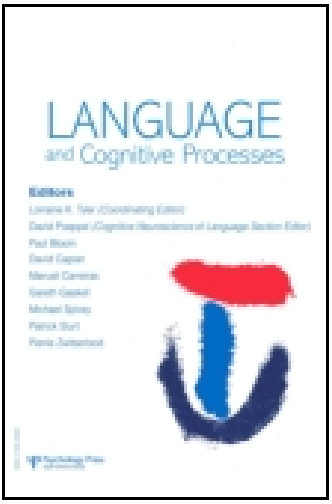

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Silent letters are activated in spoken word recognition

Larissa J. Ranbom [a] & Cynthia M. Connine [a]
[a] Department of Psychology, Binghamton University, SUNY, Binghamton, NY, USA
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Silent letters are activated in spoken word recognition

Larissa J. Ranbom and Cynthia M. Connine

Department of Psychology, Binghamton University, SUNY, Binghamton, NY, USA

Four experiments are reported that investigate processing of mispronounced words for which the phonological form is inconsistent with the graphemic form (words spelled with silent letters). Words produced as mispronunciations that are consistent with their spelling were more confusable with their citation form counterpart than mispronunciations that are inconsistent with their spelling in a same/different task. Cross-modal repetition priming for orthographically supported productions and their citation form counterparts was equivalent; in contrast, orthographically unsupported productions showed reduced priming relative to the citation form. The findings are discussed in light of models of cross-modal interaction between spoken and written lexical representations. We argue that the results support a restructuring model where reading promotes development of a phonological representation used during spoken word recognition.

Keywords: Spoken word recognition; Orthographic influence in speech perception.

Activation of phonological representations from orthographic forms (written words) has been demonstrated experimentally in a wide variety of tasks (see for instance Inhoff, Connine, & Radach, 2002; Jared, Levy, & Rayner, 1999; Lesch & Pollatsek, 1993; Lukatela & Turvey, 1994a, 1994b; Van Orden, Johnston, & Hale, 1988). Debates continue concerning the precise underlying mechanism for phonological activation during recognition of visual words but research has converged on an important role for phonology during reading (Rayner, 1998). The converse relationship, orthographic activation from speech, has received decidedly less attention. This may not be surprising, given the differences between the acquisition of written and spoken language:

Correspondence should be addressed to Cynthia M. Connine, Department of Psychology, Binghamton University, SUNY, Binghamton, NY 13902, USA. E-mail: connine@binghamton.edu

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spoken language is acquired early (and precedes written mastery) and without explicit teaching while literacy is acquired through formal instruction. Furthermore, in the absence of pathology, all humans acquire spoken language perception but many individuals remain illiterate and in some cases belong to cultural groups without a written form of language. Because spoken language precedes written language, and because fluency in a written language is optional while fluent speech learning occurs without instruction (given the appropriate input), one might reasonably predict that there is no functional utility for an influence of the written form of language on spoken word recognition. To the contrary, orthographic influences in speech processing have been observed consistently in a variety of experimental paradigms. We focus on the role of orthography in spoken word recognition and in particular on the extent to which orthographic knowledge contributes to the development of a phonological lexical representation use for spoken word recognition.

Researchers have generally approached the study of orthographic activation in speech perception by examining the impact of orthographic consistency. Orthographic consistency refers to the extent to which a single spelling maps on to more than one sound. This characteristic varies across words and languages: some, such as Greek, have high orthographic consistency with relatively shallow orthographies, approaching a one-to-one relationship between graphemes and phonemes. In a comparatively deep orthography such as English, orthographic consistency is relatively low and can be observed in the classic example of the spelling -ough (found in through, cough, rough, and plough). Phonological consistency (a single phoneme that maps to only one orthographic symbol is consistent; a single phoneme that can be represented with multiple orthographic forms is inconsistent) also varies across languages and is exploited in jokes such as the use of "ghoti" as a spelling for fish (the -gh from cough, the -o from women, and the -ti from nation). In languages such as French, as contrasted with English, orthographic consistency is found but phonological consistency is low: most orthographic symbols represent a single sound, but sounds can map to numerous spellings (as in chaud, faux, haut, trop, and mot).

The variability in the mapping between phonology and orthography has provided a vehicle for investigating the nature of orthographic influences in the spoken domain. One such study (Seidenberg & Tanenhaus, 1979) compared processing of rhyming words with identical coda spellings (e.g., "light" and "bright") to rhyming pairs with different coda spellings (e.g., "key" and "knee"). Rhyme judgements with identical coda pairings showed an advantage for the rhyming pairs. Nonrhyme pairs showed the inverse relationship—a similarly spelled word pair (e.g., "tease" and "lease") had slower judgements compared to a dissimilarly spelled pair (e.g., "tease" and "piece"). Seidenberg and Tanenhaus argued that these results support a role for orthographic information when processing spoken words.

Other investigations have focused on the extent to which orthographic influences in spoken word recognition are beneficial or detrimental to task performance. A Stroop-type task in which naming a target word colour was preceded by either an auditory or a visual prime, showed increased colour naming latencies for phonologically similar primes (i.e., bed and bread), orthographically similar primes (i.e., bead and bread), and both phonologically and orthographically similar primes (i.e., dead and bread) relative to an unrelated control prime (Tanenhaus, Flanigan, & Seidenberg, 1980). These findings suggest that orthographic influences in the auditory domain are not restricted to conditions in which orthography enhances processing.

The degree of orthographic and phonologic overlap among spoken words also contributes to processing. Slowiaczek, Soltano, Wieting, and Bishop (2003) found auditory priming effects from word pairs with both phonological and orthographic overlap (i.e., funnel and funny) and from pairs with orthographic overlap (i.e., ratio and ratify). Chéreau, Gaskell, and Dumay (2007) showed that, in an auditory priming task, both phonological and orthographic rime overlap (i.e., dream and gleam) facilitate lexical decision. Dijkstra, Roelofs, and Fieuws (1995) capitalised on the fact that the phoneme /s/ can be orthographically realised in Dutch with one of two graphemes, the primary "s" and the secondary "c" and showed that phoneme detection in spoken Dutch words is faster for the primary spelling than for a secondary spelling (with a larger effect when the phoneme occurs after the uniqueness point). Spelling also influences judgements about syllabic content of a spoken stimulus: words such as "validity" are judged to contain the first syllable /væl/ (rather than the correct spoken form) presumably because the vowel /æ/ is more consistent with the orthography (Taft & Hambly, 1985). In a gating task Hallé, Chereau, and Segui (2000) demonstrated that in words such as French "absurde" /apsyrd/, perception of the acoustically present /p/ shifts to a perceived (but not present) segment that is found in the word's spelling "b"; this occurs prior to the word's uniqueness point, suggesting that listeners exploit a language's orthographic regularities when interpreting speech sounds.

