Journal of Experimental Psychology:
Human Perception and Performance
1999, Vol. 25, No. 2, 461-481

0096-1523/99/$3.00

Lexical and Nonlexical Phonological Priming in Reading Aloud

Kathleen Rastle and Max Coltheart
Macquarie University

Five homophone priming experiments were reported in which the lexicality of primes and targets were varied, so that primes and targets were either nonword homophones (*keff–keph*), word homophones (*brake–break*), pseudohomophones (*brayk–braik*), or of mixed lexicality (*brake–brayk* and *brayk–break*). Results showed that naming of targets was facilitated by a phonologically identical prime *only* when a word was in the prime–target pairing. Simulations of these data using the dual-route cascaded model of reading (e.g., M. Coltheart, B. Curtis, P. Atkins, & M. Haller, 1993) were also reported. These results are evidence against the view that there is a critical early stage in the process of visual word recognition in which words are represented in purely phonological form, and they are evidence for the view that knowledge of orthography and phonology is represented locally in the reading system.

In the research reported here we used a single experimental technique—phonological priming of reading aloud—to explore two theoretical issues relevant to modeling the reading system. The first of these issues concerns the role of phonology in visual word recognition: We investigated the view that visual word recognition depends entirely on phonology in the sense that, at some point during the recognition of a visually presented word, that word is represented solely in a phonological form (e.g., Lukatela & Turvey, 1994a, 1994b; Van Orden, 1987; Van Orden, Johnston, & Hale, 1988).

The second issue concerns the nature of representation in the reading system: We investigated whether there are any levels in that system at which words are treated differently from nonwords. In other words, are there any levels at which words are represented as whole units (i.e., words have local representations)? We investigated this issue by seeking to adjudicate between two computational models of reading aloud. According to one of these models (Plaut, McClelland, Seidenberg, & Patterson, 1996), there is no level at which the forms of words are represented locally: There is just a single level of orthographic representation, at which both words and nonwords are represented in a distributed fashion, and just a single level of phonological representation, at which both words and nonwords are again represented in a distributed fashion. According to the other model—the dual-route cascaded (DRC) model (Coltheart, Curtis, Atkins, & Haller, 1993; Coltheart & Rastle, 1994; Rastle & Coltheart, 1998, 1999)—there is an orthographic system, the *orthographic lexicon,* in which words are represented as word-specific units (i.e., are represented locally), and also a phonological system, the *phonological lexicon,* in which words are represented as word-specific units (i.e., are represented locally). Nonpseudohomophonous nonwords are not represented in either of these lexical systems.

The Role of Phonology in Visual Word Recognition

Despite early work suggesting that phonology mediates orthographic lexical access during reading (e.g., Rubenstein, Garfield, & Millikan, 1970; Rubenstein, Lewis, & Rubenstein, 1971; see also McCusker, Hillinger, & Bias, 1981, for a review of early work in this area), Coltheart (1980) concluded that there was little or no evidence that phonological representations played any major role in the recognition or comprehension of single printed words by skilled readers of English. Recently, however, two groups of authors have argued to the contrary.

Van Orden and colleagues (Van Orden, 1987, 1991; Van Orden et al., 1988; Van Orden, Pennington, & Stone, 1990; Van Orden et al., 1992) have argued that word meaning is accessed via the phonological representation of a printed word. Using the semantic categorization task, in which participants are asked to respond "yes" or "no" to questions such as "Is this a flower?", they generally find that pseudohomophone targets (e.g., *roze*) and homophone targets (e.g., *rows*) produce more false acceptances and slower response latencies than do control items. On the strength of such findings, Van Orden and colleagues have suggested that the phonological representation of a word constrains lexical access absolutely.

This view has also been argued by Lukatela and Turvey (1991, 1994a, 1994b). Their arguments are based on data collected by means of the homophone and pseudohomophone priming techniques. Because we also used this technique in the experiments reported here, we discuss their work in some detail.

In several experiments, Lukatela and Turvey (1994b),

Kathleen Rastle and Max Coltheart, Department of Psychology, Macquarie University, Sydney, New South Wales, Australia.

This work was supported by a National Science Foundation Graduate Research Fellowship awarded to Kathleen Rastle. We are grateful to Stuart Bernstein, Dave Plaut, and two anonymous reviewers for their comments on earlier versions of this article. We are also grateful to Michael Haller, Breck Thomas, and Steve Saunders for programming assistance.

Correspondence concerning this article should be addressed to Kathleen Rastle, who is now at the Centre for Speech and Language, Department of Experimental Psychology, University of Cambridge, Downing Street, Cambridge CB2 3EB, England. Electronic mail may be sent to kathy@currawong.bhs.mq.edu.au.

using stimulus onset asychronies (SOAs) of 30, 60, and 250 ms, studied the homophone and pseudohomophone priming of reading aloud. At the two short SOAs, primes were masked by the targets; at the long SOA, primes were clearly visible. Lukatela and Turvey (1994b) reported that a target word such as *toad* was primed at all three SOAs by a homophone prime (*towed*) and also by a pseudohomophone prime (*tode*), compared with control primes matched for visual similarity.

Lukatela and Turvey (1994a) also studied associative priming—the priming of the target *frog,* for example, by the primes *toad, towed,* and *tode*—using these same SOA conditions. At the two short SOAs, all three priming conditions yielded facilitation. However, at the SOA of 250 ms, only the appropriate homophone prime (*toad*) and the nonword prime (*tode*) produced associative priming on the target *frog.* There was no significant priming exerted by the inappropriate homophone prime *towed.*

This apparent paradox at the 250-ms SOA was critical, as it allowed Lukatela and Turvey (1994a, 1994b) to constrain their theoretical account greatly. At this SOA, *towed* did not prime *frog.* However, *towed* did prime *toad.* Why, then, did this phonological priming not extend to *toad*'s associate *frog?*

According to Lukatela and Turvey (1994a, 1994b), lexical access during reading is purely phonological. Every letter string is converted to a phonological form prior to lexical access, and if that letter string is a word or a pseudohomophone, an entry in the lexicon will be accessed. After this phonologically mediated lexical access occurs, the spelling appropriate for that lexical entry is retrieved, and this retrieved spelling is checked against the actual spelling of the stimulus. This is essential, of course, because otherwise words could not be distinguished from pseudohomophones.

If the stimulus is a homophone such as *towed,* more than one lexical entry will be activated, and so more than one spelling will be retrieved (the spellings *towed* and *toad* in this case). The matching procedure will identify which is the correct entry, as a result of which the inappropriate entry, initially activated, will be inhibited. Because this inhibition procedure takes time, it cannot be completed at the short SOAs but can be completed at the 250-ms SOA.

Critical to their argument is the claim that inhibition of lexical entries occurs only when (a) there are initially two lexical entries activated and (b) the stimulus is a word. Thus, no inhibition will occur for nonhomophonous word items, because here two lexical entries will not be activated. Furthermore—and this is a key point—*no inhibition will occur for pseudohomophone items,* because here the stimulus is not a word.

Suppose now that the prime is *towed* and the target is *frog.* At the long SOA, the entry for *toad*—initially excited by the prime *towed*—will be inhibited after the spelling check succeeds for the entry *towed.* Lukatela and Turvey (1994b) assumed that the entries for all associates of *toad* (such as *frog*), initially excited because *toad* was initially excited, will also be inhibited. It follows that *towed* will prime *frog* at short SOAs (because a spelling check cannot be completed in that time) but not at long SOAs (because a spelling check can be completed in that time, and that will cause the inhibition of the entry for *toad,* initially excited by the prime *towed*).

Next suppose the prime is *tode* and the target is *frog.* When the pseudohomophone prime is being read, none of the retrieved spellings (*towed, toad*) will yield a successful match with the input string during the spelling check. Therefore, no activated lexical entry will be inhibited, leaving *toad* (and thus *frog*) active. According to Lukatela and Turvey (1994a), that is why *tode* primes *frog* at long SOAs (even though *towed* does not).

Notice that this explanation depends critically on the idea that when the input is a pseudohomophone, no lexical entry receives any inhibition. It is because of this that the lexical entry for *toad* can remain active (and therefore can generate priming) when the input was *tode,* whereas the lexical entry for *toad* is inhibited (and so cannot cause priming) when the input was *towed.*

Given this information, what would we expect at an SOA of 250 ms if the prime is *towed* and the target is *toad?* Because the entry for *toad* will be inhibited in this case, one might expect negative priming. But Lukatela and Turvey (1994b) instead found positive priming: The prime *towed* facilitates response to the target *toad* at this SOA.

Severely constrained by their account of associative priming, Lukatela and Turvey (1994b) proposed to reconcile this apparent conflict by arguing that the locus of homophone priming is *prelexical;* that is, homophone and pseudohomophone priming occurs at the stage of the initial phonological code computed from words or nonwords. The facilitation is one that accelerates the formation of this prelexical phonological code; it is not a facilitation in the time to access a lexical entry.

Lukatela and Turvey (1994b) thus suggested that at an SOA of 250 ms (when the lexical entry for *toad* has been inhibited following the successful spelling check of the prime *towed*),

> the target toad, however, can still benefit from TOWED. In both bottom-up and top-down processing, TOWED supports the relevant phonology /toad/. A similar account can be given of TODE–toad, the only difference being that, in the absence of an addressed spelling for TODE, the spelling check will fail, and both *towed* and *toad* will continue to be active and to sharpen, by means of feedback, the phonological pattern. (Lukatela & Turvey, 1994b, p. 349)

It follows from Lukatela and Turvey's (1994b) account that whether the prime is *towed* or *toad* or *tode,* any subsequent target that has an identical phonological representation will benefit, because this phonological pattern will have been "[sharpened] by means of feedback" (Lukatela & Turvey, 1994b, p. 349). This will be true regardless of whether the target is a word or a pseudohomophone and whether the prime is a word or a pseudohomophone. In other words, whenever priming of reading aloud occurs because the target's pronunciation is the same as the prime's pronunciation, the amount of such priming will be independent of whether the prime is a word or not; it will also be independent of whether the target is a word or not.

Thus far we have not considered the effect of the interval between prime and target—the interstimulus interval (ISI)—on the size of these phonological priming effects. No doubt everyone would expect priming to decrease as this interval increases because of decay of the representations that support the priming. If there has been little decay, then there is little opportunity to detect differences in the amount of priming between conditions. Imagine that instead one used a longer ISI, and one found that there was still priming of one homophone by another—that *towed* still primed *toad.* This means that at this ISI the formation of the phonological code /tOd/ is still being facilitated. Hence any prime and target pair that are phonologically identical will yield priming at this ISI as long as priming is found when prime and target are homophones of each other.

In sum, then, the Lukatela–Turvey theory predicts that if at a particular ISI, *brake* primes *break,* then at that ISI, *braik* must also prime *brayk.* One of the aims of our experiments was to investigate whether the size of the phonological priming effect is indeed independent both of prime lexicality and of target lexicality, as the Lukatela–Turvey theory predicts. Our other aim, as we indicated earlier, was to seek to adjudicate between two different computational accounts of the processes involved in reading aloud. Before discussing this further, we briefly explain our particular approach to theory adjudication in theoretical cognitive psychology.

Frameworks, Theories, and Computational Models

In our view, it is useful to distinguish between three levels of theorizing in cognitive psychology. We use the terms *theoretical framework, theory,* and *computational model* to refer to these levels. We adhere to the strong-inference tradition in the philosophy of science (e.g., Broadbent, 1958; Coltheart & Coltheart, 1972; Platt, 1964; Popper, 1972), in which scientific progress occurs only through falsification of theories (or computational models). Although theories and computational models can be falsified, theoretical frameworks cannot. One may decide that a particular theoretical framework in cognitive psychology is fruitful, or one may decide that it is barren; but one may not decide that it is false, because falsification is the demonstration that a predicted result is not observed, and theoretical frameworks do not generate predictions. What they generate is theories (which in turn can generate computational models; or indeed computational models can be generated directly from theoretical frameworks).

Occupying the base level of our scheme is the theoretical framework, which we define as a general approach toward understanding a particular cognitive domain or domains. Theoretical frameworks generally elucidate the components of the domain in question and outline the fundamental principles adopted within the approach. Schema theory, the logogen model, connectionism, the multistore model of memory, Ames-style transactional functionalism, and Gibsonian ecological psychology are all examples of what we mean by theoretical frameworks. No data could falsify any of these approaches, but theoretical frameworks like these can generate theories or computational models that are falsifiable, even though the frameworks themselves are not falsifiable. For example, the multistore-memory-model theoretical framework gave rise to the Baddeley–Hitch working memory theory (Baddeley & Hitch, 1974).

