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Masked phonological priming effects in English: Are they real? Do they matter? ☆

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Abstract

For over 15 years, masked phonological priming effects have been offered as evidence that phonology plays a leading role in visual word recognition. The existence of these effects—along with their theoretical implications—has, however, been disputed. The authors present three sources of evidence relevant to an assessment of the existence and implications of these effects. First, they present an exhaustive meta-analytic literature review, in which they evaluate the strength of the evidence for masked phonological priming effects on English visual word processing. Second, they present two original experiments that demonstrate a small but significant masked priming effect on English visual lexical decision, which persists in conditions that may discourage phonological recoding. Finally, they assess the theory of visual word recognition offered by the DRC model (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001) in the context of their empirical data. Through numerous simulations with this model, they argue that masked phonological priming effects might best be captured by a weak phonological (i.e., dual-access) theory in which lexical decisions are made on the basis of phonological information.

Keywords: Visual word recognition; Phonology; Masked phonological priming; DRC model; Reading aloud

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1. Introduction

One of the most significant controversies in the theory of reading concerns the role of phonology in visual word recognition. There is broad consensus that the recognition of a visually presented word can be influenced by the computation of its phonology. Perspectives differ considerably, however, with regard to *the extent to which* phonology influences the recognition of printed words.

The dominant perspective on visual word processing, which we refer to as "weak phonological" (after Coltheart et al., 2001), posits that the recognition of printed words proceeds both through a direct orthographic pathway and through an indirect phonologically mediated pathway. It is through the indirect phonologically mediated pathway that phonological influences on visual word recognition may arise. Though they allow for phonological influences, however, theories of this nature consider the recognition of printed words to be a process driven primarily by the analysis of orthographic form. Indeed, these theories are described as "weak" precisely because phonological influences on recognition are viewed as secondary and nonessential.

The major alternative to weak phonological theories of visual word recognition is offered by the group of "strong phonological" theorists (e.g., Drieghe & Brysbaert, 2002; Frost, 1998; Lukatela & Turvey, 1994a, 1994b; Van Orden, 1987). These theorists believe that the analysis of phonological information plays a dominant and leading role in visual word recognition, and have gone so far as to suggest that it may be an obligatory component of this process (i.e., visual word recognition *cannot occur* in the absence of a computed phonological representation; see e.g., Coltheart et al., 2001; Frost, 1998 for discussion). Theories of this nature postulate an initial assembly procedure in which the orthographic form is rapidly converted to a phonological code. It is this phonological representation, not the activation of an orthographic representation, which supports visual word recognition.

This article examines a phenomenon that could prove pivotal in adjudicating between these theoretical perspectives: masked phonological priming of visual word recognition (e.g., Ferrand & Grainger, 1992; Perfetti, Bell, & Delaney, 1988). Phonological priming effects on visual word recognition are revealed when responses to target words (e.g., CLIP) are faster or more accurate (in e.g., lexical decision, perceptual identification) when those targets are preceded by phonologically identical nonword primes (e.g., klip) than when they are preceded by phonologically dissimilar orthographic control primes (e.g., plip). These priming effects are thought to arise because phonological primes activate the lexical representations associated with their corresponding targets, thus effecting savings in the time that it takes for those target representations to reach a critical recognition threshold. Several investigators have now reported these effects under conditions in which primes have been masked and presented so briefly that they are unavailable for conscious report (e.g., Berent & Perfetti, 1995; Ferrand & Grainger, 1992; Lukatela, Frost, & Turvey, 1998; Perfetti et al., 1988; Perfetti & Bell, 1991). The fact that these effects are observed when primes are presented with such brevity and with visual masking has led these and other researchers to infer that the phonological assembly of a visual stimulus (in this case, the prime) must occur rapidly in the recognition process, and perhaps even automatically—where 'automatically' has been defined as 'without intention' (Humphreys, Evett, & Taylor, 1982), 'routine' (Perfetti et al., 1988), or 'nonoptional' (Perfetti et al., 1988).

Many influential theorists (e.g., Drieghe & Brysbaert, 2002; Frost, 1998; Lukatela & Turvey, 1994a, 1994b; Van Orden et al., 1992; Xu & Perfetti, 1999) have gone on to argue that the evidence for rapid and automatic phonological assembly provided by masked phonological priming effects is inconsistent with weak phonological theories of visual word recognition—at least some of which have described phonological assembly as a resource-demanding process (e.g., Paap & Noel, 1991) that operates relatively slowly (e.g., Harm & Seidenberg, 2004) and perhaps even serially (e.g., Rastle & Coltheart, 1999). These theorists have instead argued that masked phonological priming effects provide a primary source of evidence for a strong phonological perspective on visual word recognition, in which the rapid assembly of phonological information plays a leading and perhaps even obligatory role in visual word recognition. For example,

> . . .we take the primary and initial source of lexical activation in English to be phonological. The role of orthographic codes is then taken to be that of refining the lexical activation begun by phonology (Lukatela & Turvey, 1994a, p. 108).

> Over the last two decades, a number of studies using brief-stimulus-presentation and masked-stimulus-presentation paradigms have reported phonological effects in visual word identification. . .. These effects have been taken as major evidence for a rapid, automatic, and obligatory phonological process during lexical access. (Xu & Perfetti, 1999, p. 26).

> . . .leave little room for any hypothesis other than that which identifies a word's phonology as the initial, and perhaps solitary, code by which a word accesses its representation in the internal lexicon (Lukatela & Turvey, 1994a, p. 122).

Not all theorists of visual word recognition share this position on the significance of masked phonological priming effects, however. Indeed, the leading models of visual word processing over the past decade (Coltheart et al., 2001; Harm & Seidenberg, 2004; Plaut, McClelland, Seidenberg, & Patterson, 1996; Zorzi, Houghton, & Butterworth, 1998) have all been of the weak phonological variety (this fact is perhaps not so surprising, given that no strong phonological theory has ever been implemented as a computational model). Further, not a single one of these weak phonological theories has deemed masked phonological priming as a benchmark phenomenon requiring explanation. Given an effect that is potentially so central to our basic understanding of visual word recognition, what are the reasons for these highly divergent views?

The most immediate problem with assessing the implications of masked phonological priming effects is that there is serious disagreement on whether these effects actually exist, especially where the English findings are considered. For example, although Coltheart et al. (2001) acknowledged that "whether the [DRC] model could actually simulate these effects needs to be investigated," they argued that "there currently exist some difficulties concerning exactly what the effects are that would need to be simulated" (p. 250). They questioned whether the evidence for masked phonological priming effects is sufficiently compelling, reflecting that the effects appear to come and go as a function of factors such as relatedness proportion (Brysbaert & Praet, 1992; Verstaen, Humphreys, Olson, & d'Ydewalle, 1995) and even the lighting conditions of the testing room (Lukatela et al., 1998; Lukatela, Frost, & Turvey, 1999). Frost, Ahissar, Gotesman, and Tayeb (2003, p. 48) described the literature on masked phonological priming effects similarly, citing "controversial inconsistencies" in results from backward masking and "an even more inconsistent pattern of results" from forward masking. These descriptions of the available published data have been accompanied by unpublished datasets failing to replicate masked phonological priming phenomena (e.g., Coltheart & Woollams, unpublished; Forster & Mahoney, unpublished). Most recently, Holyk and Pexman (2004) reported two virtually identical experiments testing for masked phonological priming effects on visual lexical decision—only in one of which did they observe a phonological effect. Before one can consider the theoretical implications of masked phonological priming effects, one must establish that there is a real effect to be considered.