Spoken stimuli also preferentially activate spellings with the highest printed frequency, as observed in the case of heterographic homophones such as made and the less frequent maid (Grainger, Kang, & Segui, 2001). While a purely phonological spoken word recognition process would make no distinction between homophones, an orthographic role in speech perception predicts that dominant homophones should hold an advantage compared with the subordinate homophones. Grainger, Kang, and Segui (2001) showed that only the dominant homophone (i.e., made) was activated in cross-modal priming (but this effect occurred only when pseudohomophone distracters were used, suggesting a malleable phonological response strategy: when only word homophones are present, the response can be made solely from a phonological code and activated orthographic information is not required to perform the task). These results suggest that listeners are not only sensitive to the nature of mappings between phonology and orthography (and vice versa), but also to the frequency of these mappings (see also Peereman, Dufour, & Burt, 2009.)

The existing literature supports a role for orthography in spoken word recognition but questions remain concerning how orthography exerts an influence on the spoken domain. One aspect of the theoretical debate focuses on determining at what level phonology and orthography interact. Ziegler and Ferrand (1998) found slower lexical decision times to phonologically inconsistent words (spoken words in which the rime could be spelled in more than one way, such as the French plomb) as compared with consistent words (such as the French stage) and argued for online sublexical cross talk between the domains. Ventura, Morais, Pattamadilok, and Kolinsky (2004) reasoned that if the influence of orthography is lexical, orthographic consistency effects (in which an advantage is present for words with only one possible spelling) should not be found for pseudowords. They found no pseudoword consistency effect but also failed to find a reliable word consistency effect across tasks; the word consistency effect was found only when the shadowing task also required a lexical decision (shadow just the word stimuli), suggesting a lexical locus for the orthographic consistency effects. Other research has focused on the extent to which the influence of orthography on spoken word recognition is strategic or automatic. Taft, Castles, Davis, Lazendic, and Nguyen-Hoan (2007) suggest that strategic awareness of the relationship among stimuli in an experiment may contribute to the variability in the existing literature. To address this concern, Taft et al. developed a task in which the relationship between an auditory prime and target was minimised (by embedding the prime in babble to mimic masked visual priming paradigms). Orthographic overlap facilitation was found despite the unconscious nature of the prime/target relationship suggesting an automatic cross-domain effect.

More recently, the cross talk between visual and auditory word processing has been attributed to a representational restructuring; Ziegler, Ferrand, and Montant (2004) showed that the processing cost for words with inconsistent orthography–phonology mappings also depends on the degree of consistency of the mappings. They found a consistency effect (consistent rime words were processed faster than inconsistent words) but also found that dominant inconsistent rimes ‘‘wine’’ showed a processing advantage over subdominant inconsistent rimes ‘‘sign’’ for items matched in phonological rime. Furthermore, the consistency effects were evident in an array of tasks but were smaller in tasks presumed to involve less lexical engagement (rime detection, auditory naming). The consistency effect for matched rimes, the authors argue, provides strong evidence for an orthographic influence in spoken word processing and suggest that orthographic representations alter the specificity of a phonological representation. Inconsistent rimes, they argue, do not acquire fully specified phonological representations and the graded effect based on dominance reflects the less specified representation for the subdominant inconsistent rime. The lexical restructuring hypothesis offered by Ziegler, Muneaux, and Grainger (2003) expands on work in the language development literature in which there is a word-specific shift from holistic to segmental lexical representations as vocabulary grows throughout childhood (see for instance Goswami, 2000; Metsala & Walley, 1998). Ziegler and colleagues suggest that lexical specificity of spoken words is further influenced by factors such as neighbourhood density (words with more phonological neighbours become more specified) but crucially, graphemic information amplifies this process, with additional pressure from dense orthographic neighbourhoods yielding greater specificity (Goswami, 2000; Muneaux & Ziegler, 2004; Ziegler, Muneaux, & Grainger, 2003). Under a lexical restructuring view, rather than generating orthographic representations on-the-fly or activating an orthographic form from a lexical representation, the orthographic influence has occurred in the ongoing development of the lexicon.

While a view in which experience with written language shapes a phonological representation has been proposed (Ziegler, Muneaux, & Grainger, 2003), this view has not been well-elaborated and is currently only intermittently discussed with respect to orthographic influences in speech processing. An elaboration of this view is required that makes the functional purpose of restructuring lexical representations to conform with an orthographic rendition clear. A somewhat surprising functional explanation has begun to emerge from a seemingly unrelated set of issues concerning recognition of phonological variants. Patterson and Connine (2001) reported that word-medial flapping in American English words such as pretty [prIɾi] occurs in as many as 96% of productions as compared with the form that more closely matches the written version [prIti]. Connine (2004) demonstrated that the most frequent form, the flap, is lexically represented but also argued for a representation of the hyperaticulated [t] form based on its consistency with the orthography. Connine and Pinnow (2006) showed that the hyperarticulated form is processed quite easily (and in some conditions more quickly than the flap form despite its relatively infrequent occurrence) and suggested that an orthographic representation underlies these results. Similarly, Ranbom and Connine (2007) have shown both an influence of variant frequency for a frequent nasal flap form (e.g., gentle –> gen'l) and an overall advantage for the less frequent but orthographically supported citation form (gentle) (see also Deelman & Connine, 2001; Connine, Ranbom, & Patterson, 2008) and argued for an orthographic shaping of representations.

Others have also found an advantage (a larger long-term priming effect and larger semantic priming) for the less frequent canonical /t/ in word final position compared to a more frequent variant, a glottalised /t/ (Sumner & Samuel, 2005). Further evidence that the orthographic realisation of a word contributes to a phonological representation was found using past-tense word-final flapping (Ranbom & Connine, 2005). Within a set of regular past-tense verbs, the final -ed ending is consistently realised as a /t/. However, in a prevocalic environment, this word-final /t/ can be flapped, resulting in a more [d]-like sound and therefore a closer match to the orthographic form. A cross-modal priming study showed equivalent priming relative to an unrelated control for the [t]-final form (phonological match, orthographic mismatch) and for the [ɾ]-final form (phonological mismatch, orthographic match).

