00)	.00 (.00)	.00 (.03)	.00 (.00)	.00 (.00)