In turn, theories can generate computational models. We use the term *computational model* to mean the representation of some theory of how people perform a particular cognitive task as a computer program that is capable of carrying out that task in exactly the way that the theory imputes to people; for example, the Baddeley–Hitch working memory theory gave rise to the Burgess and Hitch (1992) computational model of the articulatory loop; the Bruce and Young (1986) theory of face recognition gave rise to the Burton, Bruce, and Johnston (1990) computational model of face recognition; and the dual-route theory of reading aloud (e.g., Coltheart, 1978, 1985; Patterson & Morton, 1985; Patterson & Shewell, 1987) gave rise to the DRC computational model of reading aloud (e.g., Coltheart et al., 1993).

Why derive computational models from cognitive theories? The virtues of this endeavor are numerous (see, e.g., Coltheart, 1996). For example, as soon as any attempt is made to turn a theory into a computational model, many hitherto-unrecognized ways in which the theory is incomplete or inexplicit become plain; the theorist is thus compelled to improve the theory. Only after all of these lacunae have been filled will the program even run. Once the program runs, the theorist can discover whether the way the model behaves is the way people behave—that is, can the model simulate the experimental data? If it cannot, what is one to think about the theory of which that computational model is an expression?

Local Representations in Reading Aloud

Now we turn to the second aim of our experiments: To adjudicate between two computational models of reading aloud on the basis of evidence that bears on the nature of representation in the reading system—in particular, whether or not the system includes local representations. As we are interested specifically in adjudicating between the networks developed by Plaut et al. (1996) and the DRC model, we describe both of these models briefly in the following sections.

The Triangle Framework and Its Implementations

Seidenberg and McClelland (1989) offered a general approach to the understanding of reading aloud that has come to be known as the *triangle model* (see, e.g., Patterson & Behrmann, 1997) but that we refer to in this article as the *triangle framework,* because as far as the terminology we are using is concerned, this approach is neither a theory nor a computational model. It is instead a theoretical framework because (a) it cannot be falsified and (b) the role it has played is to generate computational models that are based on its principles.

The first computational model to be derived from the triangle framework was that of Seidenberg and McClelland (1989); subsequent computational models were derived from this framework by Plaut et al. (1996), whose attractor network was the principal model they described.

The triangle framework is based on a number of fundamental connectionist principles such as distributed representation, and in particular it adheres to the GRAIN principles (McClelland, 1991, 1993), according to which information processing is graded, random, adaptive, interactive, and nonlinear. The triangle framework is so named because it defines the domain of reading as consisting of three representational component domains—orthography, phonology, and semantics—linked by systems of connections to form a triangular configuration, as indicated in Figure 1. Between any two domains of processing units is a set of hidden units.

The first computational model generated from the triangle framework was developed by Seidenberg and McClelland (1989; hereafter termed *SM89*). Their implementation was a three-layer network that was trained by means of backpropagation to map orthography to phonology, with a training set of just under 3,000 monosyllabic and monomorphemic words. This was a partial implementation of the triangle framework because it was a model of only one of the three processing pathways in that framework: the pathway from orthography to phonology.

Seidenberg and McClelland (1989) stressed the absence of local representations in their implementation:

> In contrast to the dual-route model, . . . there is no lexicon in which the pronunciations of all words are listed. (pp. 548–549)
>
> Lexical memory does not consist of entries for individual words; there are no logogens. Knowledge of words is embedded in a set of weights on connections between processing units encoding orthographic, phonological, and semantic properties of words, and the correlations between these properties. (p. 560)

The SM89 implementation was able to read regular words and exception words very well; however, as established by Besner, Twilley, McCann, and Seergobin (1990), the model's nonword reading performance was much poorer than that of human readers. Moreover, the model was unable to simulate various effects found in studies of human reading (Coltheart et al., 1993; Fera & Besner, 1992), and attempts at "lesioning" the model to simulate surface dyslexia were ultimately unsuccessful (Patterson, Seidenberg, & McClelland, 1989, pp. 169–176).

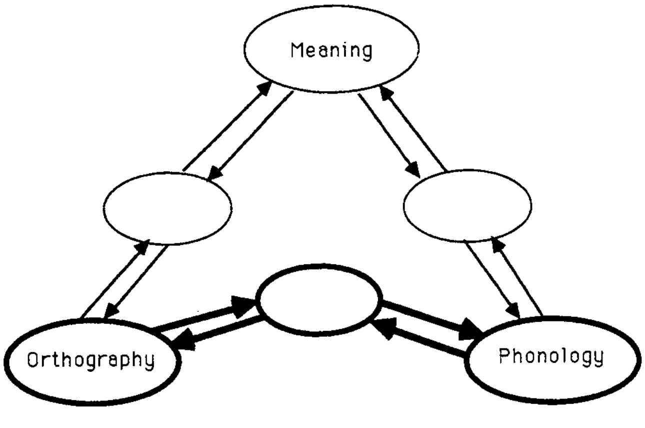

Figure 1. The triangle framework of Seidenberg and McClelland (1989). Each oval represents a group of units, and each arrow represents a group of connections. The implemented model is shown in bold. From "A Distributed, Developmental Model of Word Recognition and Naming," by M. S. Seidenberg and J. L. McClelland, 1989, *Psychological Review, 96,* p. 526. Copyright 1989 by the American Psychological Association. Adapted with permission of the authors.

Hence, this initial implementation came to be regarded as unsatisfactory, and two new partial implementations of the triangle framework were developed by Plaut et al. (1996; hereafter termed *PMSP96*). One of these was, like the SM89 implementation, a completely feedforward network; the other was an attractor network that used feedback connections from the phonological units to the hidden units. These new implementations differed from the SM89 implementation with respect to the nature of the orthographic representations (the distributed orthographic representation scheme used by SM89 was replaced by a system of local representations, each input unit representing a grapheme) and also with respect to the nature of the phonological representations (the distributed phonological representation scheme used by SM89 was replaced by a system of local representations, each output unit representing a phoneme).

Although the PMSP96 implementations used local representations of graphemes and of phonemes, these modelers continued to avoid using local representations of words, and indeed the eschewal of local representations of words in these implementations was stressed (just as it had been by SM89): "Rather, words are distinguished from nonwords only by *functional* properties of the system—the way in which particular orthographic, phonological, and semantic patterns of activity interact" (Plaut et al., 1996, p. 59).

As with SM89, both of the PMSP96 implementations of the triangle framework were partial implementations, because they were implementations of the orthographic–phonological pathway only. However, possible consequences of implementing a second of the three triangle framework pathways, the semantic–phonological pathway, were explored by providing activation externally to the phonological units in addition to the activation they received by the implemented orthographic–phonological pathway. These implementations proved superior to the SM89 implementation as far as the criticisms of Besner et al. (1990) were concerned, because the trained network generalized very well to the task of reading nonwords aloud; it also simulated the Consistency × Frequency interaction (e.g., Seidenberg, Waters, Barnes, & Tanenhaus, 1984).

The DRC Model of Reading: An Implementation of the Dual-Route Theory of Reading

The DRC model is a computational realization of the dual-route theory of reading (e.g., Coltheart, 1978), which relies on two procedures to translate print to sound: a lexical (addressed, lexical lookup) procedure and a nonlexical (assembly, rule-based) procedure. Its architecture is shown in Figure 2.

As shown in Figure 2, the lexical route and the nonlexical route share a feature identification system, a letter identification system, and a phoneme system. The feature identification system consists of eight sets of feature units, each of which contains 16 feature-present units and 16 feature-absent units. The letter identification system consists of eight

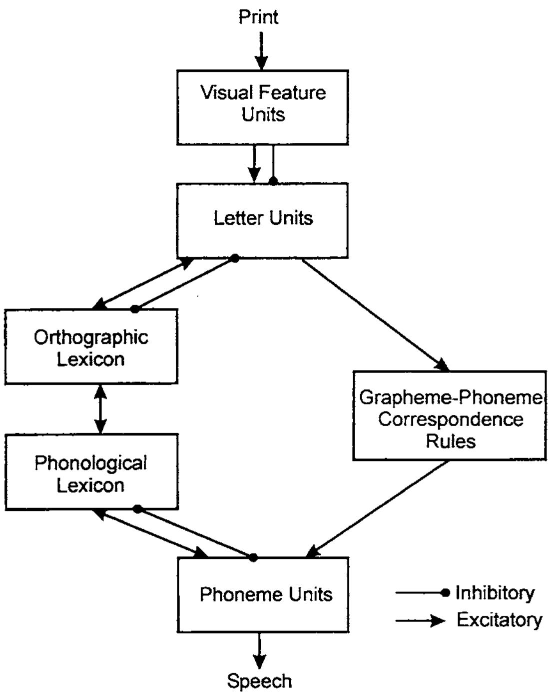

Figure 2. The architecture of the dual-route cascaded model.

sets of letter units, each of which contains 27 units, one for each letter of the alphabet and one for coding the absence of any letter in that position. Similarly, the phoneme system consists of eight sets of phoneme units, each of which contains 44 units, one for each of the 43 phonemes in English and one for coding the absence of a phoneme in that position of the output string.

The lexical route of the DRC model further houses an orthographic input lexicon that contains 7,980 monosyllabic word units and a phonological output lexicon that contains 7,117 monosyllabic word phonological units (taken from the CELEX English database; Baayen, Piepenbrock, & van Rijn, 1993). The nonlexical route operates by a grapheme-to-phoneme rule system that translates orthography to phonology serially, letter by letter, across a letter string. As shown, the modules of the lexical route are connected with bidirectional excitatory and inhibitory connections (except for the lexicons that are connected only with excitatory connections and the feature identification system that is connected to the letter identification system only unidirectionally). Inhibitory interconnectivity exists within each module of the lexical route, except for the feature identification system (see Coltheart & Rastle, 1994, and Rastle & Coltheart, 1999, for detailed descriptions of the architecture of this model).

The DRC model has simulated a range of data in lexical decision and in reading aloud. Illustrative examples of the DRC model's successful simulations of many effects, such as the position of irregularity effect, strategy effects in naming, the length effect in nonword reading, pseudohomophony effects in lexical decision and naming, and the effects of orthographic neighborhood size (as defined by Coltheart, Davelaar, Jonasson, & Besner, 1977) on *yes* and *no* responses in lexical decision have been reported by Coltheart and Rastle (1994) and by Rastle and Coltheart (1998, 1999).

It would appear, then, that there exist two implemented computational models of reading aloud—the DRC model and the PMSP96 implementations of the orthographic–phonological route of the triangle framework—that can explain certain basic effects observed in experimental studies of reading aloud. Both models produce acceptable exception word, regular word, and nonword reading. In addition, the DRC model simulates the Regularity × Frequency interaction, and the PMSP96 implementations simulate the Consistency × Frequency interaction.

Even though both models can account for the same basic set of data, the models themselves can certainly be clearly distinguished; as we have said, one major distinguishing feature is the lack of lexicons, that is, of systems of whole-word representations, in the PMSP96 implementations and the presence of such lexicons in the DRC model. It is this difference between the two models that we investigated by means of the homophone–pseudophomophone (HP) priming technique.

Homophone–Pseudohomophone Priming

By HP priming, we refer to the priming of reading aloud of a word or nonword by the prior presentation of a phonologically identical word or nonword. Homophone–pseudohomophone priming in the DRC model occurs as a result of partial residual activation left by a prime in the units of its two levels of phonological representation: the phonological lexicon and the phoneme system. Although Plaut et al. (1996) did not discuss how simulation of HP priming could be achieved in the PMSP96 implementations, we conceptualized here in the same way—as residual partial activation in the elements of a target's distributed phonological representation.

If HP priming occurs solely as a result of residual activation across phoneme units, as it might be conceptualized in the PMSP96 implementations, then it should make no difference whether the prime is a word or a nonword, nor should it make any difference whether the target is a word or a nonword, because this system of phonological representation makes no distinction between lexical and nonlexical phonology. As we discussed earlier, the same prediction regarding HP priming is made by Lukatela and Turvey (1994b) in their theory of visual word recognition, according to which the amount of such priming should be unaffected by the lexical status of the prime and of the target.