The second reason for the divergent views on the implications of masked phonological priming effects is that there are a range of possible weak phonological theories against which these effects could be measured, and refuting one theory may not necessarily refute another. One example of this problem can be found in Frost's (1998) influential manifesto on the role of phonology in visual word recognition. Frost (1998) argued that substantiating the most significant claim of strong phonological theories (i.e., that the assembly of phonology plays an obligatory role in visual word perception) presents serious challenges. For one, demonstrating phonological involvement in one visual processing task does not preclude its absence in another. Further, the mere demonstration that a phonological code is rapidly assembled in visual word processing does not necessarily indicate that it serves any functional purpose in recognition. Frost (1998) therefore advocated the strategy of attempting to falsify weak phonological theories, characterizing the weak phonological position thus:

> ...from the dual-access point of view, phonological processing is expected to be revealed in tasks that explicitly require it.... In contrast, tasks that do not explicitly involve the phonological properties of the stimulus do not result in phonological coding; even if they do, this coding being relatively slow has no substantial effect on the lexical processes under investigation. (Frost, 1998, p. 76)

Frost (1998) claimed that one could refute the weak phonological position "...by demonstrating that phonological recoding is present even in tasks in which it is not required or in which it hinders performance" (p. 76). However, even the earliest weak phonological theories (e.g., Coltheart, Davelaar, Jonasson, & Besner, 1977) recognized the routine nature of phonological recoding and its significant influence on visual word processing:

> ...our point is that the existence of a phonological Stroop effect suggests strongly that phonological encoding of legal nonwords, and hence of words too, is an automatic and very rapid process. This is evident from the results of Experiment 1 [which demonstrated a pseudohomophone effect on visual lexical decision], since the phonological encoding there was rapid enough to interfere with lexical decisions (Coltheart et al., 1977, p. 549).

One might thus view a refutation of Frost's (1998) characterization of the weak phonological position as a somewhat hollow victory.

Perhaps a more persuasive strategy would be to evaluate masked phonological priming effects against one or more of the weak phonological theories that have been implemented as computational models (Coltheart et al., 2001; Harm & Seidenberg, 2004). In each of these models, the activation of (localist or distributed) representations in the body of knowledge at which words are recognized is influenced jointly by processing along direct orthographic and indirect phonologically mediated routes. Under normal reading conditions, phonological processing *always* occurs (i.e., there is no sense in either model that phonological processing occurs only when it is required). Further, neither of these models has any obvious features that would prohibit a simulation of masked phonological priming. Indeed, despite their weak-phonological architectures, these models have yielded favourable outcomes with regard to their ability to account for phonological effects on visual word processing. Harm and Seidenberg (2004), in particular, have demonstrated that their weak phonological theory provides a sufficient account of a range of classic phonological effects on word recognition involving both homophones (e.g., Van Orden, 1987) and pseudohomophones (e.g., Van Orden, Johnston, & Hale, 1988). Similarly, using an early version of the DRC model, Coltheart and Rastle (1994) produced a small simulation of the pseudohomophone effect on lexical decision, and even expressed confidence with regard to the potential for simulating masked phonological priming effects. They explained,

> …nonlexically derived phonological representations of printed stimuli gain access to the visual word recognition system very early on in processing, certainly earlier than the point at which lexical decisions are made or a reading-aloud response occurs…. Hence, we are optimistic about the capacity of the DRC model to simulate phonological masked priming effects such as those reported by Perfetti and Bell (1991) and Ferrand and Grainger (1992). (Coltheart & Rastle, 1994, p. 1202).

Clearly, either of these weak phonological theories may be significantly more robust to masked phonological priming phenomena than the characterization, for example, put forth by Frost (1998).

In this article, we contribute to a resolution of these empirical and theoretical issues. Our first aim is to determine whether there is a masked phonological priming effect on English visual word recognition. English is of particular interest in this context not only because the major implemented models of skilled reading all deal with English stimuli but also because it provides a relatively strong test case for the existence of masked phonological priming effects (being characterized by a substantial degree of spelling-sound irregularity; see e.g., Ziegler & Goswami, 2005; Ziegler, Perry, & Coltheart, 2003 for discussion). To meet our empirical aim, we first conduct a meta-analytic literature review that describes the precise effects obtained in every published study investigating masked phonological priming in English. From this review, we establish the magnitude, effect size, and variability of masked phonological priming phenomena across various tasks, and identify possible methodological problems within relevant studies that may limit their persuasiveness. We follow this review by conducting two new masked phonological priming experiments, which address the methodological concerns unearthed in our literature review.

The second aim of this article is to contribute to a fuller understanding of the theoretical implications of masked phonological priming effects than has so far been possible. Our approach is similar to that advocated by Frost (1998): to evaluate the weak phonological perspective on visual word recognition in the context of masked phonological priming effects. For several reasons, we chose the weak phonological theory of visual word recognition implemented as the DRC model (Coltheart et al., 2001) as an excellent candidate for evaluation. In our view, this computational model provides a particularly good target for investigation both because it has been studied extensively against benchmark effects of visual word recognition and because it has been highly influential in this area for a number of years. Furthermore, the DRC model has been made available for public evaluation (see http://www.maccs.mq.edu.au/~max/DRC), thus allowing us to examine its performance explicitly on the actual stimuli used in our experiments. Finally, the DRC model is controlled by a number of parameters, each of which can be altered independently. The fact that such parametric alterations are possible in the implemented model provides scope for an evaluation of a number of potential theories of visual word recognition, ranging from theories that postulate a very "weak" phonological contribution to those that postulate a "stronger" phonological contribution to this process.

2. The masked phonological priming effect in English: What are the data?

Five experimental paradigms have been used to examine the influence of tachistoscopically presented homophonic stimuli on the processing of English target words: forward-masked perceptual identification, backward-masked perceptual identification, forward-masked reading aloud, forward-masked lexical decision, and text reading (eye movements). Though our own experimental work will use the forward-masked visual lexical decision task, we review evidence from all five of the paradigms both for completeness and to identify whether the appearance of the masked phonological priming effect might be related to particular characteristics of the performance tasks themselves. Further, we include *all* studies that fall into one of the five paradigms, even though some of these studies claimed to look for the boundary conditions of the masked phonological priming effect by using, for example, very short stimulus-onset-asynchronies, homophones in the stimulus list, or parafoveal nonword stimuli. This decision was made because researchers across paradigms have not been consistent in their views concerning the conditions under which the masked phonological priming effect occurs. Our discussion of each experimental paradigm is accompanied by tables presenting various details about each experiment considered in the meta-analysis. To enable readers to ask specific questions about the nature of the masked priming effect, we present more information concerning each experiment in the tables than we discuss in text (e.g., prime exposure duration, target duration). Our own purpose is to establish the empirical basis for a masked phonological priming effect in English, however, and so we do not entertain these more specific questions here.

2.1. Forward-masked perceptual identification

In the forward-masked perceptual identification procedure (Humphreys et al., 1982), a forward pattern mask (e.g., #########) is followed immediately by a briefly presented word or nonword prime stimulus, which is then replaced by a briefly presented target stimulus and a backward pattern mask. Prime and target are presented in different cases, and participants are asked to identify the target word. The dependent variable is the percentage of target words correctly identified. Three papers (18 experiments) using this paradigm are summarized in Table 1: Humphreys et al. (1982), Perfetti and Bell (1991, Experiment 3), and Booth, Perfetti, and MacWhinney (1999).[1]

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[1] Booth et al. (1999) reported phonological priming effects in different age groups of children. We describe here only data collected from the older children (6th grade).

Table 1

Studies of English phonological priming, using the forward-masked perceptual identification paradigm

Study	Target duration (ms)	Prime lexicality	Prime duration (ms)	% Correct: phonological	% Correct: graphemic	% Correct: unrelated	Phonological–graphemic	Phonological–unrelated
Humphreys et al. (1982), Exp. 1	35	Word	35	56	47	43	9	13
Humphreys et al. (1982), Exp. 2	40	Word	40	58	47	45	11	13
Humphreys et al. (1982), Exp. 3	35	Nonword	35	50	48	42	2	8
Humphreys et al. (1982), Exp. 4a	40	Word	40	64	53	50	11	14
Humphreys et al. (1982), Exp. 4b	40	Word	40	57	47	50	10	7
Perfetti and Bell (1991), Exp. 2a	30	Nonword	25	34	34	30	0	4
Perfetti and Bell (1991), Exp. 2b	30	Nonword	35	54	51	33	3	21
Perfetti and Bell (1991), Exp. 2c	30	Nonword	45	52	44	20	8	32
Perfetti and Bell (1991), Exp. 2d	30	Nonword	55	54	44	18	10	36
Perfetti and Bell (1991), Exp. 2e	30	Nonword	65	46	37	18	9	28
Booth et al. (1999), Exp. 1a	30	Nonword	30	76	70	33	6	43
Booth et al. (1999), Exp. 1b	30	Nonword	30	65	48	28	17	37
Booth et al. (1999), Exp. 1c	30	Nonword	30	65	53	30	12	35
Booth et al. (1999), Exp. 1d	30	Nonword	30	54	39	26	15	28
Booth et al. (1999), Exp. 2a	60	Nonword	60	71	69	18	2	53
Booth et al. (1999), Exp. 2b	60	Nonword	60	56	42	22	14	34
Booth et al. (1999), Exp. 2c	60	Nonword	60	62	52	20	10	42
Booth et al. (1999), Exp. 2d	60	Nonword	60	52	37	17	15	35

Note: Exp., Experiment.