These combined results suggest that phonological activation from reading can contribute to a phonological representation for words matching the orthographic form, even when this phonological form occurs infrequently. This is consistent with the restructuring hypothesis based on orthographic properties but also provides a functional role for an orthographically supported representation available for spoken word recognition, because it can facilitate recognition of infrequent forms. Note, however, that in each of the variants described above, the orthographically derived citation form is not a mispronunciation, it is simply an infrequent form. Other cases exist in English in which a possible pronunciation derived from the orthographic form does not occur in speech as either a citation or a variant form. These include oft-studied inconsistent words (where the dominant orthographic–phonological mapping conflicts with the spoken form) but also include cases where the orthographic symbol is not pronounced in the spoken form. For example, mapping the orthography onto phonology for the word "castle" would result in a "t" in the spoken form. This realisation would be a mispronunciation, as the "t" is never produced in the spoken version. The experiments presented here use words with silent letters to investigate processing under conditions in which the orthographically derived pronunciation of a given word would never occur in speech, even as a variant form. We refer to words with this property (orthographic letters which are never produced in the spoken form of the word) as silent-letter words.

Two sets of experiments examine this issue using words with a possible pronunciation that is licensed only by the presence of silent letters (e.g., *castle*) and for which the pronunciation derived directly from the graphemic form of the word is a mispronunciation (orthographically supported mispronunciations). If the only represented form of these words is based on the experienced speech, a production containing an articulation of the silent letter should be treated as a nonword. A second set of words were selected that did not contain a silent letter (e.g., *hassle*) and were produced both in their citation form and with an inserted segment to create a mispronunciation (orthographically unsupported mispronunciation). In Experiment 1a, [kæsl] and [hæsl] words were presented with their mispronounced orthographically supported counterpart (e.g., [kæstl]) or orthograpically nonsupported counterpart ([hæstl]) in a same–different task. The orthographically supported mispronunciations are hypothesised to activate a phonological representation available only from reading resulting in more same judgements than the nonsupported mispronunciations.

EXPERIMENT 1A

Method

Participants

Twenty-nine Binghamton University undergraduates participated in this experiment in partial fulfilment of the requirements of an introductory psychology course. All participants were native speakers of American English.

Materials

Two sets of 48 two-syllable American English words were created (Appendix 1). In the first set, orthographically supported mispronunciations, words were selected such that a silent letter in the orthography, when produced, formed a nonword (a mispronunciation) (e.g., [kæstl] from [kæsl]). For all but two of these words, the silent consonant was part of a word-medial grapheme cluster. In the second set, orthographically unsupported mispronunciations, words were selected to match the rhyme of a word from the first set (e.g., [hæsl]). A further constraint was that a nonword was created when the silent letter from its orthographically supported mispronunciation counterpart was inserted (e.g., [hæstl] from [hæsl]). When matching rhymes across the stimulus sets was not possible, words sharing the medial consonant and as much of the surrounding context as possible were selected (i.e., muscle, missile) with the proviso that a nonword was formed when inserting the silent letter from its orthographically supported mispronunciation counterpart. The mean lexical frequency for these experimental words in the CELEX corpus was 225 for the silent-letter words and 314 for the words with orthographically nonsupported mispronunciations (CELEX English database, 1993): lexical frequency in the Brown corpus was 26.75 for the silent-letter list and 18.65 for the orthographically nonsupported mispronunciation list (Francis & Kucera, 1982).

An additional set of filler items were created. The fillers included 24 two-syllable words and 72 filler nonwords.

All stimuli were recorded by a female speaker (Larissa J. Ranbom) in a soundproof booth and digitised at 44.1 kHz (16-bit resolution). Two productions of each orthographically supported mispronunciation word were recorded: one citation form production (i.e., [kæsl]) and a mispronunciation matching the orthographic form, with the silent consonant pronounced (i.e., [kæstl]). Comparable productions were recorded for the orthographically unsupported mispronunciation set, with one production as the citation form (i.e., [hæsl]) and a second mispronunciation containing the silent letter from its orthographically supported counterpart (i.e., [hæstl]). An additional 96 fillers (24 words and 72 nonwords) were recorded to serve as "same" trials in the experiment.

Procedure

Two stimuli were presented on each trial for a same/different judgement. Participants were instructed to label the two stimuli as "same" if the spoken forms were judged to be the same pronunciation; the two stimuli were to be judged as "different" if the spoken forms were judged to have different pronunciations. Ninety-six "different" trials were created by presenting pairs of orthographically supported citation form and mispronounced tokens (48 trials) along with pairs of orthographically unsupported citation form and mispronounced tokens (48 trials). Order of citation and mispronounced tokens in a pair was counterbalanced across trials: in half of the trials the citation form pronunciation was first and in the other half, the mispronunciation was first. Ninety-six "same" trials were created from the 24 nonword fillers and the 72 word fillers by repeating tokens within a pair.

Rest breaks were given after every 24 responses. The experiment was preceded by a brief practice session to ensure that participants were familiar with the task.

Results and discussion

The percentage of "same" responses for each pair of orthographically supported and orthographically unsupported stimuli was calculated. Trials with response time longer than 3000 ms were discarded (less than 1% of all data). Overall, the citation and mispronounced but orthographically consistent pairs were judged to be the same more often than the citation form and mispronounced orthographically unsupported pairs (see Table 1). The rate of "same" responses was greater than zero and less than chance for both the orthographically supported mispronunciation pairs (CI $\pm$ 11) and the orthographically unsupported mispronunciation pairs (CI $\pm$ 3). Critically, a paired-samples T-test showed that the orthographically supported mispronunciation pairs were judged to be the same more often than the orthographically unsupported mispronunciation pairs [$t_1(28) = 3.37$,

TABLE 1
Percentage of >same =judgements for orthographically supported and unsupported stimulus pairs for Experiments 1a (intact onset) and 1b (truncated onset)

	Mispronunciation orthographic support	
	Supported	*Unsupported*
Experiment 1a	22.67	6.42
Experiment 1b	6.23	6.66

SDD = 25.97, $p < .003$; $t_2(47) = 9.4$, SDD = 11.97, $p < .001$]. For the filler trials in which identical stimuli were presented, the rate of "same" responses was quite high, at 94.4%, demonstrating that participants were accurate at judging same items in the fillers.