In contrast, because HP priming in the DRC model is dependent on residual activation in units in the phonological lexicon and in the phoneme system, there is clearly the possibility in this model that lexical status of prime and/or target will modulate the amount of HP priming. Specifically, it should be the case that when words are involved in the prime–target pairing, more HP priming will occur, because these prime–target pairs may benefit from the effects of residual activation in systems of representation that are denied to nonwords: the lexicons.

Thus, experiments in which HP priming for lexical targets is compared with HP priming for nonlexical targets may not only provide an adjudication between the two models of reading aloud under investigation but may also enlighten the debate regarding phonology's role in visual word recognition.

The Experiments

In these experiments, we used a relatively long-ISI experimental paradigm in which the prime was unmasked (the very situation in which the critical effects reported by Lukatela and Turvey [1994a, 1994b] were seen). If there is a difference in the extent to which HP priming occurs for lexical and nonlexical items, then that difference should be clearly exposed in a long-ISI condition, a condition in which residual activation in the phoneme system may have decayed entirely while residual activation in the phonological lexicon may persist.

A disadvantage involved in using this long-ISI paradigm is, of course, the possibility that any effects that appear may be the result of strategic processing. We have taken two steps toward minimizing this possibility, however. First, primes and targets were presented in a continuous stream of items rather than segregated into obvious prime–target pairs, and participants were required to name primes as well as targets. This procedure has no disadvantages (all of the predictions made above still apply) and, in fact, has several advantages. Using this method ensures that participants attend fully to primes as well as to targets; failing to attend to primes cannot, therefore, be used as an explanation for the absence of priming effects. Participants cannot know which items are primes and which are targets, and thus, especially when fillers are added, this method minimizes strategic effects. Second, we followed Lukatela and Turvey (1994b) in minimizing the number of targets preceded by phonologically matching items in all of the experiments reported here. They argued that "because homophonic similarity was limited to 15% of the stimuli . . . it would seem that the success of Experiment 5 cannot be attributed to a general strategy of using phonological information to anticipate the target" (Lukatela & Turvey, 1994b, p. 342). Likewise, because only an average of 9.3% of the targets used in our experiments were preceded by phonologically matching items, we were also confident that any of the priming effects we observed could not be attributed to a general strategy of using phonological information to anticipate the target.

In five experiments, we explored HP priming with lexical and nonlexical items. In Experiment 1 we examined HP priming when prime and target were both words, compared with HP priming when prime and target were both nonwords. In Experiments 2 and 3 we examined HP priming when prime and target differed in lexical status: In Experiment 2, the prime was a pseudohomophone and the target was a word; conversely, in Experiment 3, the prime was a word and the target was a pseudohomophone. In Experiment 4 we sought to replicate the findings of Experiments 2 and 3. In Experiment 5 we investigated HP priming when both prime and target were pseudohomophones. We discuss the results of these experiments as a whole and pursue their simulation in the DRC model following the discussion.

Experiment 1

In Experiment 1 we compared priming between word prime–target homophone pairs (*brake–break*) and nonword prime–target homophone pairs (*keff–keph*) in a naming task.

Method

Participants. Thirty-two first-year psychology students from Macquarie University, Sydney, Australia, participated in the experiment. All had normal or corrected-to-normal vision and were native Australian-English speakers. Students received course credit for their participation.

Stimuli and apparatus. Forty pairs of homophones were selected. At least one member of each homophone pair had an irregular grapheme-to-phoneme correspondence (GPC), and this member became the target. Irregular targets were chosen so that use of the lexical route, and thus the phonological output lexicon, would be encouraged. Primes were either regular or irregular words.

In all of the experiments reported here, orthographic controls were generated for each homophone pair by preserving common letters in common positions between prime and target, as closely as was possible. Orthographic controls were as similar to the targets as were the primes, and they had an equal number of letters as did the primes. Moreover, the lexicality of the orthographic control always matched the lexicality of the prime. That is, if the prime was a word, the orthographic control was also a word; if the prime was a pseudohomophone, the control was also a pseudohomophone.

Forty orthographically legal and pronounceable nonwords were generated and were paired with a phonologically identical but orthographically distinct nonword prime and an orthographic control. Both nonword primes and orthographic controls were orthographically legal and pronounceable. Orthographic controls were generated in the same way as they were for word homophone pairs.

The 40 nonword targets and the 40 word targets were divided at random into two lists of 20 nonwords and 20 words each for counterbalancing purposes. Word homophones, nonword homophones, and controls are shown in Appendix A.

One hundred eighty-six fillers were generated and presented at random between each prime–target set. Ninety-three of these were orthographically legal and pronounceable nonwords, and 93 were English words with regular GPCs.

In all experiments presented in this set of experiments, presentation of words, nonwords, and fillers was controlled and randomized for each participant by means of the DMASTR software (Forster & Forster, 1990) on a 486 DeltaCom personal computer. Naming latencies were recorded with the use of a voice-key headset.

Procedure. In the experiments reported here, participants were seated approximately 16 in. (40.64 cm) from the monitor and fitted with the voice-key headset. They were instructed to read aloud the words and nonwords as quickly and as accurately as possible.

After 10 practice trials, participants began naming word prime–target pairs and nonword prime–target pairs in random order. Each prime (homophone or control) was preceded by fixation brackets eight characters wide, which lasted for 900 ms. Although target always followed prime, fixation brackets of 900 ms separated their presentation. Immediately after the participant began the naming of the prime or the target, the letter string disappeared and the fixation brackets reappeared, so that presentation was in one continuous stream of items interspersed by fixation brackets.

Nonword prime–target pairs and word prime–target pairs were presented randomly. Interspersed were the 186 filler words and nonwords. In total, participants saw 346 words and nonwords, 11.5% of which were followed by homophone letter strings. Only

5.8% of the stimuli were word targets preceded by homophone primes.

For both word primes and targets and nonword primes and targets, presentation was counterbalanced. Participants in Group 1 saw the first list of the nonword targets and word targets preceded by homophone primes and saw the second list of items preceded by orthographic controls. Participants in Group 2 saw the second list of word targets and nonword targets preceded by homophone primes and the first list preceded by orthographic controls. Every participant saw each target exactly once, and each target was presented equally often with its pseudohomophone prime and its orthographic control.

Results

Reaction times (RTs) for word and nonword targets primed by homophones and controls were recorded, and then those RTs for errors and spoiled trials were discarded. In addition, RTs for targets were discarded if the homophone prime was mispronounced but the target itself was pronounced correctly. Those data points remaining outside the second standard deviation were winsorized to the second standard deviation boundary.

Data in this experiment were analyzed in a mixed-design analysis of variance (ANOVA) with three factors: block, target lexicality, and priming. In the participant analysis, target lexicality and priming were treated as repeated factors, and block was treated as a between-groups factor. In the item analysis, priming was treated as a repeated factor, and target lexicality and block were treated as between-groups factors. Data by participants and by items are reported in Table 1. The ANOVA revealed a significant lexicality effect, with nonword targets pronounced more slowly than word targets by participants, $F_1(1, 30) = 87.94$, $p < .001$, $MSE = 748.14$, and by items, $F_2(1, 76) = 23.57$, $p < .0001$, $MSE = 2{,}659.50$. The ANOVA also revealed a significant effect of homophone priming, as homophone primes facilitated naming of targets more than did orthographic controls by participants, $F_1(1, 30) = 9.51, p < .01$, $MSE = 562.99$, and by items, $F_2(1, 76) = 16.96, p < .0001$, $MSE = 801.76$.

An interaction between homophone priming and lexicality emerged; in relation to priming from orthographic controls, homophone primes facilitated the naming of word targets more than phonologically identical nonword primes facilitated the naming of nonword targets. This analysis was significant by participants, $F_1(1, 30) = 5.60$, $p < .05$, $MSE = 443.53$, and by items, $F_2(1, 76) = 4.51, p < .05$, $MSE = 801.76$.

We conducted randomization tests (Edgington, 1995) to assess whether any priming occurred for nonword targets. Although these tests demonstrated a significant effect of priming for word targets by participants and by items ($ps < .001$), there was no such effect for nonword targets either by participants ($p = .45$) or by items ($p = .21$).

Target errors were analyzed in the same way as were the latency data. Participant analyses showed fewer errors for nonword targets than for word targets, $F_1(1, 30) = 16.18$, $p < .0001, MSE = 0.0043$. This effect was not significant by items, however, $F_2(1, 76) = 2.59$. The ANOVA on target errors also showed an effect of homophone priming, as there were fewer errors for words and nonwords primed with homophones than for words and nonwords primed with orthographic controls by participants, $F_1(1, 30) = 22.66$, $p < .0001$, $MSE = 0.004$, and by items, $F_2(1, 76) = 19.07$, $p < .0001, MSE = 0.0014$.

The interaction between homophone priming and lexicality was significant by participants, $F_1(1, 30) = 4.63, p < .05$, $MSE = 0.0027$, and was nearly significant by items, $F_2(1, 76) = 3.23, p = .076, MSE = 0.0014$. Homophone priming decreased errors more for words than for nonwords.

Because the interaction was significant by participants and was nearly significant by items, randomization tests were carried out to assess the relationship between homophone priming and target lexicality in the error data. Homophone priming decreased errors both for words ($p < .001$) and for nonwords ($p < .05$) in the participant analysis. Similarly, homophone priming decreased errors for both words ($p < .001$) and nonwords ($p < .05$) in the item analysis. The presence of this error effect for nonword pairs is troubling, considering the clear lack of an effect in the latency data. However, in Experiment 2, in which this condition was replicated exactly, there was no effect of priming in the nonword error data or in the latency data. Thus, it appears as if the latency data provide a more consistent measure of homophone effects in the priming of word and nonword prime–target pairs, and they are the focus of the discussion of these findings.

Table 1
Target Naming Latency (in Milliseconds) and Percentage Error as a Function of Lexicality Condition and Priming by Participants and Items in Experiment 1

	Primed		Unprimed	
Variable	Participants	Items	Participants	Items
	Word pairs			
Latency	474	476	495	504
% error	7.3	7.4	14.7	14.9
	Nonword pairs			
Latency	528	525	532	534
% error	4.7	5.0	8.2	8.2

Experiment 2

In Experiment 2 we examined HP priming in a condition in which a word target was preceded by a pseudohomophone prime (e.g., *mone–mown;* Besner, Dennis, & Davelaar, 1985). Because the results in Experiment 1 revealed an error effect but did not reveal a latency effect for nonword prime–target pairs, we also replicated that condition here to assess the reliability of the latency and error findings in that experiment.

Method

Participants. Participants were 18 first-year psychology students from Macquarie University. All had normal or corrected-to-normal vision and were native Australian-English speakers. None of the students had participated in the first experiment, and all received an introductory course credit for their participation.

Stimuli and apparatus. Forty irregular words were generated from the Medical Research Council (MRC) Psycholinguistic Database (Coltheart, 1981). All were paired with a pseudohomophone prime and an orthographic control, which was pseudohomophonous with another English word. In addition, the 40 nonword triplets (nonword target, nonword prime, and orthographic control) were taken from Experiment 1. Stimuli are contained in Appendix B.

Both the word targets and the nonword targets were divided into two lists of 20 words each. One hundred eighty-six word and nonword fillers from Experiment 1 were interspersed between prime–target pairs.

Procedure. The procedure was the same as that of Experiment 1. Participants in Group 1 saw the first list of targets preceded by a pseudohomophone prime and the second list of targets preceded by an orthographic control. Participants in Group 2 saw the second list of targets preceded by a pseudohomophone prime and the first list of targets preceded by an orthographic control. Each participant saw every target, and every target was presented equally often with its pseudohomophone prime and with its orthographic control. In total, participants saw 346 words and nonwords; 11.5% of these were followed by a homophone letter string, and only 5.8% of these letter strings were pseudohomophones followed immediately by their word homophone match.

Results

Data were collected and trimmed as in Experiment 1. Data in this experiment were analyzed in a mixed-design ANOVA with three factors: block, lexicality condition, and priming. The participant analysis treated lexicality condition and priming as repeated factors and block as a between-groups factor. Priming was treated as a repeated factor in the item analysis; lexicality condition and item block were treated as between-items factors. Data by participants and by items are reported in Table 2.