All of the studies presented in Table 1 compared identification accuracy when targets were preceded by homophonic word or nonword primes (e.g., maid–MADE, brane–BRAIN), graphemic controls (e.g., mark–MADE, brans–BRAIN), and unrelated controls (ship–MADE, thoke–BRAIN). The phonological priming effect is calculated by comparing identification accuracy in the homophone condition with identification accuracy in the graphemic control condition. Taken together, these studies suggest a reliable phonological priming effect across studies of 9.11% ($SD = 4.89$, $t(17) = 7.91$, $p < .01$).

2.2. Backward-masked perceptual identification

In backward-masked perceptual identification, a forward pattern mask is followed by a briefly presented target word; this target is followed by a briefly presented verbal mask, and finally a pattern mask. Verbal masks are generally nonwords (but see Tan & Perfetti, 1999, who used words of low frequency), and are presented in a different case to the target. The dependent variable is the percentage of target words correctly identified. Six articles (18 experiments) using this paradigm are summarized in Table 2: Berent and Perfetti (1995), Perfetti et al. (1988), Perfetti and Bell (1991), Tan and Perfetti (1999), Verstaen et al. (1995), and Xu and Perfetti (1999).

Comparing identification accuracy in the homophone and graphemic control mask conditions, Table 2 suggests a statistically reliable phonological priming effect of 3.89%, ($SD = 5.54$, $t(17) = 2.98$, $p < .01$).

2.3. Forward-masked reading aloud

In the forward-masked reading aloud procedure, a pattern mask is followed immediately by a briefly presented prime; this prime is masked by a target, which participants are required to read aloud. The dependent variable is the time taken to read the target word aloud. Four articles (22 experiments) using the forward-masked reading aloud task are summarized in Table 3: Berent and Perfetti (1995), Lukatela and Turvey (1994b, 2000), and Bowers, Vigliocco, and Haan (1998). Although Bowers et al. (1998) appears in Table 3, it is not included in average analyses because a graphemic control condition was not included (and therefore it is not possible to calculate the phonological priming effect). Data from this table suggests an average phonological priming effect of 10 ms in the reading aloud task, which is reliable across studies ($SD = 7.28$, $t(19) = 6.08$, $p < .01$).

2.4. Forward-masked visual lexical decision

In forward-masked visual lexical decision, a pattern mask is followed by a briefly presented prime, and this prime is masked by a target that is presented in a different case. Participants are required to make a visual lexical decision about the target. Seven articles (21 experiments) are presented in Table 4: Berent (1997), Grainger and Ferrand (1994), Lukatela and Turvey (2000), Davis, Castles, and Iakovidis (1998, Experiment 1), Lukatela et al. (1998), Bowers et al. (1998), and Holyk and Pexman (2004).

Data in Table 4 suggests a phonological priming effect of 10 ms, which is reliable across studies ($SD = 17.12$, $t(18) = 2.45$, $p < .05$). Once again Bowers et al. (1998) is not included in this average, since they did not use a graphemic control condition. Further, the data

Table 2
Studies of English phonological priming, using the backward-masked perceptual identification paradigm

Study	Target duration (ms)	Prime lexicality	Prime duration (ms)	% Correct: phonological	% Correct: graphemic	% Correct: unrelated	Phonological–graphemic	Phonological–unrelated
Perfetti et al. (1988), Exp. 1a	30	Nonword	25	55	49	32	6	23
Perfetti et al. (1988), Exp. 1b	33	Nonword	16	64	61	53	**3**	11
Perfetti et al. (1988), Exp. 2	45	Nonword	30	54	45	32	9	22
Berent and Perfetti (1995), Exp. 1a	15	Nonword	30	32	17	2	15	30
Berent and Perfetti (1995), Exp. 1b	30	Nonword	30	68	69	48	−1	20
Berent and Perfetti (1995), Exp. 1c	45	Nonword	60	82	74	57	8	25
Xu and Perfetti (1999), Exp. 1	30	Nonword	58	50	43	24	7	26
Xu and Perfetti (1999), Exp. 2	30	Nonword	62	81	78	60	3	21
Perfetti and Bell (1991), Exp. 1a	35	Nonword	30	27	21	7	6	20
Perfetti and Bell (1991), Exp. 1b	45	Nonword	30	48	43	20	5	28
Perfetti and Bell (1991), Exp. 1c	55	Nonword	30	59	55	37	4	22
Verstaen et al. (1995), Exp. 1	42	Nonword	28	69	65	53	4	16
Verstaen et al. (1995), Exp. 2	42	Nonword	28	55	56	43	−1	12
Verstaen et al. (1995), Exp. 3	56	Nonword	28	78	81	70	−3	8
Verstaen et al. (1995), Exp. 4a	42	Nonword	28	65	59	51	6	14
Verstaen et al. (1995), Exp. 4b	42	Nonword	28	60	60	51	0	9
Tan and Perfetti (1999), Exp. 1	28	Word	28	56	66	32	−10	24
Tan and Perfetti (1999), Exp. 2	42	Word	28	88	79	70	9	18

Note: Exp., Experiment.

Table 3
Studies of English phonological priming, using the forward-masked reading aloud paradigm

Study	Target duration (ms)	Prime lexicality	Prime duration (ms)	RT: phonological	RT: graphemic	RT: unrelated	Graphemic– phonological	Unrelated– phonological
Berent and Perfetti (1995), Exp. 6a	150	Nonword	60	766	779	835	13	69
Berent and Perfetti (1995), Exp. 6b	90	Nonword	30	667	670	727	3	60
Berent and Perfetti (1995), Exp. 7a	60	Nonword	15	561	554	574	−7	13
Berent and Perfetti (1995), Exp. 7b	60	Nonword	30	579	593	585	14	6
Lukatela and Turvey (2000), Exp. 3a	400	Nonword	21 + 13	524	531	541	7	17
Lukatela and Turvey (2000). Exp. 3b	400	Nonword	21 + 13	522	531	536	9	14
Lukatela and Turvey (2000), Exp. 3c	400	Nonword	21 + 13	558	576		18	
Lukatela and Turvey (2000), Exp. 4a	215	Nonword	57	510	527		17	
Lukatela and Turvey (2000), Exp. 4b	215	Nonword	57	517	529		12	
Lukatela and Turvey (2000), Exp. 4c	215	Nonword	57	500	508		8	
Bowers et al. (1998), Exp. 5a	500	Word (HF)	50	504		525		21
Bowers et al. (1998), Exp. 5b	500	Word (LF)	50	487		520		33
Lukatela and Turvey (1994b), Exp. 1a	400	Word (HF)	30	549	563	578	14	29
Lukatela and Turvey (1994b), Exp. 1b	400	Word (LF)	30	542	556	569	14	27
Lukatela and Turvey (1994b), Exp. 2a	400	Word (HF)	60	568	594	593	26	25
Lukatela and Turvey (1994b), Exp. 2b	400	Word (LF)	60	558	573	580	15	22
Lukatela and Turvey (1994b), Exp. 4a	400	Nonword	60	551	559	574	8	23
Lukatela and Turvey (1994b), Exp. 4b	400	Nonword	60	550	548	573	−2	23
Lukatela and Turvey (1994b), Exp. 6a	400	Nonword	30 + 30	518	528	538	10	20
Lukatela and Turvey (1994b), Exp. 6b	400	Nonword	30 + 30	509	518	526	9	17
Lukatela and Turvey (1994b), Exp. 7a	400	Nonword	18 + 18	530	536	542	6	12
Lukatela and Turvey (1994b), Exp. 7b	400	Nonword	18 + 18	525	529	531	4	6

Note: Exp., Experiment; HF, high frequency; LF, low frequency.