The results of Experiment 1a show that listeners are more likely to judge a mispronunciation as being the same as a citation form when the mispronunciation is consistent with the orthography. Before discussing these results in detail, it is important to rule out an alternative acoustic basis for the asymmetry in "same" judgements: it is possible that the orthographically unsupported mispronunciation tokens were acoustically more distinct than the orthographically supported mispronunciation tokens. This possibility was examined in Experiment 1b by altering the stimulus tokens to neutralise lexical information—onset segments were spliced out leaving a nonword for both the citation and mispronounced stimuli. Neutralisation of lexical information should render the orthographically supported and orthographically unsupported pairs equivalent.

EXPERIMENT 1B

Method

Participants

Thirty-three Binghamton University undergraduates participated in this experiment in partial fulfilment of the requirements of an introductory psychology course. All participants were native speakers of American English.

Materials

Stimuli for this experiment consisted of the same set of tokens recorded for Experiment 1. All stimuli were modified by digitally removing the acoustic information for the word onset (e.g., the citation form as [æsl] and the consonant-inserted mispronunciations as [æstl]). Stimuli were cut at zero crossings and left no audible disruption in the stimulus. (Five vowel-initial items, four in the orthographically supported set, and one in the orthographically unsupported mispronunciation set, were left intact and removed from the final analysis.)

Procedure

The procedure for this experiment was identical to that used in Experiment 1a.

Results and discussion

The percentage of "same" responses was calculated for each pair of stimuli (see Table 1). Trials with response time greater than 3000 ms were removed from the analysis (less than 1% of the data). The five vowel-initial items were also removed from the analysis. The per cent of "same" responses was greater than zero but less than chance for both the orthographically consistent pairs (CI $\pm$ 2.78) and for the orthographically inconsistent pairs (CI $\pm$ 5.06). However, with the word onset removed, the difference in "same" responses between the orthographically consistent and inconsistent pairs was no longer significant [$t_1(32) = 0.96$, SDD = 5.46, $p < .346$; $t_2(43) = -0.31$, SDD = 17.73, $p < .762$].[1]

The results of Experiment 1b show that the increased rate of "same" judgements for the orthographically consistent pairs found in Experiment 1a was not due to systematic acoustic differences between the orthographically consistent and orthographically inconsistent tokens. Rather, the mispronunciation effect appears to involve lexical knowledge, and specifically knowledge about how a word is spelled: a mispronunciation that is consistent with the orthographic form of the word is less discriminable from the citation form than a similar mispronunciation with no such orthographic support.

The findings of Experiments 1a and b were elaborated in two additional experiments using cross-modal priming. Experiment 2a used the orthographically supported citation and mispronunciation tokens from Experiment 1a in a cross-modal identity priming paradigm. A priming effect for the orthographically supported mispronunciation would indicate activation of a lexical representation. The extent to which a priming effect for the orthographically supported mispronunciations is uniquely attributable to an orthographically derived representation is investigated in Experiment 2b.

[1] To ensure that the five vowel-initial items did not change the data pattern for Experiment 1a, a reanalysis of the data for Experiment 1a was conducted with the five vowel-initial items removed; removal of these items did not change the data pattern (22.6% and 6.65%, orthographically supported and unsupported, respectively).

EXPERIMENT 2A

Method

Participants

Thirty Binghamton University undergraduate students participated in this experiment as partial fulfilment of an introductory psychology course. All participants were native speakers of American English.

Materials

Stimuli consisted of the set of citation forms and orthographically consistent mispronunciations from Experiment 1a. An unrelated auditory word was selected for each stimulus to serve as an auditory control that was matched in lexical frequency (CELEX lexical frequency 338; Kucera and Francis lexical frequency 28.375). Auditory presentation of a citation form, orthographically supported mispronunciation, or the unrelated control was followed by a visual target consisting of the experimental word in a cross-modal identity priming experiment. Citation, mispronunciation, and control auditory primes were counterbalanced across three experimental lists such that only one prime from a given item set was presented per participant and equal numbers of items were presented in each of the three experimental conditions.

An additional 144 auditory–visual pairs of fillers were created that included 24 matching pairs of auditory–visual words, 24 mismatching auditory word–similar visual nonword (the nonwords were formed by replacing the medial consonant of the auditory word, i.e., visual target *lummer* for auditory prime *lumber*), 24 mismatching auditory nonword–similar word pairs (i.e., auditory prime *gramber* with visual target *grammar*), and 72 auditory nonword–visual nonword pairs including 24 matching nonwords, 24 mismatching auditory nonword–similar nonword pairs, and 24 mismatching and dissimilar pairs. The filler trials served to offset the composition of the experimental trials and created equal numbers of word and nonword visual targets, decrease the overall proportion of auditory–visual matching trials, and include trials with auditory stimuli containing an inserted segment followed by a nonword target and maintain equal numbers of word and nonword targets.

Procedure

Participants heard the auditory stimuli over closed-ear headphones in a sound-dampened room. At the offset of the auditory presentation, the visual target was presented in capital letters in the centre of a 17-inch computer monitor for 250 ms; trials were separated by 1500 ms. Participants were asked to make a lexical decision to the visual target quickly and accurately by pressing an appropriately marked response box. Preceding the experiment, a brief practice session was used to familiarise participants with the task. The experimental stimuli were presented in a randomised order that differed for each participant. Rest breaks were provided after every 24 trials.

Results and discussion

Two participants were removed due to failure to understand the task. Five items (debtor, gristle, lacquer, trestle, and yachting) were removed due to fewer than 75% correct identifications averaged across all conditions, suggesting that these words were not well-known to participants. Trials with response times longer than 1500 ms or shorter than 200 ms were removed from the analysis as outliers ($<$ 1% of data). Percentage correct and reaction time as a function of prime type (citation form, orthographically supported mispronunciation, and control) are shown in Table 2.