The ANOVA revealed a significant lexicality effect by participants, with nonword targets producing slower RTs than word targets, $F_1(1, 16) = 18.19, p < .001, MSE = 699.42$. This effect was not significant by items, however, $F_2(1, 76) = 1.53$.

A main effect of homophone priming emerged; those words and nonwords primed with homophones produced faster RTs than those items primed with controls. This effect was significant by participants, $F_1(1, 16) = 28.42, p < .001, MSE = 242.91$, and by items, $F_2(1, 76) = 9.69, p < .01, MSE = 1,756.14$.

Table 2
Target Naming Latency (in Milliseconds) and Percentage Error as a Function of Lexicality Condition and Priming by Participants and Items in Experiment 2

Variable	Primed		Unprimed	
	Participants	Items	Participants	Items
Pseudohomophone–word pairs				
Latency	503	516	536	550
% error	9.2	9.2	8.6	8.6
Nonword pairs				
Latency	544	546	549	553
% error	8.6	8.3	8.1	8.1

Lexicality condition and homophone priming interacted, as word targets benefited more from pseudohomophone priming than did nonword targets. This interaction was significant by participants, $F_1(1, 16) = 13.18, p < .01, MSE = 243.89$, and by items, $F_2(1, 76) = 4.38, p < .05, MSE = 1,756.14$.

Randomization tests again demonstrated that although priming reduced naming latency significantly for pseudohomophone–word pairs by participants ($p < .0001$) and by items ($p < .001$), priming had no effect on nonword pairs by participants ($p = .52$) or by items ($p = .49$).

Error data were analyzed in the same way as were the latency data. Analyses of the error data produced no significant effects. There was no effect of lexicality, as there were no more errors for nonword targets than there were for word targets by participants, $F_1(1, 16) = 0.15$, or by items, $F_2(1, 76) = 0.07$. There was no effect of homophone priming, as targets primed with homophones did not produce significantly fewer errors than did targets primed with controls by participants, $F_1(1, 16) = 0.19$, or by items, $F_2(1, 76) = 0.06$. Furthermore, there was no interaction in the error data between lexicality condition and homophone priming by participants, $F_1(1, 16) = 0.00$, or by items, $F_2(1, 76) = 0.01$.

Experiment 3

In Experiment 3 we examined HP priming in word–pseudohomophone pairs (e.g., *ghoul–goole*) relative to priming in control–target pairs (e.g., *glows–goole*).

Method

Participants. Twenty first-year psychology students from Macquarie University participated in the experiment. All had normal or corrected-to-normal vision and were native Australian-English speakers. Students received an introductory course credit for their participation.

Stimuli and apparatus. Forty irregular prime words were selected from the MRC Psycholinguistic Database (Coltheart, 1981). All were paired with a pseudohomophone target and an orthographic control. Orthographic controls were constructed in the same way as they were in Experiment 1. Stimuli are contained in Appendix C.

The 40 words were divided into two lists of 20 words each for counterbalancing purposes. One hundred eighty-six fillers were used from Experiment 1, and they were interspersed randomly among prime–target pairs.

Procedure. The procedures used in this experiment were the same as those used in Experiment 1. Half of the participants saw the first list of pseudohomophone targets paired with homophone primes and the second list of targets paired with orthographic controls. The other half of the participants saw the second list of pseudohomophone targets paired with homophone primes and the first list of targets paired with orthographic controls. Each participant saw every target, and every target was presented equally often with its homophone prime and its orthographic control. In total, participants saw 266 words and nonwords. Only 7.5% of these letter strings were pseudohomophones preceded by a homophone.

Table 3
Naming Latency (in Milliseconds) and Percentage Error as a Function of Priming by Participants and Items in Experiment 3

	Primed		Unprimed	
Variable	Participants	Items	Participants	Items
Latency	534	538	540	541
% error	2.5	2.5	7.3	7.3

Results

Data were collected and trimmed as they were in Experiment 1. Reaction times for pseudohomophone targets were analyzed as a function of prime type (within groups) and block (between groups) in a mixed-design ANOVA. Latency and error data by participants and by items are shown in Table 3.

The participants analysis revealed no significant difference in naming latency between targets primed with homophones and targets primed with orthographic controls: $F_1(1, 18) = 0.35$. Similarly, the item analysis revealed no significant difference between those targets primed with homophones and those targets primed with orthographic controls: $F_2(1, 38) = 0.03$.

An analysis of the errors, however, showed that targets primed with homophones showed fewer errors than did targets primed with orthographic controls by participants, $F_1(1, 18) = 7.30, p < .05, MSE = 0.0033$, and by items, $F_2(1, 38) = 6.43, p < .05, MSE = 0.0071$.

Experiment 4

Because Experiments 2 and 3 both revealed HP priming in mixed-lexicality pairs but revealed this priming in the error measure in one case and in the latency measure in the other case, in Experiment 4 we sought to replicate the findings of Experiments 2 and 3 in a within-subjects, more tightly controlled design.

Method

Participants. Twenty first-year students from Macquarie University were tested. All participants had normal or corrected-to-normal vision and received course credit for their participation. They were all native speakers of Australian English.

Stimuli and apparatus. Forty irregular words were selected from the MRC Psycholinguistic Database (Coltheart, 1981). These 40 words were paired with phonologically identical pseudohomophones (*goole–ghoul*). Half of the time, the pseudohomophone was the target and the word was the prime; half of the time, the word was the target and the pseudohomophone was the prime. Two orthographic controls were created for each pair, one to match the pseudohomophone prime and one to match the word prime. Controls were constructed as they were in the other experiments. The orthographic controls that matched the pseudohomophone primes were pseudohomophones of other English words, and those that matched the word primes were other English words. The 40 quadruplets were divided into four lists of 10 quadruplets each, as each participant could see only one phonological form of each target during the session. Stimuli are contained in Appendix D.

One hundred and sixty fillers were created. Eighty of these were pseudohomophones of English words, and 80 were English words. Fillers were randomly inserted between prime–target pairs.

Stimuli were presented in the same manner as in Experiment 1; a 486 DeltaCom computer and the DMASTR (Forster & Forster, 1990) presentation software were used.

Procedure. Participants were tested individually by means of the same procedure as was used in Experiment 1. Four separate groups of participants were tested such that every person saw every phonological target (either *goole* or *ghoul*) only once, primed either by the homophone match or by the orthographic control. Participants saw 240 stimuli in total. Of these stimuli, 8.3% were followed by homophone letter strings, and only 4.2% of the stimuli were words preceded by a pseudohomophone prime.

Results

Data were collected and trimmed by means of the same procedures described in the other experiments. Reaction times were analyzed by participants and by items in a mixed-design ANOVA with three factors: block, lexicality condition, and priming. Both participant and item analyses treated lexicality condition and prime type as repeated factors; block was treated as a between-groups factor. Latency and error data by participants and by items are shown in Table 4.

An effect of lexicality emerged, as pseudohomophone targets were pronounced more slowly overall than were word targets; this effect was significant both by participants, $F_1(1, 16) = 5.97, p < .05, MSE = 1{,}551.94$, and by items, $F_2(1, 36) = 4.89, p < .05, MSE = 7{,}982.51$. There was no main effect of priming by participants, $F_1(1, 16) = 0.65$; however, a trend emerged in the item analysis, as primed targets were named more quickly than were unprimed targets: $F_2(1, 36) = 3.44, p = .07$. Critically, there was an interaction between lexicality condition and priming; priming facilitated target naming in pseudohomophone–word pairs but not in word–pseudohomophone pairs by participants, $F_1(1, 16) = 18.96, p < .001, MSE = 497.91$, and by items, $F_2(1, 36) = 8.26, p < .01, MSE = 2{,}697.39$.

Randomization tests confirmed that although priming facilitated naming in the latency measure in pseudohomophone–word pairs by participants and by items ($ps < .005$), it did not facilitate naming in word–pseudohomophone pairs, either by participants ($p = .13$) or by items ($p = .37$).

Table 4
Naming Latency (in Milliseconds) and Percentage Error as a Function of Lexicality Condition and Priming by Participants and Items in Experiment 4

	Primed		Unprimed	
Variable	Participants	Items	Participants	Items
	Pseudohomophone–word pairs			
Latency	507	507	534	544
% error	7.5	7.0	8.5	8.5
	Word–pseudohomophone pairs			
Latency	550	562	534	552
% error	2.5	3.0	10.5	11.0

Error data were analyzed in the same way as were the latency data. All of the errors for word targets were regularization errors. Forty percent of the errors for nonword targets were lexicalization errors. The remainder of the nonword errors were due to incorrect stress application (32%) and miscellaneous phoneme mispronunciations (28%).

The error analysis did not show any main effect of lexicality, as there were no more errors for word targets than for pseudohomophone targets by participants, $F_1(1, 16) = 0.89$, or by items, $F_2(1, 72) = 0.06$. There was, however, an effect of priming; there were fewer errors for primed targets than for unprimed targets by participants, $F_1(1, 16) = 6.29$, $p < .05$, $MSE = 0.0063$, and by items, $F_2(1, 72) = 6.05$, $p < .05$, $MSE = 0.0149$. An interaction between lexicality condition and priming emerged, however, because priming reduced errors for word–pseudohomophone pairs more than it reduced errors for pseudohomophone–word pairs, $F_1(1, 16) = 6.43$, $p < .05$, $MSE = 0.0038$. This interaction approached significance by items, $F_2(1, 72) = 2.83$, $p = .097$, $MSE = 0.0149$. Planned randomization tests showed that although errors were reduced by homophone primes in word–pseudohomophone pairs by participants ($p < .005$) and by items ($p = .02$), errors were not reduced by homophone primes in pseudohomophone–word pairs by participants ($p = .86$) or by items ($p = .68$). Thus, word targets preceded by pseudohomophone primes were facilitated in the latency measure, whereas pseudohomophone targets preceded by word primes were facilitated in the error measure.

Experiment 5

In Experiment 5 we examined the extent to which homophone priming occurs in a condition in which a pseudohomophone prime precedes a pseudohomophone target (e.g., *braik–brayk*).

Method

Participants. Participants were 20 first-year psychology students at Macquarie University who had not participated in the preceding experiments. All had normal or corrected-to-normal vision and were native Australian-English speakers. They received an introductory course credit for their participation.

Stimuli and apparatus. Forty words were chosen from the MRC Psycholinguistic Database (Coltheart, 1981). Two pseudohomophones were generated for each of these words, one to act as the target, and one to act as the prime (e.g., *braik–brayk*). An orthographic control was generated for each pseudohomophone as in the other experiments. The 40 pseudohomophone pairs were split at random into two groups of 20 pairs each for counterbalancing purposes. Pseudohomophone primes, targets, and controls are shown in Appendix E. One hundred eighty-six word and nonword fillers were used from Experiment 1 and were randomly interspersed between prime–target pairs.

Procedure. The same procedure as in Experiment 1 was used here. One group of participants saw the first list of targets preceded by a pseudohomophone prime and the second list of targets preceded by an orthographic control. The other group of participants saw the second list of targets preceded by a pseudohomophone prime and the first list of targets preceded by an orthographic control. Each participant saw every target, and every target was presented equally often with its pseudohomophone prime and its orthographic control. In total, participants saw 266 items; 7.5% of these items were followed by a homophone letter string.

Table 5
Naming Latency (in Milliseconds) and Percentage Error as a Function of Priming by Participants and Items in Experiment 5

	Primed		Unprimed	
Variable	Participants	Items	Participants	Items
Latency	618	613	610	613
% error	4.37	3.85	5.96	5.90

Results

Data were collected and trimmed as in the other experiments. Latency and error data by participants and by items are shown in Table 5.[1] A mixed-design ANOVA with priming (within groups) and block (between groups) as factors revealed no significant effects of priming by participants, $F_1(1, 18) = 0.40$, or by items, $F_2(1, 37) = 0.01$; there was no difference between the latencies of targets primed by pseudohomophones and those primed by orthographic controls.

The error data showed no significant effect of priming, because the pseudohomophone targets primed with pseudohomophones produced no fewer errors than those targets primed with orthographic controls by participants, $F_1(1, 18) = 0.94$, or by items, $F_2(1, 37) = 2.73$. Thus, these error data are in accord with the latency data in this experiment. There is no effect of priming in pseudohomophone prime–target pairs.