Table 4
Studies of English phonological priming, using the forward-masked lexical decision paradigm

Study	Target duration (ms)	Prime lexicality	Prime duration (ms)	RT: phonological	RT: graphemic	RT: unrelated	Graphemic–phonological	Unrelated–phonological
Berent (1997), Exp. 1	142	Nonword	43	633	653	637	20	4
Berent (1997), Exp. 2	142	Nonword	43	679	704	692	25	13
Grainger and Ferrand (1994), Exp. 3	>500	Word (HF)	57	617	670	648	53	31
Lukatela and Turvey (2000), Exp. 1a	72	Nonword	14	569	583		14	
Lukatela and Turvey (2000), Exp. 1b	72	Nonword	14	571	567		−4	
Davis et al. (1998), Exp. 1	710	Both	57	570	562	565	−8	−5
Davis et al. (1998), Exp. 3a	710	Nonword	57	541	546	545	5	4
Davis et al. (1998), Exp. 3b	710	Nonword	57	527	550	540	23	13
Lukatela et al. (1998), Exp. 1a	545	Nonword	43	595	599		4	
Lukatela et al. (1998), Exp. 1b	545	Nonword	57	597	619		22	
Lukatela et al. (1998), Exp. 1c	545	Nonword	72	548	567		19	
Lukatela et al. (1998), Exp. 3	545	Nonword	57	531	546		15	
Lukatela et al. (1998), Exp. 5	72	Nonword	29	547	546		−1	
Bowers et al. (1998), Exp. 5c	500	Word (HF)	50	591		608		17
Bowers et al. (1998), Exp. 5d	500	Word (LF)	50	574		570		−4
Holyk and Pexman (2004), Exp. 1a.1	130	Nonword	15	562	547	591	−15	29
Holyk and Pexman (2004), Exp. 1a.2	130	Nonword	15	566	572	595	6	29
Holyk and Pexman (2004), Exp. 1b.1	130	Nonword	15	558	585	633	27	75
Holyk and Pexman (2004), Exp. 1b.2	130	Nonword	15	578	561	601	−17	23
Holyk and Pexman (2004), Exp. 2a	130	Nonword	15	615	612	657	−3	42
Holyk and Pexman (2004), Exp. 2b	130	Nonword	15	603	601	641	−2	38

Note: Exp., Experiment; HF, high frequency; LF, low frequency.

from Grainger and Ferrand (1994) should be treated with some caution, because their 53 ms priming effect was based upon a between-target comparison.

2.5. Text reading

A final paradigm that has been used to investigate the effect of early phonological influences on the identification of written words involves the tracking of eye movements when words in parafoveal vision are manipulated. Pollatsek, Lesch, Morris, and Rayner (1992) asked participants to read sentences such as "The generous man gave every cent to charity," but while the target word "cent" remained in parafoveal vision, it was replaced with a homophone ("sent") or a graphemic control. Pollatsek et al. (1992) measured target gaze duration as a function of the type of parafoveal prime. In three subsequent articles (Lee, Binder, Kim, Pollatsek, & Rayner, 1999a; Lee, Rayner, & Pollatsek, 1999b; Rayner, Sereno, Lesch, & Pollatsek, 1995), this technique was modified slightly such that the target word was masked while it remained in parafoveal vision. The moment that the eyes landed on the target, it was changed very briefly to a prime, before changing back again to the target. Once again, target gaze duration was the dependent variable. Data from these four articles (28 experiments) are summarized in Table 5.

Comparing gaze durations in the homophone and graphemic control conditions, Table 5 suggests a phonological effect of 8 ms, which is reliable across studies ($SD = 19.93$, $t(27) = 2.13$, $p < .05$). This paradigm deviates somewhat from the others, however, because there are strong indications that the phonological priming effect is larger for (high-frequency) word primes than for nonword primes (see Lee et al., 1999a).

2.6. Effect size calculation

To compare effect sizes across the different paradigms, we calculated a standardized effect-size measure. The measure chosen was the product-moment correlation (r), expressed as the point-biserial correlation between the dummy-coded conditions ($0 =$ homophonic, $1 =$ orthographic control) and the dependent variable (accuracy or latency). A r value of 0 means that there is no reliable difference between conditions; a r value close to 1 means that nearly all variability in the dependent measure is due to the experimental manipulation. Usually, a value of $r = .1$ is considered a small effect (1% of the variance accounted for by the manipulation), a value of $r = .3$ is considered a medium effect (9% variance accounted for), and a value of $r = .5$ is considered a large effect (25% of the variance accounted for). Rosnow and Rosenthal (e.g., Rosnow & Rosenthal, 1996; Rosnow, Rosenthal, & Rubin, 2000) have advocated the use of the r measure because it is easy to understand, it is versatile, and it is calculated in the same manner for repeated and unrepeated designs (which is not the case for Cohen's d statistic). When only two conditions are compared with one another (as was the case for our meta-analysis), the r statistic can be calculated with the equations

$$r = \sqrt{\frac{t^2}{t^2 + df_{\text{within}}}} \quad \text{and } r = \sqrt{\frac{F}{F + df_{\text{error}}}}.$$

Thus, if a particular study reported a significant difference between the phonological and graphemic control conditions of $t(19) = 2.094$, $p < .05$, we calculated r as

Table 5
Studies of English phonological priming, using the text reading paradigm

Study	Target duration	Prime lexicality	Prime duration (ms)	RT: phonological	RT: graphemic	RT: unrelated	Graphemic–phonological	Unrelated–phonological
Rayner et al. (1995), Exp. 1a	Reading time	Word	36	370	400	432	30	62
Rayner et al. (1995), Exp. 1b	Reading time	Nonword	36	378	405	411	27	33
Rayner et al. (1995), Exp. 2a	Reading time	Word	30	370	371	400	1	30
Rayner et al. (1995), Exp. 2b	Reading time	Nonword	30	368	366	406	−2	38
Rayner et al. (1995), Exp. 3a	Reading time	Word	24	349	351	379	2	30
Rayner et al. (1995). Exp. 3b	Reading time	Nonword	24	358	349	376	−9	18
Lee et al. (1999a), Exp. 1a	Reading time	Word (HF)	35	370	400	430	30	60
Lee et al. (1999a), Exp. 1b	Reading time	Word (HF)	42	402	382	415	−20	13
Lee et al. (1999a). Exp. 1c	Reading time	Nonword	35	379	381	401	2	22
Lee et al. (1999a), Exp. 1d	Reading time	Nonword	42	380	364	404	−16	24
Lee et al. (1999a), Exp. 2a	Reading time	Word (HF)	32	312	352	388	40	76
Lee et al. (1999a), Exp. 2b	Reading time	Word (HF)	38	329	330	387	1	58
Lee et al. (1999a), Exp. 2c	Reading time	Word (HF)	32	310	351	373	41	63
Lee et al. (1999a), Exp. 2d	Reading time	Word (HF)	38	339	346	347	7	8
Lee et al. (1999a), Exp. 2e	Reading time	Word (LF)	32	361	343	400	−18	39
Lee et al. (1999a), Exp. 2f	Reading time	Word (LF)	38	354	344	380	−10	26
Lee et al. (1999a), Exp. 2g	Reading time	Word (LF)	32	327	329	371	2	44
Lee et al. (1999a), Exp. 2h	Reading time	Word (LF)	38	333	328	383	−5	50
Lee et al. (1999a), Exp. 2i	Reading time	Nonword	32	326	332	389	6	63
Lee et al. (1999a), Exp. 2j	Reading time	Nonword	38	334	312	371	−22	37
Lee et al. (1999a), Exp. 2k	Reading time	Nonword	32	308	314	383	6	75
Lee et al. (1999a), Exp. 2l	Reading time	Nonword	38	321	322	344	1	23
Lee et al. (1999b), Exp. 1a	Reading time	Word (HF)	29	358	399		41	
Lee et al. (1999b), Exp. 1b	Reading time	Word (HF)	32	367	398		31	
Lee et al. (1999b), Exp. 1c	Reading time	Word (HF)	35	349	394		45	
Lee et al. (1999b), Exp. 1d	Reading time	Word (HF)	38	375	370		−5	
Lee et al. (1999b), Exp. 1e	Reading time	Word (HF)	41	371	376		5	
Pollatsek et al. (1992), Exp. 2	Reading time	Word	Parafovea 306	317	331	349	14	32

Note: Exp., Experiment; HF, high frequency; LF, low frequency.