An overall ANOVA conducted on accuracy data showed a significant effect of prime type [$F_1(2, 54) = 9.22$, $MSE = 39.19$, $p < .001$; $F_2(2, 84) = 9.26$, $MSE = 78.56$, $p < .001$]. Planned comparisons showed that responses were more accurate in the citation form (99%) than in the mispronunciation condition [92%; $F_1(1, 27) = 21.55$, $MSE = 31.18$, $p < .001$; $F_2(1, 42) = 17.09$, $MSE = 81.91$, $p < .001$] and the control condition [93%; $F_1(1, 27) = 11.79$, $MSE = 30.98$, $p < .002$; $F_2(1, 42) = 13.48$, $MSE = 46.84$, $p < .001$]. No difference in accuracy was found for the mispronounced and control productions [$F_1(1, 27) < 1$; $F_1(1, 42) = 1.41$, $MSE = 106.93$, $p < .242$].

Response time analyses showed an overall significant prime type effect [$F_1(2, 54) = 38.9$, $MSE = 2325.81$, $p < .001$; $F_2(2, 84) = 25.72$, $MSE = 5364.4$, $p < .001$], with significant priming effects present for both the citation condition (588 ms) relative to the control (696 ms) [$F_1(1, 27) = 61.6$, $MSE = 2656.2$, $p < .001$; $F_2(1, 42) = 59.1$, $MSE = 4274.6$, $p < .001$] and for the mispronunciation condition (612 ms) relative to the control [$F_1(1, 27) = 43.2$, $MSE = 2315.8$, $p < .001$; $F_2(1, 42) = 24.44$, $MSE = 6018.8$, $p < .001$]. The difference in priming effect sizes (108 ms priming for the citation form, 84 ms priming for the mispronounced form, both relative to the same control

TABLE 2
Reaction time and accuracy (%) as a function of prime type (Experiment 2a)

Prime type		
Correct pronunciation	Orthographically supported mispronunciation	Control
588 (99)	612 (92)	696 (93)

condition) was not significant [marginal in subjects: $F_1(1, 27) = 3.88$, $MSE = 2005.39$, $p < .06$; $F_2(1, 42) = 2.44$, $MSE = 5799.85$, $p < .126$].

The citation form word prime yielded higher accuracy than either the mispronounced and unrelated control conditions. In order to determine the extent to which the differences in accuracy contributed to the priming pattern, a posthoc subanalysis was conducted that included only those items for which accuracy was equivalent across mispronounced and citation primes (within 1%). Similar to the overall analysis, no difference in response time (and therefore in priming as the same control is used for both conditions) for the citation (571 ms) and mispronounced (592 ms) productions was present [$F_2(1, 23) < 1$].

These results are consistent with an orthographically derived phonological representation along with the citation spoken form. Experiment 2b paralleled the logic of Experiment 1a in examining an alternative interpretation of the results: the orthographically supported mispronunciation may be sufficiently similar to the represented citation form for lexical activation. A strict view of similarity matching would predict reduced priming for the mispronunciation relative to the citation pronunciation (Connine, Titone, Deelman, & Blasko, 1997) but it is important to rule out this alternative interpretation. Accordingly, Experiment 2b uses the orthographically unsupported mispronunciations from Experiment 1a (i.e., hassle, hastle). If the data pattern found in Experiment 2b is comparable to Experiment 2a, then phonological closeness, rather than an influence of orthographic knowledge underlies the results of Experiment 2a. However, if the orthographically unsupported mispronunciations do not show a significant priming effect or an effect comparable in size to the citation productions, a similarity-based explanation can be ruled out as the sole explanation for the results of Experiment 2a.

EXPERIMENT 2B

Method

Participants

Thirty-two Binghamton University undergraduate students participated in this experiment as partial fulfilment of an introductory psychology course. All participants were native speakers of American English.

Materials

Experimental stimuli consisted of the 48 stimulus pairs used in the orthographically unsupported condition in Experiment 1a. As in Experiment 2a, each word was matched with an unrelated word and presented with a visual target consisting of the experimental word for a cross-modal priming experiment. Filler words and their visual targets were the same as those used in Experiment 2a.

Procedure

The procedure was identical to that used in Experiment 2a.

Results and discussion

Three items, which were identified as words on fewer than 75% of trials averaged across all conditions, were removed from the analysis (tussle, bassoon, and backer). Trials with response time less than 200 ms or greater than 1500 ms were also removed ($<3\%$ of data). Percentage correct and reaction time as a function of prime type (citation form, orthographically inconsistent mispronunciation, and control) are shown in Table 3.

Analysis of accurate responses showed a significant effect of prime type across subjects that was marginal by items [$F_1(2, 54) = 3\ 32$, $MSE = 24.1$, $p < .044$; $F_2(2, 88) = 2.78$, $MSE = 44.94$, $p < .068$]. Paired comparisons showed that the visual target was accurately identified more often for the citation form (97%) than for the mispronounced primes [94%; $F_1(1, 27) = 7.22$, $MSE = 21.86$, $p < .013$; $F_2(1, 44) = 5.93$, $MSE = 41.56$, $p < .019$]. No significant difference was found between the citation form and control (96%) primes [$F_1(1, 27) < 1$; $F_2(1, 44) < 1$] or between the mispronounced primes and control primes [$F_1(1, 27) = 2.38$, $MSE = 24.43$, $p < .135$; $F_2(1, 44) = 1.78$, $MSE = 49.35$, $p < .189$].

The response time analysis similarly showed an overall significant effect [$F_1(2, 54) = 34.17$, $MSE = 2665.56$, $p < .001$; $F_2(2, 88) = 34.49$, $MSE = 5275.03$, $p < .001$], with significant priming for the citation form condition (623 ms) relative to the control [735 ms; $F_1(1, 27) = 66.81$, $MSE = 2613.3$, $p < .001$; $F_2(1, 44) = 89.84$, $MSE = 3702$, $p < .001$] and a marginal priming effect (significant in subjects) for the mispronounced production condition (699 ms) relative to the control [$F_1(1, 27) = 5.39$, $MSE = 3311.25$, $p < .029$; $F_2(1, 44) = 2.85$, $MSE = 6420.24$, $p < .099$]. Crucially, the 112 ms priming effect present for the citation condition was larger than the 36 ms priming

TABLE 3
Reaction time and accuracy (%) as a function of prime type (Experiment 2b)

Prime type		
Correct pronunciation	Orthographically unsupported mispronunciation	Control
623 (97)	699 (94)	735 (96)

effect for the mispronounced condition [$F_1(1, 27) = 38.99$, $MSE = 2072.09$, $p < .001$, $F_2(1, 44) = 33.17$, $MSE = 5702.9$, $p < .001$].