Discussion of Experiments 1–5

In five experiments with human readers, we explored the extent to which homophone priming in reading aloud occurs when the lexicality of primes and of targets is varied. Critically, we showed that in the ISI conditions used here, homophone priming occurs only when a word is in the prime–target pairing; there is no homophone priming in these conditions when both prime and target are pseudohomophones or when both prime and target are nonwords.

A curious result emerged in the mixed-lexicality prime–target pairs: In the pseudohomophone–word condition, priming was revealed in the latency measure but not in the error measure; conversely, in the word–pseudohomophone condition, priming was revealed in the error measure but not in the latency measure. Because this result was replicated in the experiments presented here, we believe it to be reliable; however, we have little to say regarding its cause. Most important, the fact that priming occurred in these conditions

---

[1] One of the target items was inadvertently included even though it was a word. The item, *bate*, in both the primed and unprimed conditions, was removed from the analysis.

supports the general pattern of results that we have reported: In long-ISI conditions, the prime–target pairing must comprise at least one word for priming to occur.

We have suggested that these data are relevant to the general issue of the role of phonology in visual word recognition, one theory of which has been advanced by Lukatela and Turvey (1994a, 1994b) and is the focus of the discussion here. As we have argued, because this theory proposes that the locus of homophone priming is prelexical, it must predict that for any ISI value, if homophone priming for word primes and targets occurs, then it must also occur for pseudohomophone primes and targets because activation for these items is boosted by feedback from lexical entries that match their pronunciation. The results presented here are inconsistent with this prediction. Homophone priming occurred in all cases except when pseudohomophone targets were followed by pseudohomophone primes. The condition in which nonpseudohomophonous nonword primes followed nonpseudohomophone nonword targets is not relevant to Lukatela and Turvey's theory because these items receive no feedback from lexical entries.

It might be argued that some properties of the pseudohomophones that we have used functioned to slow the generation of a phonological representation and thus slowed access to the relevant lexical entries that support these representations; for example, these items may have been less consistent or less wordlike than lexical items. If this were the case, we might expect that nonlexical items would show less priming than lexical items, even when the locus of this priming is prelexical—exactly the result we observed. We do not believe that this is a possibility, however. If it were, then we would expect to observe a prime lexicality effect, in which homophone priming did not occur when primes were pseudohomophones. Priming did occur, however, when a word target followed a pseudohomophone prime. Thus, we argue that these data are inconsistent with the theory advanced by Lukatela and Turvey (1994a, 1994b) and that the locus of homophone priming is not prelexical.

We have similarly suggested that these data are relevant to two computational models of reading, the DRC model and the PMSP96 implementations, which can be contrasted regarding their claims about the nature of representation in the reading system. As we have argued, the DRC model—by virtue of its local word representations—predicts that for any ISI condition, if there is priming for lexical items, this priming must be larger than it is for nonlexical items. By contrast, we propose that the PMSP96 implementations, because they make no distinction between lexical and nonlexical items at input or output, predict that there will be no difference between priming of lexical items and priming of nonlexical items, whether they are pseudohomophones or nonwords. Although the data we have presented are consistent with the DRC model, they are inconsistent with the predictions we have made regarding the PMSP96 implementations.

It is, of course, possible that we are incorrect in our claims regarding the PMSP96 implementations. It might be the case that once homophone priming is achieved in the PMSP96 implementations, the pattern of data we have presented emerges in simulation work. If this is the case, then the PMSP96 implementations will have advanced in the range of data that they address; more important, their simulations will have shown that the pattern of data that we have reported does not require separate representational systems for words and nonwords. It is also possible that we are correct in our claims regarding the PMSP96 implementations and that a new implementation is required to simulate the data that we have reported.

How might the existing PMSP96 implementations be altered to accommodate these findings? Here we refer to the history of implementations based on the triangle framework. Recall that the major difference between the SM89 implementation and the PMSP96 implementations that followed was the move from input and output representations that were distributed to ones that were local, in the form of graphemes and phonemes. Although this advancement overcame the inadequacies of the SM89 implementation identified by Besner et al. (1990), it was a surprising move considering that the use of distributed representations has been touted as fundamental to the framework on which the implementation is based (see, e.g., Seidenberg, 1993). As was the case in the second implementation of the triangle framework, it might be possible to simulate the data we have presented here in a third implementation by adding local word representations to the model; this feature of the model would also enable it to perform the lexical decision task, the simulation of which the current implementation has been unsuccessful at achieving. After a move to local word representations, the addition of a serial process may be required, of course, to simulate data regarding serial effects in reading (Rastle & Coltheart, 1998, 1999).

We have argued that the data reported here are consistent with the predictions of the DRC model, but like our claims regarding the PMSP96 implementations, it is possible that we have developed predictions that are untrue of the DRC model. Thus, the next section is dedicated both to a discussion about how priming may be achieved in the DRC model and to simulation of the data we have presented here.

Simulation

Simulating priming in an interactive-activation model like the DRC model is dependent on implementing a function whereby residual activation from the prime can influence naming of the target. One reasonably straightforward way of doing this is to institute a decay of activation between the naming of the prime and the presentation of the target, so that when the target is presented to the model for naming, activation throughout the system is not reset but instead persists and alters the resting level of activation for the target. The role of decay in output activation for each unit is expressed by the following DRC activation equation:

$$O_n = O_{n-1} + (1 - O_{n-1}) \cdot (I + F + N) \cdot A - (D \cdot O_{n-1}),$$

with O_n representing the new output activation, O_{n-1} representing the old output activation, I representing the input activation (dependent on several factors such as neighbors), F representing a frequency parameter ranging between $-.05$ (least frequent) and zero (most frequent), N representing noise, A representing activation rate, and D representing the proportion of decay.

Recall that activation in the DRC model is graded (Coltheart & Rastle, 1994), and thus instituting a massive decay of activation over one cycle is a violation of this processing principle. Moreover, instituting decay in this manner does not produce sensible simulations. Decay must be applied gradually, a small proportion of the total activation at a time, over many processing cycles. The effects of decay are far different if applied gradually over many cycles than if applied in one processing cycle, even though the total amount of decay is equal in both situations. The reason for this property of the decay function is that activation is calculated after every cycle based, in part, on the net input aspect of the activation equation described above:

$$\text{net input} = I + F + N.$$

Because new activations are calculated on the basis of prior input, frequency, and noise after every cycle, some items—particularly those of high frequency or those with many neighbors—become resistant to decay. These properties cannot alter the effects of decay if decay is implemented over one cycle only. Thus, the total amount of decay a unit undergoes must be determined by (a) the proportion of decay and (b) the number of cycles of decay.

Using these properties of decay, how might we then go about simulating the data reported here? One way to simulate priming for lexical items while simulating no priming for nonlexical items is to decay letter and phoneme units more than orthographic and phonological units, over each cycle. By using differential decay values in each module, we have found simulating the pattern of data reported here to be easily accomplished.

Could this pattern of data be simulated without using differential decay values, using instead only one value of decay for units in these four modules? This simulation would be a strong test of our claims about lexical and nonlexical representational systems; if this simulation could be achieved, we could argue that facts about lexical knowledge enabled greater priming for word items than for nonword items, perhaps by enabling word items to resist decay. We have attempted to simulate the human data under these more stringent conditions.

In every simulation of the word–word condition and the pseudohomophone–pseudohomophone condition that we carried out, which varied proportion of decay and length of decay, word items showed more priming than pseudohomophone items. Figure 3 shows the average amount of priming in the word–word condition compared with the average amount of priming in the pseudohomophone–pseudohomophone condition over 10 values of the length of decay parameter when proportion decay is .15. As shown in Figure 3, at every length of decay, word pairs produced more priming than pseudohomophone pairs. As was reported in the human data, at 46 cycles of decay, priming for pseudohomophone pairs is not significant, but priming for word pairs, though small, is significant.

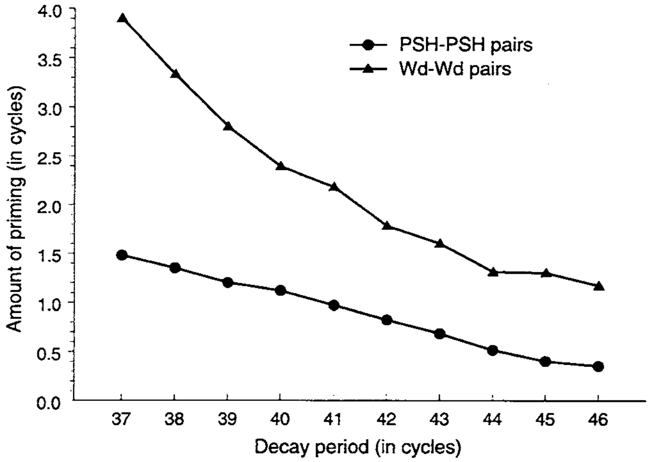

Figure 3. Priming for word (Wd) pairs and for pseudohomophone (PSH) pairs as the length of decay between prime and target increases.

The simulation procedure was as follows: The prime or control word was presented until it was named; without resetting, the system underwent a decay period of 46 cycles at 15% decay per cycle; without resetting, the target was presented until it was named; after naming, the system was reset, and the next prime or control word was presented. Each target's latency (in cycles) was measured when presentation followed the homophone prime and when presentation followed the orthographic control. We examined only the conditions relevant to word and pseudohomophone priming, because the condition that investigated nonword–nonword priming is not relevant to our conclusions regarding Lukatela and Turvey (1994a, 1994b).

The DRC parameters used in all simulations reported here are the standard set of parameters that have been shown to simulate a number of effects detailed by Rastle and Coltheart (1998, 1999). The use of decay in the DRC model is relevant only to priming situations, and as we have previously not explored priming in the model, the use of this parameter does not compromise any of our other simulation findings.

Simulation 1

In Simulation 1 we investigated whether, within the chosen parameter values, the DRC model shows priming for word–word pairs but not for pseudohomophone–pseudohomophone pairs, as was the case in the human data.

Stimuli

Word and pseudohomophone triples were selected from Experiments 1 and 5. Those triples containing disyllables were excluded because the DRC model currently names only monosyllabic letter strings correctly. Three of these word–word homophone pairs were not identified as homophones in the CELEX database (Baayen et al., 1993), even though they are homophones in Australian English and were used in Experiment 1. These items were excluded from the simulation. Twenty-nine word triples (prime–control–target) remained from Experiment 1, and 26 pseudohomophone triples remained from Experiment 5.

Results

The DRC model produced no errors for word items and one error for pseudohomophone items: It pronounced *brane* as *bran* in both the primed and unprimed conditions. This item was removed from the analysis. Remaining naming latencies are shown in Table 6, and full item data are contained in Appendix F.

An ANOVA in which lexicality was treated as a between-items variable and priming as a within-items variable showed significant effects of lexicality, $F(1, 52) = 447.09$, $p < .0001$, $MSE = 209.97$, and priming, $F(1, 52) = 32.68$, $p < .0001$, $MSE = 0.42$, and a significant interaction between these two factors, $F(1, 52) = 8.04$, $p < .01$, $MSE = 0.42$; words showed significantly greater priming than pseudohomophones. Randomization tests confirmed that no priming occurred between pseudohomophone pairs ($p = .11$), whereas priming did occur between word pairs ($p < .0001$).

Simulation 2

Simulation 1 confirmed that there is a set of decay values in the DRC model which shows no priming between pseudohomophone prime–target pairs and significant priming between word prime–target pairs. Simulation 2 seeks to investigate whether, using these values, the DRC model can also simulate priming in mixed lexicality pairs, as was shown in Experiments 2–4.

Stimuli

The stimuli used in the simulation were the prime–control–target triples used in Experiments 2–4. Those triples that contained a disyllabic item were excluded. This left 24 triples in the pseudohomophone–word condition and 16 triples in the word–pseudohomophone condition. These items were submitted to the DRC model for simulation by means of the priming procedure and parameter set described in Simulation 1.

Table 6
Naming Latency (in Processing Cycles) as a Function of Lexicality Condition and Priming in the DRC Model: Simulations 1 and 2

Condition	Primed	Unprimed
Simulation 1		
Word–word pairs	83.76	84.83
Pseudohomophone–pseudohomophone pairs	143.24	143.60
Simulation 2		
Pseudohomophone–word pairs	86.30	86.70
Word–pseudohomophone pairs	136.75	137.81

Note. DRC = dual-route cascaded.