Table 6
Mean effect sizes and 95% confidence limits for masked phonological priming effects reported in five experimental paradigms

Task	Mean effect size (r)	.05 Lower limit	.05 Upper limit
Forward-masked perceptual identification	.240	.116	.356
Backward-masked perceptual identification	.193	.020	.354
Forward-masked reading aloud	.312	.158	.451
Forward-masked lexical decision	.204	.057	.341
Text reading	.234	−.036	.472

$$r = \sqrt{\frac{4.385}{4.385 + 19}} = .433.$$

The same value would be obtained for a study in which the difference between the phonological and graphemic control conditions is reported as $F(1,19) = 4.385$. When the data were not reported as a main effect between the two conditions but as an omnibus test involving more conditions, the F_{contrast} was calculated as described in Rosnow and Rosenthal (1996, pp. 336–337) and used to calculate the effect size. Finally, when no further indication was given other than $F < 1$, we used values of $r = +.05$ for a trend in the expected direction and $r = -.05$ for a trend in the opposite direction. Standardized effect sizes were calculated only when there were independent samples of participants. Studies were weighted for their numbers of participants to calculate their overall effect size and confidence limits.

Table 6 reports the average effect sizes for the five paradigms, together with their .05 confidence intervals. As shown, all effect sizes varied around $r = .22$ (5% variance explained), which indicates a small to medium effect. Whenever possible, we also calculated the effect sizes for analyses over items. On average, these were comparable but slightly smaller than the ones presented in Table 6.

3. Some insights from the literature review

Of the published literature identified, it appears as if the processing of a target word is facilitated by the presentation of a masked homophone (word or nonword) prime relative to the presentation of a graphemic control. The influence of a masked phonological prime on target processing is small (particularly in backward masking), but statistically reliable across studies within every experimental paradigm considered. At the same time, however, the literature review unearthed a number of methodological issues, which in our view limit the persuasiveness of the existing findings and call for further empirical evidence to substantiate the effect.

3.1. A prime–response correlation in lexical decision

In all but one of the lexical decision experiments reviewed in Table 4, pseudohomophone primes were *always* followed by word targets requiring the "YES" response.[2]

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[2] The exception is Berent (1997, Experiment 2), in which pseudohomophone foils were preceded by identity primes. This aspect of Berent's (1997) study may be undesirable nevertheless, because there is evidence that participants can exploit information disclosed by primes and targets in combination (e.g., Ratcliff & McKoon, 1988). In the experimental situation reported by Berent (1997), the lexical decision response was "NO" whenever the overlap between primes and targets was maximal.

It is possible that this stimulus arrangement created the conditions for particularly rapid "YES" responses, which may have had nothing to do with the phonological overlap between primes and targets. Rather, *any* information accessible to participants that distinguished pseudohomophone primes from other primes in these experiments—for example, the total activation that these primes produce in the phonological lexicon (cf. Grainger & Jacobs, 1996)—could have cued a rapid "YES" response, and thus the appearance of a phonological priming effect. This possibility is not unreasonable, especially given the body of research demonstrating response congruity effects for subliminally presented primes (e.g., Dehaene et al., 1998; Forster, 2004; Reynvoet, Caessens, & Brysbaert, 2002).

This problem with the existing lexical decision data is very important to us, because we prefer that task to the others for several reasons. For one, we consider the lexical decision task to be the most appropriate with which to examine weak phonological theories of visual word recognition implemented as computational models. For example, whereas the DRC model has implemented procedures for carrying out visual lexical decision, neither perceptual identification nor gaze duration has been considered. Even apart from the DRC model, though, we prefer the forward-masked visual lexical decision task to the other tasks for both theoretical and empirical reasons. Showing a phonological priming effect in reading aloud, for example, is theoretically less interesting than in lexical decision, because there is no disagreement between weak and strong phonological theories that a phonological representation must be computed prior to the reading aloud response. Similarly, showing the effect in forward or backward masked perceptual identification may be empirically less interesting than in lexical decision, because we do not know to what extent these tasks involve off-line guessing (see e.g., Brysbaert & Praet, 1992; and Perry & Ziegler, 2002 for evidence that masked perceptual identification may be subject to undesirable effects of guessing). Finally, the eye-movement data deviate from the other findings, because the effect seems to be particularly robust with high-frequency word primes (Lee et al., 1999a).

3.2. What makes an adequate graphemic control?

Phonological primes typically overlap their targets on both phonological and orthographic dimensions (e.g., kake–CAKE). The influence of phonological overlap alone is therefore obtained by comparing the phonological priming condition to a graphemic control priming condition (e.g., pake–CAKE), the logic being that any additional priming observed in the phonological priming condition must be due to phonological overlap alone. This logic hinges on the requirement that phonological primes and graphemic control primes share equivalent orthographic similarity with their targets. If targets are more orthographically similar to their phonological primes than to their graphemic control primes, then any benefit yielded by the phonological primes can be ascribed to the orthographic similarity between primes and targets instead of their phonological similarity. Conversely, if targets are more orthographically similar to their graphemic control primes than to their phonological primes, then any additional benefit yielded by phonological overlap may be hidden.

How, then, might we ensure that graphemic controls and phonological primes have equivalent orthographic similarity to targets? The vast majority of articles that we surveyed reported constructing graphemic controls such that they preserved the number of shared letters in common positions across phonological primes and targets, beginning at the left boundary of each stimulus (e.g., Berent, 1997; Davis et al., 1998; Humphreys et al., 1982; Perfetti et al., 1988; Perfetti & Bell, 1991; Rayner et al., 1995). For example, Lukatela and Turvey (1994b) designed the graphemic control "brack" for the prime–target pair braik–BRAKE because it shares the position-specific letters shared by the prime and target (bra–): The control "brack" and the prime "braik" therefore share equivalent orthographic overlap with the target BRAKE.

Ensuring the orthographic similarity of prime–target and control–target pairs is not quite this easy, however. In general, judgements about the orthographic similarity of two stimuli depend on one's theory of orthographic input coding (i.e., one's theory of the representation of letters and letter position). Two stimuli that have a large orthographic overlap according to one theory of input coding may have much less overlap according to another theory of input coding. This problem is nicely illustrated by considering pairs of stimuli that differ in length such as *phail–FAIL*. On the popular left-aligned slot-based coding scheme—the scheme assumed by all of the investigators referred to in the previous paragraph—these two stimuli have no orthographic overlap whatsoever because they share no letters in common positions. Conversely, these stimuli share a great deal of orthographic overlap on a number of other coding schemes including vowel-aligned slot-based coding (e.g., Harm & Seidenberg, 2004), onset-nucleus-coda coding (e.g., Plaut et al., 1996), onset-rime coding (e.g., Zorzi et al., 1998), and spatial coding (e.g., Davis, 1999).

There are two points especially worth noting relevant to this issue. First, it now seems apparent that left-aligned slot-based coding may not provide an adequate characterization of letter representations in reading (e.g., Andrews, 1996; Davis, in press; Davis & Taft, 2005; De Moor & Brysbaert, 2000; Perea & Lupker, 2003; Perea & Lupker, 2004)—potentially calling into question the majority of results appearing in Tables 1–5. Second, there is currently no consensus on the true nature of orthographic input coding (see e.g., Bowers, 2002; Coltheart et al., 2001; Davis, 1999; Davis, in press; Grainger & Jacobs, 1996; Grainger & van Heuven, 2003; Harm & Seidenberg, 2004; Plaut et al., 1996; Schoonbaert & Grainger, 2004; Seidenberg & McClelland, 1989; Zorzi et al., 1998 for different examples of input coding schemes). This theoretical void means that particular care must be taken in interpreting priming effects that require measurement against an orthographic control (e.g., phonological priming effects, morphological priming effects).

Like some investigators that have come before us (e.g., Van Orden et al., 1988), we have adopted a pragmatic approach to this problem. In the experiments presented below, we base our stimulus design on a left-aligned slot-based coding scheme (such that graphemic controls preserve position-specific shared letters across primes and targets). However, we also made every effort to ensure the adequacy of graphemic controls in other ways. For example, we preserved in graphemic controls shared onsets, nuclei, and codae across phonological primes and targets, except in rare cases in which this was not possible. Further, we equated in graphemic controls the number of position-nonspecific shared letters in phonological primes and targets. These steps were taken to reduce the possibility that our findings were due to orthographic similarity, although we cannot (and do not want to) exclude the possibility our effects, along with those reported in Tables 1–5, are orthographic—that they could be captured by a different input coding scheme without recourse to phonology.