A combined analysis with Experiment 2a was conducted to determine whether the pattern of priming effects differed between the two experiments. The priming effects for the citation and mispronounced conditions were compared across word type (orthographically supported and orthographically unsupported stimuli). Critically, an interaction was present [$F_1(1, 54) = 8.76$, $MSE = 2203.25$, $p < .005$; $F_2(1, 84) = 7.04$, $MSE = 5387.01$, $p < .01$], showing that the pattern of priming effects in Experiment 2a differed from those in Experiment 2b. Individual comparisons showed no difference between the priming effect sizes across the two experiments for the citation pronunciations [$F_1(1, 54) < 1$; $F_2(1, 84) < 1$]. However, a significant difference was present between the priming effects for the mispronounced pronunciations [$F_1(1, 54) = 7.19$, $MSE = 5648.47$, $p < .01$; $F_2(1, 84) = 5.58$, $MSE = 10981.3$, $p < .021$], showing that the priming effect size is greater for orthographically supported mispronunciations (Experiment 2a) than orthographically unsupported mispronunciations (Experiment 2b).

The results of Experiment 2b differ from those of Experiment 2a: while in Experiment 2b, the mispronounced production primes approach significance, the priming effect is smaller than that found for the citation production prime. However, when orthographic support for the mispronunciation is available (Experiment 2a), a priming effect is found that is equivalent to the priming effect found for the citation form prime. The combined results of Experiments 2a and b show that the match to the orthography compensates for the mismatch to the citation phonological form. The impact of orthography supports the view that computation of a phonological representation derived from reading establishes an alternate phonological representation corresponding to the orthographic form. Moreover, the orthographically derived phonological representation takes on a functional role in spoken word recognition. Computing an orthographic form from the phonological input takes longer than using a direct representation: allowing the direct representation of the mispronounced orthographically supported form to be activated for word recognition accounts for the lack of a priming difference between the orthographically supported mispronunciations and the citation forms.

GENERAL DISCUSSION

Two groups of experiments used silent-letter words to examine the influence of orthography in speech. Mispronounced words were presented that were supported or unsupported by the orthographic form. Experiment 1a used a discrimination task for citation forms and mispronounced productions when the mispronounced production was supported by the orthography (i.e., *castle*) and when the mispronounced production was not supported by the orthography (i.e., *hassle*). The results showed that citation and mispronounced productions were more confusable when the mispronunciation was supported by the orthographic form. Experiment 1b used the same task for stimuli in which the initial consonant information was excised to create nonwords for both the citation and mispronounced tokens, and showed equivalent effects for the orthographically supported and nonsupported forms. This suggests that the findings from Experiment 1a did not stem from acoustic differences between the stimulus sets. Two additional experiments used cross-modal priming for orthographically supported (Experiment 2a) and nonsupported (Experiment 2b) mispronunciations. When a mispronunciation was orthographically supported, equivalent priming was found for the mispronounced and citation forms; when the mispronunciation was not orthographically supported, a smaller priming effect was present compared with the citation form.

We have not here addressed the question of a contribution from morphology, specifically the role of morphological relatives in which the putative silent letter is realised in the spoken form (i.e., *muscle*-*muscular, Christmas*-*Christian*). The presence of a morphological neighbour may contribute to the effects we report either through their impact on the development of multiple phonological representations or via higher-level links in the lexicon. Such an influence would weaken the attribution of multiple representations as developing through knowledge of and exposure to a written form. If this is the case, then we would expect to see differences in the pattern of priming effects for words with morphological forms in which the putative "silent letter" is found in the surface production. An analysis of the words used in Experiments 1a and 2a indicates that 14 of the stimuli had morphological forms of this type (*muscle*-*muscular*). A posthoc analysis on the priming data from Experiment 2a (citation forms and orthographically supported prime relative to the control) was conducted. Analysis of the 14 items with clear morphological relations (i.e., *bomber*-*bombard*) showed no difference in response time (and therefore no difference in priming effect size) across citation (600 ms) and mispronunciation (620 ms) conditions [$F_2(1, 13) < 1$]. A second analysis with these 14 items removed from the data also showed comparable response times (and therefore no difference in priming effects) for the citation (583 ms) and mispronunciation (611 ms) conditions [$F_2(1, 28) = 2.45$, $MSE = 4796.74$, $p < .13$]. Thus, response times in the citation and mispronunciation conditions were equivalent for stimuli with and without morphological forms in which the silent letter was produced and suggests that morphology is not the critical factor in these results.

Overall, the experiments show a pattern of results that implicate a role for orthography in refining a representation for spoken word recognition—processing an orthographically supported mispronounced form is functionally equivalent to the citation phonological form. An explanation of this pattern of findings must account for the ability of a mispronounced but orthographically supported form to prime its target word as well as a citation production. How might reading contribute to the development of an orthographically supported phonological representation? One potential explanation for these results suggests that experience with the written form of a word changes the nature of a lexical representation. A phonological representation will be a by-product of reading if encounters with written words, and particularly early encounters with written language, lead to a process of phonological assembly using grapheme–phoneme correspondence rules. As a result of this assembly, a phonological form would be computed that functions similarly to a phonological form derived from speech. For a silent-letter word such as *castle*, the application of this assembly process would result in computation of a previously unknown (never heard) phonological form.

Part of the logic of this assembly process rests on the assumption that the mapping from the orthographic form to a phonological form includes a phonological realisation for the silent letter. We have defined "silent letters" here for a set of specific words, but it is important that the grapheme–phoneme correspondences favour an assembly process in reading in which the silent letters in our word set would be more frequently realised. That is, an assembly process in reading in which the phonology of "silent" letters is (erroneously) computed requires that such a correct mapping is supported by the majority of other words. This assumption is supported by examination of the contexts of these silent letters across all words. A search of the MRC database (Wilson, 1988) for a subset of the silent-letter contexts in the current stimuli (-st-, -mb-, -sw-, -sth-, -ght-, -pb-, -bt-) was conducted.[2] This analysis showed that only 18.3% of the silent-letter strings are produced with a silent letter; in the remainder, the "silent" letter is pronounced (i.e., *mortgage* has a silent letter, but the majority of words, like *vortex,* does not). The proportion of silent letters which are produced in our sample drops to 9.3% if the universally silent -ght words (i.e., *straighten*, one stimulus in the experiment) are excluded. Because of the prevalence of the pronounced form, and the relative rarity of the silent-letter forms, orthography–phonology correspondence schemes would default to phonological activation of a pronounced form in silent-letter words when reading; we argue that the

[2] A subset of the contexts was used to make the analysis computationally feasible. Note that in all MRC database searches, proper nouns, hyphenated items, and words that did not pass a spell check in Microsoft Excel XP were excluded from the results.

nonsilent letter phonological form is lexicalised and activated during spoken word recognition. The resulting represented phonological form has an orthographic source, in contrast to phonological forms that develop through experience with spoken language.