Results

In the pseudohomophone–word condition, the DRC model produced errors on two target items: It pronounced *isle* as *ill* in both primed and unprimed conditions and *tsar* as /ts/ in both primed and unprimed conditions. These items were removed from the analysis. Remaining DRC latencies are shown in Table 6, and complete item data are contained in Appendix G.

An ANOVA in which priming was treated as a within-items variable and prime–target order (word–pseudohomophone or pseudohomophone–word) as a between-items variable was carried out on the remaining data. Results showed that word-target items were named more quickly than pseudohomophone-target items, $F(1, 36) = 177.87$, $p < .01$, $MSE = 266.19$. Word and pseudohomophone items were named more quickly if they were primed by a homophone item, $F(1, 36) = 33.86$, $p < .01$, $MSE = 0.28$, than if they were primed by an orthographic control. Pseudohomophone–word pairs showed less priming than word–pseudohomophone pairs, $F(1, 36) = 8.13$, $p < .01$, $MSE = 0.28$. Randomization tests confirmed that the priming effect was significant in both the pseudohomophone–word condition ($p = .008$) and in the word–pseudohomophone condition ($p < .0001$).

Discussion of Simulations 1 and 2

By implementing a decay function between prime and target in the DRC model, we enjoyed a certain degree of success in simulating the general pattern of data shown by human readers. Although priming did not occur in pseudohomophone–pseudohomophone pairs, it did occur in word–word pairs and in mixed-lexicality pairs. As we have discussed, variations in the values of decay produce similar results; in every case, more priming occurs when a word is involved in the prime–target pairing than when a word is not involved in the pairing. It should be stressed, however, that within these decay values, we have been able to simulate only the general pattern of human data; the DRC model did not produce the curious result produced by people presented with mixed-lexicality pairs, in which priming was revealed in the error measure for word–pseudohomophone pairs and in the latency measure for pseudohomophone–word pairs. The DRC model has nothing to say about why this result occurred in the human data, and we are unable to speculate on how the result might be achieved in the DRC model.

It is easy to understand why both the word–word and the word–pseudohomophone conditions showed more priming than the pseudohomophone–pseudohomophone condition in the DRC model. When the prime is a word homophone of the target, activation for the target phonology in the phonological output lexicon reaches a much greater value than when the prime is a pseudohomophone of the target. After a decay period, this value is still substantially higher than when the prime is a pseudohomophone, and so it facilitates naming of the target, whether it is a word or a pseudohomophone, because its activation cascades down to the phoneme system.

It is more difficult to understand why the DRC model shows significant pseudohomophone–word priming but does not show significant pseudohomophone–pseudohomophone priming within the decay parameters we have used. In both cases, the prime is a pseudohomophone; thus, after it is named and the model undergoes a decay period, the state of the model is the same in both conditions. Why, then, does this residual activation facilitate naming when the target is a word but does not when the target is a pseudohomophone?

We investigated this question by studying DRC performance on one pseudohomophone–pseudohomophone pair (*staik–stayk* vs. *stauk–stayk*) and on one pseudohomophone–word pair (*staik–steak* vs. *styck–steak*). The results of this simulation, along with unprimed latencies for *steak* and *stayk*, are shown in Table 7.

As shown in Table 7, neither of the control primes (*styck* or *stauk*) facilitates naming beyond a totally unprimed condition: *stayk* is named in 140 cycles in both cases, and *steak* is named in 80 cycles in both cases. Why, then, does the prime *staik* facilitate naming for the target *steak* but not for the target *stayk*, given that the state of the network is exactly the same in both conditions after the prime and the decay period?

Naming in the DRC model occurs when each of the phoneme units in the item and the null phoneme unit reach a critical activation (set at .43 in the standard set of parameters). Consider, then, Table 8, which displays the cycle numbers at which each of the five relevant phonemes in *steak* and *stayk* (/s/, /t/, /1/, /k/, /null/) reach critical activation when the prime is *staik* (remember that the item *steak* is named in 79 cycles and *stayk* is named in 140 cycles).

As shown, the critical phoneme in *steak* is /1/, whereas the critical phoneme in *stayk* is the null phoneme. Thus, even though the first four phonemes in *stayk* (/s/, /t/, /1/, /k/) might be primed by residual activation left from *staik*, that priming is not realized because the model's response must wait until the null phoneme has reached critical activation. If there is enough residual activation from *staik* to support priming, it is captured by *steak* because it is one of the first four phonemes—and not the null phoneme—that is critical to the naming response.

Why is the null phoneme critical in the naming of *stayk*, whereas it is not critical in the naming of *steak*? In the DRC model, although lexical activation of the phoneme level occurs in parallel, nonlexical activation of this level occurs serially. Thus, when *stayk* is named by the nonlexical route, its letters, which include a null letter character at the end of the item, are submitted to the phoneme system by the GPC rule system one at a time, from left to right, at intervals of 17 cycles in the standard set of parameters. Its relevant phonemes thus rise in serial order. When *steak* is processed lexically, however, the null phoneme begins rising immediately because of the parallel operation of that route. Of course, *stayk* has five neighbors, which means that the lexical route contributes to its naming; however, inhibition at the orthographic level ensures that it does not contribute to a large degree.

Table 7
Example of the Effect of Pseudohomophone Priming on Word and Pseudohomophone Target Naming Latency (in Processing Cycles) in the DRC Model

Stimulus	Homophone prime	Control prime	No prime
Steak	*staik*	*styck*	
Latency	79	80	80
Stayk	*staik*	*stauk*	
Latency	140	140	140

Note. DRC = dual-route cascaded.

Table 8
Cycle Number at Which Relevant Phonemes in Word and Pseudohomophone Targets Reached Critical Activation After Homophone Priming in the DRC Model: An Example

	Phoneme				
Stimulus	/s/	/t/	/1/	/k/	/null/
Steak	61	63	79	76	76
Stayk	107	111	137	137	140

Note. DRC = dual-route cascaded.

Consider now the pseudohomophone–pseudohomophone simulation and the pseudohomophone–word simulation reported here. When the targets were pseudohomophones, the critical phoneme for the naming response was the null phoneme in 52% of the cases (in 13 of the 25 pairs). When the targets were words, the critical phoneme for the naming response was the null phoneme in only one case out of the 22 pairs that were named correctly.

Thus, it appears as if the impact of the null phoneme in the naming response differs for word targets and for pseudohomophone targets in the DRC model. This difference is due to separate representational systems for words and for nonwords in the model: Whereas words enjoy parallel activation, nonwords are processed primarily serially. We claim that it is this fact—that words and nonwords are treated differently by the model—that explains why priming generally occurs in pseudohomophone–word pairs but not in pseudohomophone–pseudohomophone pairs within the decay values that we have selected. We posit that this is also the case for human readers.

The simulations that we have reported here replicate the human data to some degree in their general pattern, but do so to a far lesser degree than simulations we have reported elsewhere regarding the position of irregularity effect (Rastle & Coltheart, 1999) and the whammy effect (Rastle & Coltheart, 1998).

A number of problems are evident in the simulations.[2] First, we were unable to replicate the curious pattern that emerged in Experiments 2, 3, and 4, in which priming occurred only in the error data for word–pseudohomophone pairs and in the latency data for pseudohomophone–word pairs. Furthermore, although the DRC model simulates the general pattern of human data, the magnitude of the priming effects

---

[2] We are grateful to Tom Carr for pointing out these deficiencies to us.

in the DRC model are much smaller than in human readers. Second, there appears to be a serious problem with scaling. Whereas 46 cycles of decay are required to simulate the 900-ms ISI used by human readers (making each cycle equal to around 20 ms), the DRC model takes around 80 cycles to pronounce words that people pronounce in 500–530 ms (making each cycle equal to around 6.5 ms). A third problem is that the DRC model seems to produce a much larger lexicality effect than that produced by human readers.

What might account for these failures in the simulations we have reported? If each relevant module were decayed at a different rate, then might we produce a superior simulation? We have explored this possibility, and although the magnitude of priming effects look more like those produced by people, the scaling problem and the oversized lexicality effect persists. We have used here the standard set of parameters used to simulate the position of irregularity and whammy effects, but perhaps a further search through parameter space would yield a better simulation result. Of course, until we find another set of parameters that simulates every other effect that we have successfully simulated, we cannot know how this might affect the simulations reported here. However, we believe that the problems we have highlighted would not be overcome through finding a new set of parameters. Finally, it is possible that priming should be implemented in the model differently than we have suggested here. For example, it is possible that a prime could, instead of influencing target naming through residual activation, produce short-term weight changes in connections. Further work with the decay function in the DRC model would enlighten us as to whether the problems that we have highlighted could be overcome if priming were implemented differently, if priming could be simulated in this manner at all.

One of the simulation weaknesses that we have discussed is not related to priming, however, and was also a weakness of the strategy simulation reported by Rastle and Coltheart (1999): the size of the lexicality effect in the model. In the unprimed condition of Simulation 1, the word targets that were preceded by words averaged 84.83 cycles, whereas the pseudohomophone targets that were preceded by pseudohomophones averaged 143.60 cycles. Looking at Experiments 1 and 5 from which these stimuli were drawn, one may see that the averaged unprimed latency of word targets preceded by words was 495 ms, whereas the average unprimed latency of pseudohomophone targets preceded by pseudohomophones was 610. Thus, although the pseudohomophones were named 1.7 times more slowly than the words in the simulation, they were named only 1.2 times more slowly than the words when read by individuals.

However, it is a mistake to compare the lexicality effects in people and in the model in this manner, because human RTs include time-consuming nonlinguistic processes that are beyond the scope of the DRC model. Some of these processes occur prior to access to the reading system (e.g., early visual analysis), and others occur after exit from the reading system (e.g., articulation). The times taken by such processes do not contribute to DRC naming latency, but they do contribute to human naming latency.

How, then, might we isolate the component of human naming latency that represents the DRC naming latency and compare these two measures? To explore this problem, we regressed DRC unprimed naming latencies in Simulations 1 and 2 onto human naming latencies for these items in the experiments. The resulting regression equation revealed that at a DRC naming latency of zero, the human latency was 427 ms, with a regression coefficient of just over 1 ($y = 426.91 + 1.015 \cdot x$), $r^2 = .208$. Thus, we can think of 427 ms as that time consumed by those processes that are beyond the scope of the DRC model.

When this 427-ms nonlinguistic component is subtracted from human latencies for unprimed word items (495 ms), it is evident that what takes the DRC model 84.83 cycles to read occurs in 68 ms in humans; thus, each millisecond takes 1.25 cycles in the DRC model. Given this, can human naming latency now be predicted for unprimed pseudohomophone items preceded by pseudohomophones? The DRC model took 143.60 cycles to name these items; multiplying this figure by 1.25 and adding 427 results in 607 ms, which is extremely close to the 610 ms actually taken by individuals to name these items.

Thus, we believe that the large lexicality effect in the DRC model is reconcilable with the size of the lexicality effect in humans if one takes into consideration that human naming latency is consumed by various processes beyond the scope of the model. This solution does not assist in understanding the deficiencies in the simulations caused by priming, of course, but it brings us a step closer to reconciling human performance with model performance in the simulations presented here.

Conclusions

With respect to the role of phonology in visual word recognition, we conclude that the target lexicality and prime lexicality effects we have demonstrated are inconsistent with the view that lexical access in reading is purely phonological; our conclusion concurs with the conclusion of a recent review of this issue (Coltheart & Coltheart, 1997).

With respect to the second issue to which our article is relevant—adjudication between competing computational models of reading aloud—our approach is, as we discussed earlier, to identify contrasting properties of such models about which we can generate contrasting predictions for experimentation. One property on which the DRC and the PMSP96 models can be contrasted is the presence versus absence of serial processing. Investigations of contrasting predictions derived from this contrast in model properties have led us elsewhere to favor the DRC model (Coltheart & Rastle, 1994; Rastle & Coltheart, 1999). Another property on which the two models can be contrasted is the presence versus absence of local word representations. In this article, investigations of contrasting predictions about phonological priming derived from this contrast in model properties have led us to adjudicate in favor of that general approach to modeling reading in which the existence of local representations of words is proposed; we are also in favor of a specific model—the DRC model—which adopts that approach, although we have highlighted a number of ways in which that model's simulation of priming effects is unsatisfactory.