3.3. Are all phonological primes equal?

Phonological priming effects are thought to reflect savings on target processing due to phonological overlap between prime and target, once the savings from orthographic overlap between prime and target has been eliminated. At first sight, this seems to suggest that the smaller the orthographic overlap between phonological prime and target, the more room there is for phonological savings. Consider the phonological priming effects that might be obtained with the items "yuice–USE" and "klip–CLIP." Primes and targets comprising these pairs are phonologically identical, yet the pairs vary considerably in terms of their orthographic overlap. Will this difference have an effect on the magnitude of the phonological priming effect, obtained by comparing the above primes with their graphemic controls "douke–USE" and "plip–CLIP"? The theories under consideration may make different predictions concerning this issue.

Frost's (1998; Frost et al., 2003) strong phonological theory claims that the phonological code upon which lexical identification is based is underspecified, making it difficult to observe a reliable phonological priming effect when homophonic and graphemic control primes are only minimally (phonologically) different (e.g., klip/plip–CLIP). On this theory, phonological priming effects would be most evident in situations in which the graphemic control can be made maximally (phonologically) different from the target (e.g., yuice–USE versus douke–USE). Empirical effects supporting the underspecification claim have been observed in Hebrew perceptual identification (Gronau & Frost, 1997) and forward-masked lexical decision (Frost et al., 2003). In both cases, the advantage conferred by a homophone prime on target recognition (e.g., QPIT–KPIT; /kapit/-/kapit/) is greater when it is compared with the advantage conferred by an orthographically equivalent but phonologically dissimilar prime (e.g., KPZT–KPIT; /kapezet/-/kapit/) than the advantage conferred by an orthographically equivalent but phonologically similar prime (e.g., KPIZ–KPIT; /kapiz/-/kapit/). It is important to appreciate, however, that the Hebrew case described here is very different from the English yuice/douke–USE case. In the Hebrew case, a large phonological alteration is induced by a small orthographic alteration, whereas in the yuice/douke–USE case, the large phonological alteration between control and target is accompanied by a large orthographic alteration between phonological prime and target. Effects of this nature (i.e., more phonological priming when there is low orthographic similarity between prime and target) on English word processing have so far been limited to forward-masked perceptual identification in young readers (Booth et al., 1999; see also Brysbaert, 2001, who made a similar claim on the basis of a near-significant post hoc analysis of perceptual identification data in Dutch).

In contrast to the strong phonological theory, current weak phonological theories (Coltheart et al., 2001; Harm & Seidenberg, 2004) predict that phonological priming effects should be greatest when orthographic overlap between prime and target is high (e.g., the klip/plip–CLIP case). In each of these models, the activation of the orthographic and/or semantic units monitored in lexical decision[3] is determined jointly by orthographic and phonological information. Therefore, while a prime like "klip" will activate its target "CLIP" via both

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[3] Lexical decisions in the DRC model (Coltheart et al., 2001) are made on the basis of two sources of information: total activation in the orthographic lexicon and maximum activation in the orthographic lexicon. The simulations of Harm and Seidenberg (2004) trialled a number of potential orthographic and semantic sources of information for making lexical decisions, but did not make a firm commitment to any of these.

orthographic and phonological pathways, a prime like "yuice" will activate its orthographic target "USE" only via the phonological pathway. Further, at least in the DRC model, the prime "yuice" will *actively inhibit* the activation of the orthographic unit "USE." Simulations using these models have shown a pattern of performance consistent with this verbal account. For example, Coltheart and Rastle (1994) demonstrated that the activation of the orthographic unit COAT is influenced far more strongly by the visually similar stimulus "koat" than by the visually distinct stimulus "kote". Similarly, Harm and Seidenberg (2004) demonstrated that pseudohomophones which are visually similar to their base words (e.g., "nat") activate appropriate semantic features (e.g., insect) along the orthography-semantics pathway to a far greater degree than do pseudohomophones which are visually dissimilar to their base words (e.g., "nox"). Thus, each of these models predicts phonological priming effects to be most evident in situations in which orthographic overlap between prime and target is high.

Just as phonological primes and their targets can vary in the extent to which they involve orthographic change, they also vary in terms of the position at which this change occurs (e.g., *k*lip–*C*LIP versus gro*e*–GRO*W*). While many theories (e.g., Frost, 1998; Harm & Seidenberg, 2004) predict that phonological coding occurs in parallel for all letters of the input and would thus predict no influence of overlap position, some theories predict that this factor may have an influence on phonological priming (e.g., Berent & Perfetti, 1995; Coltheart & Rastle, 1994; Coltheart et al., 2001; Perry & Ziegler, 2002; Rastle & Coltheart, 1999). In the DRC model (Coltheart et al., 2001), for example, nonlexical letter-to-sound conversion procedures operate serially, from left-to-right, across the input string. Phonological priming effects might therefore be most evident in situations in which the orthographic change between primes and targets is early (e.g., klip–CLIP versus plip–CLIP), though this prediction would need to be verified through simulation.

In our experiments, we wished to ensure that the presence or absence of a masked phonological priming effect did not rest inadvertently on uncontrolled aspects of the degree and location of orthographic overlap between primes and targets (see e.g., Lukatela et al., 1998, who used only a single type of orthographic change, e.g., klip–CLIP, in their investigation). We therefore took care in designing the stimulus set used in Experiments 1 and 2 to include prime–target pairs representing the full range of orthographic overlap and position of that overlap. Given the humble effect sizes revealed in our meta-analysis, however, our purpose was *not* to test for differences across these types of overlap. For readers interested in specific post hoc contrasts, we have included complete item data for each experiment in Appendix A.

4. Experiment 1

For Experiment 1, we conducted a "typical" forward-masked lexical decision experiment in which pseudohomophones primes always mapped onto a "YES" response. Given these circumstances, we expected an overall phonological priming effect of approximately 10 ms, in line with those studies reviewed in Table 4.

4.1. Method

4.1.1. Participants

Participants were 42 students from Macquarie University. All participants were native speakers of Australian or New Zealand English, and reported normal or corrected-to-normal vision. Participants received either course credit or payment of $10 Australian dollars (approximately $4 US dollars) for their participation.

4.1.2. Stimuli and apparatus

One hundred and twelve pseudohomophone primes, each comprising three phonemes, were selected from the ARC Nonword Database (Rastle, Harrington, & Coltheart, 2002). Phonologically identical English word targets were derived from these pseudohomophone primes by changing one, two or all three of the graphemes in the pseudohomophone. For example, the target RAISE was derived by changing all three of the graphemes in the pseudohomophone WRAZE (WR → R, A.E → AI.E, and Z → S), whereas the target FARM was derived by changing only one of the graphemes in the pseudohomophone PHARM (PH → F). Sixteen English word targets were derived by changing all three graphemes within the pseudohomophone prime; 48 English word targets were derived by changing two graphemes within the pseudohomophone prime; and 48 English word targets were derived by changing one grapheme within the pseudohomophone prime.

Within the sets of prime–target pairs derived by a one- or two-grapheme change, we further varied the position at which the graphemic change was made. Within the prime–target pairs derived by a two-grapheme change, the graphemic similarity structure between prime and target could be ‘different-different-same’ (e.g., koan–CONE), ‘different-same-different’ (e.g., writch–RICH), or ‘same-different-different’ (e.g., beize–BAYS), with 16 prime–target pairs falling into each similarity-structure type. Within the prime–target pairs derived by a one-grapheme change, the graphemic similarity structure could be ‘different-same-same’ (e.g., pharm–FARM), ‘same-different-same’ (e.g., nurve–NERVE), or ‘same-same-different’ (e.g., skee–SKI), with 16 prime–target pairs falling into each similarity-structure type.

Graphemic controls were generated for each prime–target pair. All shared letters in shared positions by primes and targets were preserved in graphemic controls (e.g., the pair groe–GROW shares the GRO component, and this is preserved in the graphemic control, groy). Other letters shared by primes and targets, but not in shared positions, were also included in controls (e.g., pharm/gharm–FARM) except in very rare cases in which this was impossible (in such instances, we compensated for this on another item of the same type). Whenever possible, shared onsets, nuclei, and codae between phonological primes and targets were preserved in graphemic controls. Graphemic controls and pseudohomophone primes always contained the same number of letters. All stimuli are listed in Appendix A.