Theories with linkages between orthographic and phonological lexicons propose a processing approach in which orthographic information is implicated during phonological activation. This view is consistent with dual-route models of visual word recognition (see for instance Coltheart, Curtis, Atkins, & Haller, 1993; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). In dual-route models, written words are processed along two paths: in a lexical path, phonological activation occurs via a direct route of activation of a lexical entry. In the other path, grapheme–phoneme conversion rules are used for serial assembly of a phonological form. As a result, a phonological form can be created on the fly or can be activated from lexical storage; however, this view only incorporates phonological activation from orthography. An online view of orthographic influence in speech can be found in the bimodal interactive activation model (Grainger & Ferrand, 1996; Kiyonaga, Grainger, Midgley, & Holcomb, 2007). This framework proposes that phonological units are indirectly mapped to orthographic units (and vice-versa) via an intermediate interface at a prelexical level. At a lexical level, this framework proposes that orthography and phonology are connected both by the intermediate interface and by a direct mapping. This framework can explain how a phonological representation for a word with a silent letter, such as *castle*, is formed through reading; as is depicted in Figure 1 (panel 1), lexical activation via spelling will co-occur with the generation of a phonological form consistent with the orthography via the orthography–phonology interface.

Given auditory input of the citation form, the orthography–phonology interface will be engaged but the fastest route to lexical activation occurs when a represented citation form is present. This route to recognising a citation form is shown in Figure 1 (panel 2): incoming acoustic information is mapped to phonemes which then activate a phonological representation.

Somewhat more problematic for the bimodal interactive activation model (e.g., without additional lexical representations) is the finding of statistically equivalent priming effects for the citation forms and mispronounced but orthographically supported productions. The pathway to processing an auditory input of the noncitation, but orthographically supported form is depicted in Figure 1 (panel 4) where without a represented form, the architecture of the model must be exploited. The nature of the connections between spoken and written word recognition systems in the bimodal interactive activation model suggest that both an assembly process (sub-lexical) and cross-modal activation of a represented form (lexical) occur in word recognition for either modality. In the absence of a representation (e.g., for [kæstl]), activation of the correct word would take place through the

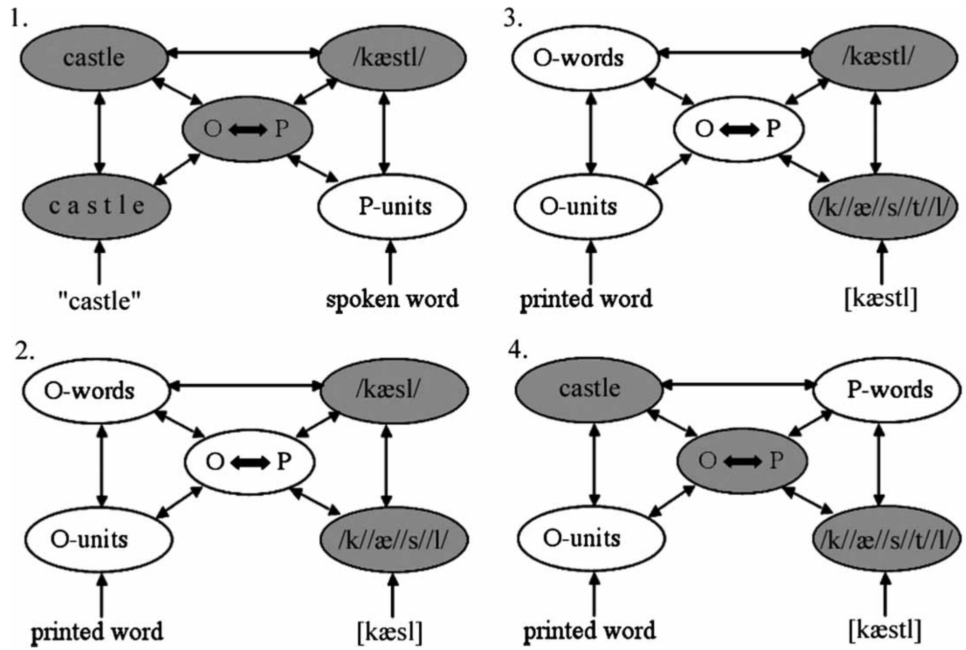

Figure 1. (Panel 1) Tracing the path of the orthographic stimulus ‘castle’ through the bimodal interactive activation framework (adapted from Kiyonaga, Grainger, Midgley, and Holcomb, 2007). (Panel 2) The auditory input of the citation form of the word ‘castle’ should most quickly activate a phonological representation. (Panel 3) If a phonological representation is present for the orthographically supported form, auditory presentation of this form can also take the fastest path through the framework to a phonologically represented form. (Panel 4) If no phonological representation is present for the orthographically supported form, auditory presentation of this form must be translated into an orthographic representation to activate a lexical entry.

orthographic route: an assembly of an orthographic form would be computed to match the represented orthographic form for the word. The resulting additional processing required to activate a lexical representation should result in a smaller priming effect for the orthographically supported mispronounced form.

Figure 1 (panel 3) depicts the recognition process for the noncitation, but orthographically supported form given a lexical representation. With a represented form, the fastest route is identical to that for the citation form: the incoming orthographically consistent input gives way to phonemes, which are able to access the appropriate, orthographically consistent phonological representation generated through reading. With an additional representation, this framework can accommodate our data without making any changes to the architecture that would potentially diminish its ability to account for pre-existing findings.