References

Baayen, R. H., Piepenbrock, R., & van Rijn, H. (1993). *The CELEX lexical database* [CD-ROM]. Philadelphia: University of Pennsylvania, Linguistic Data Consortium.

Baddeley, A. D., & Hitch, G. (1974). Working memory. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 8). New York: Academic Press.

Besner, D., Dennis, I., & Davelaar, E. (1985). Reading without phonology? *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 37A,* 477–491.

Besner, D., Twilley, L., McCann, R., & Seergobin, K. (1990). On the connection between connectionism and data: Are a few words necessary? *Psychological Review, 97,* 432–446.

Broadbent, D. E. (1958). *Perception and communication.* Elmsford, NY: Pergamon Press.

Bruce, V., & Young, A. (1986). Understanding face recognition. *British Journal of Psychology, 77,* 305–327.

Burgess, N., & Hitch, G. J. (1992). Towards a network model of the articulatory loop. *Journal of Memory and Language, 31,* 429–460.

Burton, A. M., Bruce, V., & Johnston, R. (1990). Understanding face recognition with an interactive activation model. *British Journal of Psychology, 81,* 361–380.

Coltheart, M. (1978). Lexical access in simple reading tasks. In G. Underwood (Ed.), *Strategies of information processing* (pp. 151–216). London: Academic Press.

Coltheart, M. (1980). Reading, phonological recoding, and deep dyslexia. In M. Coltheart, K. E. Patterson, & J. C. Marshall (Eds.), *Deep dyslexia* (pp. 197–226). London: Routledge & Kegan Paul.

Coltheart, M. (1981). The MRC psycholinguistic database. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 33A,* 497–505.

Coltheart, M. (1985). Cognitive neuropsychology and the study of reading. In M. I. Posner, & O. S. M. Marin (Eds.), *Attention and performance XI* (pp. 3–37). Hillsdale, NJ: Erlbaum.

Coltheart, M. (1996). Computational modelling and cognitive psychology [On-line]. *Noetica* (Issue 1). Retrieved November 25, 1998 from the World Wide Web: http://psy.uq.edu.au/CogPsych/Noetica/OpenForumIssue1/Coltheart.html.

Coltheart, M., & Coltheart, V. (1972). On Rumelhart's model of visual information processing. *Canadian Journal of Psychology, 26,* 292–295.

Coltheart, M., & Coltheart, V. (1997). Reading comprehension is not exclusively reliant upon phonological representation. *Cognitive Neuropsychology, 14,* 167–175.

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

Coltheart, M., Davelaar, E., Jonasson, J. T., & Besner, D. (1977). Access to the internal lexicon. In S. Dornic (Ed.), *Attention and performance VI* (pp. 535–555). Hillsdale, NJ: Erlbaum.

Coltheart, M., & Rastle, K. (1994). Serial processing in reading aloud: Evidence for dual-route models of reading. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 1197–1211.

Edgington, E. S. (1995). *Randomization tests.* New York: Marcel Dekker.

Fera, P., & Besner, D. (1992). The process of lexical decision: More words about a parallel distributed processing model. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 18,* 749–764.

Forster, K. I., & Forster, J. C. (1990). *User's guide to the DMASTR display system: Laboratory software for mental chronometry.* Tucson: University of Arizona.

Lukatela, G., & Turvey, M. T. (1991). Phonological access of the lexicon: Evidence from associative priming with pseudohomophones. *Journal of Experimental Psychology: Human Perception and Performance, 17,* 951–966.

Lukatela, G., & Turvey, M. T. (1994a). Visual lexical access is initially phonological: 1. Evidence from associative priming by words, homophones, and pseudohomophones. *Journal of Experimental Psychology: General, 123,* 107–128.

Lukatela, G., & Turvey, M. T. (1994b). Visual lexical access is initially phonological: 2. Evidence from phonological priming by homophones and pseudohomophones. *Journal of Experimental Psychology: General, 123,* 331–353.

McClelland, J. L. (1991). Stochastic interactive processes and the effect of context on perception. *Cognitive Psychology, 23,* 1–44.

McClelland, J. L. (1993). The GRAIN model: A framework for modeling the dynamics of information processing. In D. E. Meyer & S. Kornblum (Eds.), *Attention and performance XIV: Synergies in experimental psychology, artificial intelligence, and cognitive neuroscience* (pp. 655–688). Hillsdale, NJ: Erlbaum.

McCusker, L. X., Hillinger, M. L., & Bias, R. G. (1981). Phonological recoding and reading. *Psychological Bulletin, 89,* 217–245.

Patterson, K. E., & Behrmann, M. (1997). Frequency and consistency effects in a pure surface dyslexic patient. *Journal of Experimental Psychology: Human Perception and Performance, 23,* 1217–1231.

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

Patterson, K. E., Seidenberg, M. S., & McClelland, J. L. (1989). Connections and disconnections: Acquired dyslexia in a computational model of reading processes. In R. G. M. Morris (Ed.), *Parallel distributed processing: Implications for psychology and neuroscience* (pp. 131–181). London: Oxford University Press.

Patterson, K. E., & Shewell, C. (1987). Speak and spell: Dissociations and word-class effects. In M. Coltheart, G. Sartori, & R. Job (Eds.), *The cognitive neuropsychology of language* (pp. 273–294). London: Erlbaum.

Platt, J. R. (1964). Strong inference. *Science, 146,* 347–353.

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

Popper, K. R. (1972). *Objective knowledge.* Oxford, England: Clarendon Press.

Rastle, K., & Coltheart, M. (1998). Whammies and double whammies: The effect of length on nonword reading. *Psychonomic Bulletin & Review, 5,* 277–282.

Rastle, K., & Coltheart, M. (1999). Serial and strategic effects in reading aloud. *Journal of Experimental Psychology: Human Perception and Performance, 25,* 482–503.

Rubenstein, H., Garfield, L., & Millikan, J. A. (1970). Homographic entries in the internal lexicon. *Journal of Verbal Learning and Verbal Behavior, 9,* 487–494.

Rubenstein, H., Lewis, S. S., & Rubenstein, M. A. (1971).

Evidence for phonemic recoding in visual word recognition. *Journal of Verbal Learning and Verbal Behavior, 10,* 645–657.

Seidenberg, M. S. (1993). Connectionist models and cognitive theory. *Psychological Science, 4,* 228–235.

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

Seidenberg, M. S., Waters, G. S., Barnes, M. A., & Tanenhaus, M. K. (1984). When does irregular spelling or pronunciation influence word recognition? *Journal of Verbal Learning and Verbal Behavior, 23,* 383–404.

Van Orden, G. C. (1987). A ROWS is a ROSE: Spelling, sound, and reading. *Memory & Cognition, 15,* 181–198.

Van Orden, G. C. (1991). Phonologic mediation is fundamental to reading. In D. Besner & G. W. Humphreys (Eds.), *Basic processes in reading: Visual word recognition* (pp. 77–103). Hillsdale, NJ: Erlbaum.

Van Orden, G. C., Johnston, J. C., & Hale, B. L. (1988). Word identification in reading proceeds from spelling to sound to meaning. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 14,* 371–386.

Van Orden, G. C., Pennington, B. F., & Stone, G. O. (1990). Word identification in reading and the promise of subsymbolic psycholinguistics. *Psychological Review, 97,* 488–522.

Van Orden, G. C., Stone, G. O., Garlington, K. L., Markson, L. R., Pinnt, G. S., Simonfy, C. M., & Brichetto, T. (1992). "Assembled" phonology and reading: A case study in how theoretical perspective shapes empirical investigation. In R. Frost & L. Katz (Eds.), *Orthography, phonology, morphology, and meaning* (pp. 249–292). Amsterdam: Elsevier.

Appendix A

Item Means (in Milliseconds) for Experiment 1

Target	Primed	Unprimed	Prime	Control	Target	Primed	Unprimed	Prime	Control
chord	470	514	cord	crowd	tobe	517	517	toeb	toib
build	484	500	billed	boiled	mauce	504	542	mawse	malve
sword	418	473	soared	soiled	jeffen	528	503	jephen	jecken
break	460	495	brake	brook	rockses	570	564	roxes	romes
ceiling	465	508	sealing	reeling	zaut	525	513	zawt	zait
heart	439	519	hart	hurt	jeppy	492	506	jeppie	jeppos
dough	548	510	doe	dot	hoken	503	541	hoaken	holken
pear	445	563	pair	pier	fasser	525	577	phasser	chasser
liquor	517	539	licker	limber	reen	494	493	rien	ryen
tied	452	460	tide	till	mawt	498	492	maught	maffet
died	426	467	dyed	deed	roiph	518	612	wroif	sroid
cereal	443	474	serial	aerial	cheener	530	531	cheaner	chenner
thyme	587	603	time	tame	noars	471	519	knores	snocks
yolk	469	515	yoke	your	kwib	527	559	quib	stib
mown	466	541	moan	moon	raim	521	465	rame	rond
soul	441	432	sole	sold	buke	434	582	bewck	boker
bowled	535	541	bold	boss	feen	487	538	phean	smern
great	441	468	grate	grant	beevie	521	562	beavy	besvo
rose	454	479	rows	robs	phurky	593	659	furky	nurky
cruise	468	515	crews	crows	bealie	536	578	beely	bevly
route	495	455	root	roast	zay	489	478	zeigh	zomar
thrown	475	469	throne	throat	nare	477	452	knair	snart
bear	459	447	bare	bark	pumb	591	541	pum	spum
hymn	508	528	him	ham	woal	537	522	wole	wote
bread	479	444	bred	brew	soojie	611	540	pseujy	feejum
steak	423	445	stake	story	doyck	597	577	doick	doack
seize	472	442	seas	sell	pite	510	507	pight	piest
chute	460	613	shoot	short	jestick	510	562	jestik	jestil
earn	465	494	urn	born	trife	515	469	trighf	tridek
wear	499	451	where	west	zair	501	512	zare	zoir
bruise	435	491	brews	brims	keff	519	523	keph	kess
through	485	579	threw	thrust	ratch	498	475	wratch	fratch
phrase	502	528	frays	grams	devave	542	555	devaive	devalve
pour	456	488	poor	port	zapher	515	535	zaffer	zaster
bald	472	495	bawled	bailed	mokes	511	523	moaks	mocks
draught	501	549	draft	drain	nate	475	479	nait	nast
ewe	514	557	you	red	quipher	604	581	quiffer	quisper
suite	467	513	sweet	sheet	saring	562	555	sairing	sapring
queue	505	495	cue	sue	neepped	622	563	kneapped	snerpped
mousse	535	537	moose	morse	rotes	481	507	roats	rorks

(*Appendixes continue*)

Appendix B

Item Means (in Milliseconds) for Experiment 2

Target	Primed	Unprimed	Prime	Control	Target	Primed	Unprimed	Prime	Control
sword	493	467	soard	scard	feen	582	551	phean	smern
break	485	526	braik	bruid	zay	461	479	zeigh	zomar
adage	526	652	adij	aded	beevie	557	618	beavy	besvo
colonel	529	700	kirnal	phynel	nare	514	504	knair	snart
queue	542	523	kue	fue	phurky	668	619	furky	nurky
bored	488	475	bord	borz	bealie	574	610	beely	bevly
racquet	486	587	raket	raist	pumb	573	694	pum	spum
bury	691	629	berie	bernz	buke	630	560	bewck	boker
steak	439	538	staik	styck	woal	526	521	wole	wote
ache	539	498	aik	awt	raim	497	517	rame	rond
mild	427	470	miled	maled	soojie	635	524	pseujy	feejum
align	493	499	aline	alite	doyck	645	632	doick	doack
ghoul	599	602	goole	grone	kwibe	657	592	quibe	stibe
bruise	507	496	brooz	brane	pite	503	527	pight	piest
isle	528	566	ile	ise	noars	533	559	knores	snocks
design	440	519	dezine	devine	jestick	538	573	jestik	jestil
marine	489	537	mareen	marjen	cheener	561	573	cheaner	chenner
soul	417	503	soal	soyl	trife	535	522	trighf	tridek
great	481	455	grait	gript	roiph	558	672	wroif	sroid
guise	550	522	gize	gide	zair	482	573	zare	zoir
yacht	495	563	yot	yor	keff	494	508	keph	kess
died	488	526	dide	dize	mawt	569	527	maught	maffet
phoenix	544	613	feenix	pannix	ratch	493	524	wratch	fratch
cough	423	515	cof	coi	reen	447	500	rien	ryen
mown	587	551	mone	moal	tobe	531	478	toeb	toib
chord	482	518	kord	kard	devave	581	615	devaive	devalve
quay	671	795	kee	iph	pailor	510	493	peilor	poiler
seize	465	498	seez	selz	zapher	496	512	zaffer	zaster
buffet	497	540	buffay	buffah	hoken	522	575	hoaken	holken
cafe	491	480	kafay	larfed	mokes	478	481	moaks	mocks
chorale	422	656	koral	loral	jeppy	496	538	jeppie	jeppos
cuisine	595	567	kwizeen	phyckel	nate	495	499	nait	nast
baggage	505	532	bagij	baygl	zaut	508	490	zawt	zait
fasten	516	520	farsen	fawlen	quipher	639	572	quiffer	quisper
tsar	579	783	zar	kar	rockses	678	617	roxes	romes
choir	558	533	quire	fraze	sairing	558	560	saring	sapring
canoe	492	526	kanoo	dantz	jeffen	585	521	jephen	jecken
loser	461	480	loozer	loone	neeped	537	542	kneaped	snerped
steady	450	466	steddy	sterdy	mauce	479	595	mawse	malve
busy	468	507	bizzy	bordy	rotes	521	511	roats	rorks