Triplets from each of the seven similarity-structure types were divided into two equal lists for counterbalancing purposes. Each subject saw each target, participated in both levels of the priming variable (related and unrelated), but saw each target only once. An unrelated control condition (present in many of the studies reviewed in Table 4) does not reveal information with respect to the issue of phonological priming; as such, it was not included in the present experiments since it would have reduced the number of useful observations per participant.

One hundred and twelve nonword targets, each with three phonemes and with similar orthographic characteristics to the word targets, were selected from the ARC Nonword Database (Rastle et al., 2002). Nonword targets had a similar number of letters to word targets (words: mean 4.25 letters, range 3–6; nonwords: mean 4.22 letters, range 3–6, $t(222) < 1$), as well as similar neighborhood properties (words: mean 8.39 neighbors, range 0–21; nonwords: 8.29 neighbors, range 0–20, $t(222) < 1$).

Phonological primes and orthographic control primes were created for each of these nonword targets in the same way as was accomplished for the word targets. For 56 of the nonword targets, a phonologically identical nonword prime was generated that differed by one (e.g., sig–CIG), two (e.g., deck–DEAK), or three (e.g., wreese–REACE) graphemes. Within the sets of nonword prime–target pairs derived by a one- or two-grapheme change, we further varied the position at which the graphemic change was made in exactly the same manner as was accomplished for word prime–target pairs. For the other 56 nonword targets, a phonologically dissimilar nonword control prime was generated that differed from the target by one (e.g., cheve–BEVE), two (e.g., dack–LECK), or three (e.g., bleigh–FREW) graphemes. Within the sets of nonword control–target pairs derived by a one- or two-grapheme change, we varied the position at which that graphemic change was made in the same way as was done for the word control–target pairs. Nonword stimuli are presented in Appendix B.

These 112 nonword targets, together with their phonologically identical or phonologically dissimilar primes were presented in both versions of the experiment. There was no counterbalancing of nonword items.

Stimulus presentation and data recording were accomplished via the DMDX software (Forster & Forster, 2003) running on a Pentium III PC. A two-button response box was used to record lexical decisions, in which the YES response was controlled by the dominant hand.

4.1.3. Procedure

Participants were tested individually in a dimly lit room. They were advised that they would be seeing a series of uppercase letter strings presented one at a time, and that they would be required to decide as quickly and as accurately as possible whether each letter string was a word or not a word. Participants were told that each letter string would be preceded by a series of hash marks, but were not told of the existence of a prime stimulus. All primes were presented in lower case for 58 ms (7 ticks on a monitor with a 8.33 ms refresh rate). Each prime was preceded by a mask of 500 ms (60 ticks) consisting of hash marks, and was followed immediately by a target in uppercase that remained on screen until a response was made. Targets were presented in a different random order for each participant. Ten practice trials preceded the main experiment. Twenty-one subjects participated in each of the two counterbalancing versions of the experiment.

4.2. Results

Reaction times (RTs) and error rates were collected and cleaned in three ways. First, data for participants with unusually slow and/or error prone performance relative to the rest of the sample were excluded. In this experiment, one participant was removed following a nonword false positive rate above 25%, and another was removed because of an average YES response time above 1200 ms. Second, word targets that induced error prone responding relative to the rest of the item sample were removed. In this experiment, eight word targets that produced average error rates above 35% (FOES, NORSE, BADE, DUES, FOB, FIN, WAIF, and VAT) were excluded. Finally, for the YES response, individual data points with outlying RTs were removed. In this experiment, 13 data points greater than 1750 (0.33% of the remaining data) were removed. Item data are presented in Appendix A.

Phonological priming effects on RTs and error rates were ascertained by means of by-subject and by-item analyses of variance (ANOVAs), in which prime type (2 levels: phonological prime versus graphemic control) and list version (2 levels) were treated as factors. In analyses by subjects and by items, prime type was treated as a repeated factor and list version was treated as an unrepeated factor. Latency data revealed that word targets were recognized 13 ms faster when preceded by the pseudohomophone primes (603 ms, by items) than when preceded by the graphemic control primes (616 ms, by items), $F_1(1,38) = 7.25$, $p < .05$, $MSE = 337.93$, $F_2(1,102) = 7.42$, $p < .01$, $MSE = 1241.21$. Effect size calculation (using the formulas described in the Introduction) yielded r values of .40 and .26 for the analyses by subjects and by items, respectively. Error data revealed more accurate responding when targets were preceded by the pseudohomophone primes (5.8% errors, by items) than when preceded by the graphemic control primes (7.4% errors, by items), $F_1(1,38) = 4.30$, $p < .05$, $MSE = .001$, $F_2(1,102) = 4.14$, $p < .05$, $MSE = .003$.

5. Experiment 2

In Experiment 1 (like in the studies reviewed in Table 4) pseudohomophone primes were always followed by a YES response. Thus, the phonological priming effect could have arisen if participants were sensitive to the pseudohomophone status of the prime. In Experiment 2, we dealt with this possibility in two ways. First, we investigated whether participants were able to identify the pseudohomophone status of the masked primes explicitly. Second, we eliminated the correlation between the pseudohomophone status of the prime and the response, such that the pseudohomophone primes equally predicted the YES and NO responses of the visual lexical decision task. This more desirable situation was achieved by replacing the nonword foils in Experiment 1 with pseudohomophones. These pseudohomophone foils were preceded by pseudohomophone and graphemic control primes (e.g., koat–KOTE; lirt–HIRT), which had been manipulated in exactly the same manner (i.e., amount of orthographic overlap, position of overlap) as pseudohomophone and graphemic control primes for word targets.

Though our primary reason for replacing the nonword foils with pseudohomophone foils was to eliminate the correlation between the pseudohomophone status of the prime and the response, this adjustment may have had the additional effect of making phonological recoding disadvantageous for good task performance. Because phonological recoding in this situation makes the word–nonword discrimination particularly difficult, participants might be especially encouraged to avoid it (e.g., Pugh, Rexer, & Katz, 1994; but see Pexman, Lupker, & Jared, 2001 for a different view). Thus, we believed that these conditions presented a particularly strong test of the existence of masked phonological priming effects (see also Ferrand & Grainger, 1996).

5.1. Method

5.1.1. Participants

Participants were 86 students from Macquarie University. All participants were native speakers of Australian or New Zealand English, and reported normal or corrected-to-normal vision. Participants received either course credit or payment of $10 Australian dollars (approximately $4 US dollars) for their participation. None of the participants in this experiment contributed to Experiment 1.

5.1.2. Stimuli and apparatus

For the YES response of the visual lexical decision task, pseudohomophone primes, graphemic controls, and word targets were taken from Experiment 1. These were divided into counterbalancing conditions in exactly the same manner as in Experiment 1.

For the NO response, one hundred and twelve pseudohomophone targets, each with three phonemes, were selected from the ARC Nonword Database (Rastle et al., 2002). Pseudohomophone targets were equated to word targets on number of letters (words: mean 4.25 letters, range 3–6; pseudohomophones; mean 4.25 letters, range 3–6, $t(222) = 0.00$), and neighborhood size (words: mean 8.39 neighbors, range 0–21; pseudohomophones: 7.83 neighbors, range 0–21, $t(222) < 1$).

Pseudohomophone primes and graphemic controls were created for each of these pseudohomophone targets in the same way as was accomplished for the word targets. For 56 of the pseudohomophone targets, a phonologically identical pseudohomophone prime was generated that differed by one (e.g., phite–FITE), two (e.g., phib–FIBB), or three (e.g., wrighs–RIZE) graphemes. Within the sets of pseudohomophone prime–target pairs derived by a one- or two-grapheme change, we further varied the position at which the graphemic change was made in exactly the same manner as was accomplished for word prime–target pairs. For the other 56 pseudohomophone targets, a phonologically dissimilar nonword control prime was generated that differed from the target by one (e.g., biss–BUSS), two (e.g., leeth–LAIM), or three (e.g., marf–BEED) graphemes. Within the sets of control–target pairs derived by a one- or two-grapheme change, we manipulated the position at which that graphemic change was made in the same manner as was done for word control–target pairs. Prime–target pairs for the NO response are contained in Appendix B.