When there is no mismatch between the spoken phonological form and the written phonological form (as in our *hassle* items), the phonological form activated through reading is identical to the spoken form. However, in the case of the silent-letter words used in the experiments described above, the combined experience with written and spoken forms would result in two representations: reading will establish a phonological representation that is consistent with the orthographic form and listening to speech will establish a representation that is consistent with the citation spoken form. This view extends a phonological restructuring view (Metsala & Walley, 1998; Ziegler, Muneaux, & Grainger, 2003) in which learning to read simply modifies existing phonological representations in the lexicon by creating more detailed and more finely specified phonological representations for words in dense orthographic neighbourhoods (supported by data showing that higher orthographic neighbourhood density is associated with facilitatory effects for spoken words). Our data suggest that reading not only leads to a more detailed phonological representation, but can also create an additional phonological representation that contains features or segments not present in the spoken form. We suggest that the phonological lexicon adapts to reading by computing and representing phonological forms with no spoken equivalents. Taft (2006) makes a parallel argument for instances in which a speaker's dialect differs from the orthographic specification (e.g., nonrhotic speakers phonologically represent the rhotic form of "corn" via experience with the orthography).

An additional issue we have not yet addressed is the possible role of strategic factors in our results. One specific concern is that the interval between the prime and target stimuli in Experiments 1a and b was potentially of sufficient duration (700 ms) to invoke strategic activation of orthographic information (some studies have shown that a very short ISI between an auditory prime and target results in no orthographic effects, Pattamadilok, Kolinsky, Ventura, Radeau, & Morais, 2007). While this remains a possible contributing factor in our findings, it has also been shown that effects of orthographic consistency are quite early (in ERP data) in a semantic category task (Pattamadilok, Perre, Dufau, & Ziegler, 2009). Pattamadilok, Kolinsky, Luksaneeyanawin, and Morais (2008) have also found that orthographic effects in a rhyme judgement task emerge only when the to-be-judged word pairs are separated by a long interval suggesting a later occurring, perhaps strategic, component to orthographic influences. Irrespective of a role for strategic activation of orthographic information, a related concern is the extent to which our results support the phonological restructuring view vs. a simple coactivation of orthographic information. The latter view derives from the observation that spoken and written words are often paired during literacy development and this pairing creates a strong linkage among modality specific representations, a linkage that produces activation of an orthographic representation on encountering a spoken word. Phonological restructuring and coactivation have been expressed in the current literature as mutually exclusive possibilities in accounting for orthographic influences in spoken word recognition (see for example, Peere, Pattamadilok, Montant, & Ziegler, 2009). While we have argued for a restructuring account, we do not wish to deny a potential role for coactivation via cross-modality linkages in our data. However, for silent-letter words, coactivation would have to occur between the mispronounced phonological form and spelling of the silent-letter word; this necessarily requires that the mispronounced form is represented, an assumption that is central to our account. With regards to our data, Experiment 2a showed comparable priming for the citation words and the mispronounced (but orthographically supported) counterparts but we also found a (small) accuracy advantage for the citation forms. While the priming data support the restructuring account, the accuracy advantage for the citation forms suggests a role for coactivation of the orthographic representation (with more effective coactivation given the citation form, particularly potent in a paradigm using cross-modal presentation). Furthermore, the accuracy advantage for citation forms would not be anticipated by a representational scheme with equivalent phonological representations for citation and mispronounced forms and suggests that the phonological form derived from the spoken domain has a representational advantage in lexical memory. The implications of this for the modification of the bi-modal activation model we have proposed is that the representation of the phonological form derived from orthography is somewhat weaker than for the phonological form derived from the spoken domain.

The notion that there are multiple phonological representations in the lexicon is consistent with proposals in the auditory domain for regular phonological variation. In the case of the word-medial American English flap (i.e., pretty [prIɾi]), the highly frequent flap form is represented along with a representation of the [t] form presumed to be partly derived from orthography (Connine, 2004). Similarly, Ranbom and Connine (2007) proposed that multiple phonological representations for the nasal flap and [nt] variant forms are used in speech recognition, and Connine, Ranbom, and Patterson (2008) provided evidence for multiple representations of words with potential schwa vowel deletion that are graded based on variant frequency. The cognitive mechanisms that compute a phonological representation based on orthography provide lexical memory with a representation that is functionally equivalent to phonological representations developed from spoken language. Our more radical approach to the lexical restructuring hypothesis gives a role to these computed forms, allowing them to function similarly to forms consistent with speech. In the silent-letter data presented here, the equivalent priming found for the citation forms and the orthographically supported mispronunciations suggests a similar additional phonological representation derived from orthography.

Finally, our findings also have implications for debates concerning the nature of the representational substrate that underlies spoken word recognition. Episodic perspectives posit lexical representations that continually develop with each auditory encounter of a word (i.e., Goldinger, 1996; Johnson, 2004). Such representations are assumed to be holistic and lack the abstract properties assumed by some theories of spoken word recognition (Norris, 1994) and some theories of phonological representation in reading (Ziegler, Ferrand, & Montant, 2004). An orthographically supported representation for silent-letter words available for spoken word recognition is highly unlikely to have as its genesis an auditory episode. The likely route, a phonological representation derived from an orthography–phonology assembly process via experience with the written form is, by its nature, abstract (see also Taft, 2006). Our view of lexical representation, then, provides support for abstract representations in spoken word recognition that are in this case, derived from computing grapheme–phoneme correspondences during reading.

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Appendix 1

Silent-letter words (orthographically supported mispronunciations).

answer	cupboard	jostle	science
asthma	debto	lacquer	scissors
bomber	descend	limbless	soften
bridges	doubted	listen	straighten
bristle	dumber	moisten	subtle
bustle	exhaust	mortgage	thistle
castle	fasten	muscle	thumbnail
christen	glisten	nestle	tombstone
christmas	gristle	numbing	trestle
climbing	handsome	plumber	whistle
combing	hustle	rustle	wrestle
crumby	island	salmon	yachting

Words with orthographically unsupported mispronunciations.

aimless	dismal	lesson	ransom
backer	dresser	mammal	rubbish
bargain	drummer	massive	sassy
bassoon	drumstick	melon	silence
battle	exalt	message	sisters
blossom	fossil	missile	stammer
censor	fragile	mitten	stutter
chimney	hammer	passing	summer
coffin	hammock	passive	swimming
cosmic	hassle	posse	tassle
cutting	hissing	pouted	timing
digit	kissing	pressing	tussle