Appendix C

Item Means (in Milliseconds) for Experiment 3

Target	Primed	Unprimed	Prime	Control	Target	Primed	Unprimed	Prime	Control
goole	587	543	ghoul	glows	soal	483	511	soul	soil
kue	515	523	queue	suede	farsen	521	544	fasten	fallen
soard	478	483	sword	scored	koral	556	527	chorale	floral
braik	502	540	break	brick	zar	536	540	tsar	afar
adij	760	668	adage	adult	grait	522	525	great	grant
ile	513	512	isle	idle	kanoo	525	561	canoe	valor
dezine	603	586	design	decide	loozer	516	594	loser	lover
aik	510	566	ache	aged	buffay	579	548	buffet	buffer
aline	485	502	align	alike	kord	471	543	chord	fjord
miled	514	523	mild	milk	bizzy	495	500	busy	body
dide	524	564	died	dies	mone	526	567	mown	moon
brooz	497	515	bruise	brains	kwizeen	605	685	cuisine	thimble

Appendix C *(continued)*

Target	Primed	Unprimed	Prime	Control	Target	Primed	Unprimed	Prime	Control
feenicks	673	673	phoenix	picnics	gize	564	615	guise	gable
yot	517	461	yacht	yodel	kee	485	488	quay	disk
staik	503	472	steak	stalk	pirl	518	563	pearl	peril
raket	497	522	racquet	ratchet	kafay	543	613	cafe	rafts
mareen	536	509	marine	margin	steddie	509	498	steady	steeds
berie	560	517	bury	bird	quire	557	539	choir	right
cof	522	472	cough	caught	woome	567	511	womb	worm
kirnal	656	584	colonel	channel	krape	485	523	crepe	drape

Appendix D

Latency (in Milliseconds) and Error Means for Experiment 4

	Primed		Unprimed					Primed		Unprimed			
Target	RT	Error (%)	RT	Error (%)	Prime	Control	Target	RT	Error (%)	RT	Error (%)	Prime	Control
goole	547	0	501	0	ghoul	glows	ghoul	558	20	640	0	goole	grone
kue	596	0	796	40	queue	suede	queue	489	0	470	0	kue	fue
soard	570	0	645	20	sword	scored	sword	426	20	441	20	soard	scard
braik	525	0	478	0	break	brick	break	489	0	544	0	braik	bruid
adij	687	20	796	40	adage	adult	adage	451	80	652	40	adij	aded
ile	507	0	551	0	isle	idle	isle	571	0	545	0	ile	ise
dezine	600	20	667	40	design	decide	design	558	0	416	0	dezine	devine
aik	546	0	490	0	ache	aged	ache	461	0	479	0	aik	awt
aline	455	0	471	0	align	alike	align	512	0	457	0	aline	alite
miled	499	0	429	0	mild	milk	mild	495	0	472	0	miled	maled
dide	513	0	511	20	died	dies	died	490	0	481	0	dide	dize
brooz	579	0	590	0	bruise	brains	bruise	508	0	516	0	brooz	brane
feenicks	665	0	608	20	phoenix	picnics	phoenix	564	0	631	0	feenicks	pannix
yot	472	0	573	0	yacht	yodel	yacht	496	0	577	0	yot	yor
staik	465	0	515	0	steak	stalk	steak	507	0	509	20	staik	styck
raket	511	0	522	0	racquet	ratchet	racquet	557	0	578	0	raket	raist
mareen	562	0	480	0	marine	margin	marine	432	0	613	0	mareen	marjen
berie	666	0	510	0	bury	bird	bury	502	0	552	0	berie	bernz
cof	503	0	515	0	cough	caught	cough	491	0	510	0	cof	coi
kirnal	721	0	670	0	colonel	channel	colonel	582	20	781	60	kirnal	phynel
soal	539	0	522	40	soul	soil	soul	517	0	419	0	soal	soyl
farsen	507	20	539	20	fasten	fallen	fasten	519	0	494	0	farsen	fawlen
koral	540	40	505	0	choral	floral	chorale	685	40	693	20	koral	loral
zar	612	0	557	0	tsar	afar	tsar	646	0	631	20	zar	kar
grait	517	0	481	0	great	grant	great	507	0	496	0	grait	gript
kanoo	500	20	485	0	canoe	valor	canoe	505	0	507	0	kanoo	dantz
loozer	593	0	450	0	loser	lover	loser	482	0	459	0	loozer	looner
buffay	608	0	596	0	buffet	buffer	buffet	534	0	550	0	buffay	buffah
kord	517	0	497	0	chord	fjord	chord	466	0	550	20	kord	kard
bizzy	535	0	499	0	busy	body	busy	454	0	540	0	bizzy	bordy
mone	567	0	565	20	mown	moon	mown	579	40	578	0	mone	moal
kwizeen	623	0	704	80	cuisine	thimble	cuisine	480	0	556	0	kwizeen	phickel
gize	620	0	574	60	guise	gable	guise	415	20	628	40	gize	gide
kee	646	0	546	20	quay	disk	quay	502	40	629	80	kee	iph
pirl	605	0	599	20	pearl	peril	pearl	477	0	509	0	pirl	phel
kafay	572	0	624	0	cafe	rafts	cafe	421	0	530	0	kafay	larfed
steddie	553	0	475	0	steady	steeds	steady	417	0	486	0	steddie	sterdy
quire	546	0	511	0	choir	right	choir	586	0	600	0	quire	fraze
woome	499	0	516	0	womb	worm	womb	488	0	498	20	woome	woarz
krape	582	0	511	0	crepe	drape	crepe	457	0	551	0	krape	trupe

Note. RT = reaction time.

(*Appendixes continue*)

Appendix E

Item Means (in Milliseconds) for Experiment 5

Target	Primed	Unprimed	Prime	Control
wayd	575	598	waid	waud
cozie	603	548	coezy	cophs
leeph	533	658	lefe	lene
rade	639	542	wrayd	crait
fyckel	767	661	phickel	maicker
knede	612	556	nead	nerv
bate	607	537	bayt	baik
rayn	585	552	rane	raze
throo	626	523	thrue	thred
staik	599	546	stayk	stauk
brane	591	532	brayn	braiv
freaz	602	588	phreze	strete
kwoat	708	634	kwote	kwota
cheak	661	645	cheke	chepe
raik	613	579	wrayk	wrack
hoez	596	613	hoze	hors
kwyre	762	730	kwire	kwere
brayk	626	619	braick	brakit
roez	646	589	roze	rozy
phlue	709	622	floo	cloo
fayd	639	627	phaid	slaid
chooz	585	570	chuze	cheze
leest	540	655	leesed	leesez
fraze	559	636	phraiz	strate
leev	545	557	leve	lede
bote	617	637	boet	bost
nife	535	620	kniphe	gnitee
holee	543	616	hoalee	hockee
meak	512	537	meke	mene
fleze	556	583	phleaz	relese
kain	554	599	cayn	cann
fansie	633	662	phansey	chansez
kanoo	552	630	canue	dantz
larph	569	569	lahf	layk
phorm	655	667	fawm	faim
laiz	567	588	layz	lamz
brooz	635	591	bruze	breze
daiz	558	631	dayz	dabz
reech	591	560	wreech	preech
skroo	661	601	skrue	skrap

Appendix F

Item Data (in Processing Cycles) for Simulation 1

Target	Primed	Unprimed	Prime	Control
break	76	77	brake	brook
dough	86	87	doe	dot
thyme	75	78	time	tame
mown	89	90	moan	moon
queue	87	88	cue	sue
chord	97	97	cord	crowd
heart	80	81	hart	hurt
pear	88	89	pair	pier
tied	77	78	tide	till
died	78	78	dyed	deed
yolk	95	97	yoke	your
soul	83	83	sole	sold
bowled	91	93	bold	boss
great	71	73	grate	grant
cruise	80	80	crews	crows
route	82	84	root	roast
thrown	76	76	throne	throat
bear	84	85	bare	bark
hymn	75	76	him	ham
bread	75	76	bred	brew
seize	96	98	seas	sell
chute	100	101	shoot	short
earn	95	95	urn	born
wear	77	80	where	west
bruise	78	79	brews	brims
through	86	87	threw	thrust
phrase	77	77	frays	grams
suite	83	85	sweet	sheet
mousse	92	92	moose	morse
wayd	129	129	waid	waud
cheak	139	140	cheke	chepe
phlue	158	158	floo	cloo
fraze	163	163	phraiz	strate
phorm	149	149	fawm	faim
leeph	160	162	lefe	lene
rade	151	151	wrayd	crait
knede	174	174	nead	nerv
rayn	126	126	rane	raze
throo	129	132	thrue	thred
staik	143	142	stayk	stauk
brane	—	—	brayn	braiv
freaz	147	147	phreze	strete
raik	134	133	wrayk	wrack
hoez	137	137	hoze	hors
fayd	138	138	phaid	slaid
leev	132	133	leve	lede
bote	138	139	boet	bost
meak	128	130	meke	mene
kain	130	129	cayn	cann
larph	159	159	lahf	layk
laiz	138	138	layz	lamz
brooz	146	146	bruze	breze
daiz	139	139	dayz	dabz
reech	144	145	wreech	preech
skroo	150	151	skrue	skrap

Note. Dashes indicate errors by the dual-route cascaded model.

Appendix G

Item Data (in Processing Cycles) for Simulation 2

Target	Primed	Unprimed	Prime	Control
steak	79	80	staik	styck
great	72	73	grait	gript
died	78	79	dide	dize
mild	87	88	miled	maled
bored	78	79	bord	borz
guise	84	84	gize	gide
isle	—	—	ile	ise
yacht	94	95	yot	yor
chord	98	98	kord	kard
seize	97	98	seez	selz
tsar	—	—	zar	kar
soul	83	83	soal	soyl
pearl	95	95	pirl	phel
ghoul	85	85	goole	grone
queue	88	88	kue	fue
sword	91	91	soard	scard
bruise	79	79	brooz	brane
crepe	83	83	krape	trupe
break	76	77	braik	bruid
cough	76	76	cof	coi
quay	91	91	kee	iph
ache	108	108	aik	awt
mown	91	91	mone	moal
womb	91	91	woome	woarz
goole	149	150	ghoul	glows
kue	120	122	queue	suede
soard	149	150	sword	scored
brooz	145	146	bruise	brains
krape	172	172	crepe	drape
braik	137	137	break	brick
cof	118	119	cough	caught
kee	125	126	quay	disk
aik	120	120	ache	aged
mone	144	144	mown	moon
woome	147	147	womb	worm
miled	139	140	mild	milk
dide	129	132	died	dies
grait	136	139	great	grant
staik	140	142	steak	stack
soal	118	119	soul	soil

Note. Dashes indicate errors by the dual-route cascaded model.

Received March 3, 1997
Revision received February 2, 1998
Accepted March 23, 1998 ■