5.1.3. Procedure

The procedure for running the experiment was identical to that used in Experiment 1, with one alteration. To ascertain whether participants could identify explicitly the pseudohomophone status of the masked primes, stimuli were presented to each participant a second time immediately following the main experiment. Targets remained on screen for 416 ms, and were preceded by the 58 ms masked primes. At this point, participants were told of the existence of the prime, and were asked to decide as quickly and as accurately as possible whether that prime sounded like an English word. Participants indicated their decisions on a two-button response box, as in the main experiment.

5.2. Results

Reaction time and error data were collected and cleaned in the same manner as in Experiment 1. Six participants with unusually slow and/or error prone responses relative to the rest of the sample were removed: Five participants were removed because of a rate of false positive responses exceeding 25%, and one participant was removed because of an average NO response RT greater than 1500 ms. Six word targets were removed because they produced an error rate exceeding 35%: NORSE, BADE, DUES, FOB, WAIF, and VAT. Finally, 17 outlying data points exceeding 2400 ms (0.21% of the remaining data points) were removed from the YES data. (Note that responding in this experiment was generally slower than in Experiment 1, and this is reflected in the trimming criteria). Item data are presented in Appendix A.

As in Experiment 1, we assessed phonological priming effects on RT and error data by conducting by-subjects and by-items ANOVAs which treated prime type (2 levels: phonological prime versus graphemic control) and list version (2 levels) as factors. In analyses by-subjects and by-items, prime type was treated as a repeated factor and list version was treated as an unrepeated factor. Analyses of the latency data revealed that responses to target words were facilitated by the presence of a masked phonological prime (634 ms, by items) relative to a graphemic control prime (643 ms, by items), $F_1(1,78) = 4.31$, $p < .05$, $MSE = 773.59$, $F_2(1,104) = 3.75$, $p = .056$, $MSE = 1144.90$. Effect size calculation (using the formulas described in the Introduction) yielded r values of .23 and .19 for the analyses by subjects and by items, respectively. Although the priming advantage was also seen numerically in the error data (primed: 5.7% errors; unprimed 6.4% errors, by items), this difference did not reach statistical significance, $F_1(1,78) = 1.77$, n.s., $F_2(1,104) = 1.46$, n.s.

To ascertain whether participants were able to identify the pseudohomophone status of the masked primes, we examined error data for the second presentation of the stimulus materials (in which participants were asked if the prime sounded like a word). There was no evidence that participants could identify the pseudohomophone status of the prime stimuli under these conditions (48.24% errors, by items, where chance performance is equal to 50%).

6. Simulation

Having confirmed the existence of the masked phonological priming effect on lexical decision, we are now in a position to consider its theoretical implications for weak phonological theories of visual word recognition. For several reasons outlined in the introduction, we chose to evaluate the weak phonological theory of visual word recognition expressed by the DRC model (Coltheart et al., 2001) in this context. It may in future be important to complement this investigation of the DRC model with an investigation of the triangle model of Harm and Seidenberg (2004)—another computational implementation of a weak phonological theory. We were not able to pursue this route because, unlike the DRC model, this model is not presently available for public evaluation. Even if it were available, however, investigating its performance would have required us to make crucial decisions about the simulation of lexical decision. Though the authors of this model have drafted some ideas about the source of information used to make lexical decisions (e.g., activation of semantic feature units, semantic stress, orthographic stress, orthographic distance), they have not made any commitments concerning this issue. Further, there has been considerable scepticism about whether this model (and those related to it) could perform the lexical decision task in the manner in which human readers accomplish the task (e.g., Borowsky & Besner, in press; Coltheart, 2004; Rastle & Coltheart, in press). For these reasons, it seems that much further work on this model may be necessary before it can be evaluated in the context of masked phonological priming effects.

6.1. Approaches to simulation

The DRC model of visual word recognition (Coltheart et al., 2001) is represented in Fig. 1. Lexical decisions in the model are made on the basis of an analysis of activity in units of the orthographic lexicon. As shown, the activation of these orthographic units

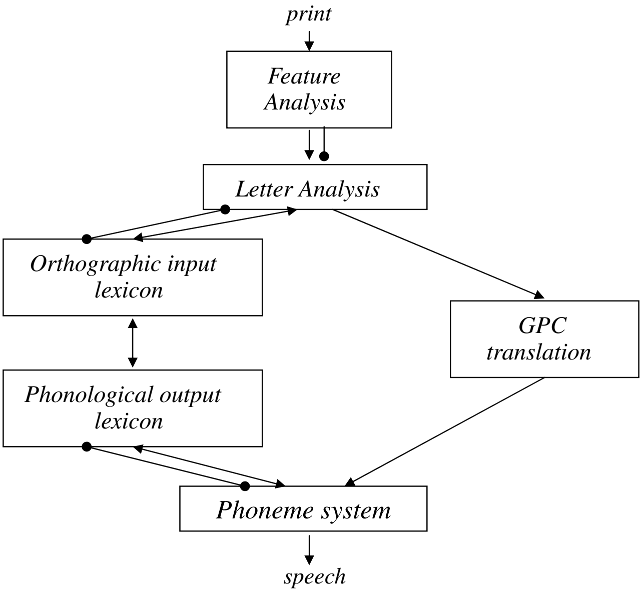

Fig. 1. The DRC model of Coltheart et al. (2001).

is influenced by information (i.e., excitation and inhibition) from both letter units and phonological units. Phonological units can be activated via feedback from the phoneme units, which are activated via nonlexical grapheme-to-phoneme (GPC) translation of the stimulus. It is this input from the phonological assembly procedure to orthographic lexical entries that may provide an avenue for simulating fast phonological priming effects on lexical decision (Coltheart & Rastle, 1994).

On the lexical decision rule described by Coltheart et al. (2001), the "YES" response in the lexical decision task is made if (a) the activation of any single unit in the orthographic lexicon reaches a critical value, A; or (b) if the summed activation of every unit in that lexicon reaches a critical value, S (i.e., the "fast guess" mechanism of Grainger & Jacobs, 1996). In a priming situation, therefore, primes can affect target lexical decisions by (a) influencing the activation of any single unit in the orthographic lexicon (e.g., the unit representing the target); or (b) influencing the total activation of the orthographic lexicon.

In an ideal world, DRC simulations would thus comprise the following approach: Primes would be presented for some number of cycles consistent with the 58-ms exposure duration used in the experiments; targets would then be presented (without resetting activations in the model) until a lexical decision was made; lexical decision latencies would be compared across phonological priming and graphemic control priming conditions; and finally, priming data from the model would be compared with priming data from human readers. However, two main issues preclude this approach. First, the account of masked priming offered by the DRC model is not well developed. Coltheart, Woollams, Kinoshita, and Perry (1999) conducted a preliminary exploration of masked priming using a 15-cycle prime exposure duration followed immediately by presentation of the target. However, the authors of the DRC model (Coltheart et al., 2001, p. 250) emphasise that the work of Coltheart et al. (1999) provides only a very coarse approximation to an adequate simulation of masked priming. It is not yet clear whether masked priming should be modelled simply as residual activation due to a briefly exposed prime, or whether additional mechanisms are needed to simulate the masking effect of the target. Second, the visual lexical decision rule currently employed by the DRC model is crude (e.g., it allows only two values of the "NO" response) and requires detailed reformulation.

We wanted to ensure that the success or failure of the model to reproduce the pattern of human data did not reflect these more peripheral characteristics. Thus, we sought to identify the conditions under which there may be scope in the DRC model for a simulation of a "fast" phonological priming effect (i.e., an effect that arises with only limited exposure to the prime), if, indeed, there are any such conditions. Our specific approach was to present the 112 phonological and 112 graphemic control primes used in our experiments to the DRC model under several different parameterizations, and to monitor their influence over a 100-cycle period on (a) the activation of target units in the orthographic lexicon (e.g., activation of the unit RIP on presentation of RYP and ROP) and (b) the total activation of units in the orthographic lexicon. We then compared the influence of the phonological primes and the graphemic controls on these two activation measures at three time points in the 100-cycle period (25, 50, and 100 cycles). Our reasoning was that if phonological primes yielded greater target activation or total activation than did graphemic controls, then this would indicate scope in the DRC model for a simulation of phonological priming effects on visual lexical decision. Further, if this pattern of activations could be obtained early in processing (e.g., 25 cycles), then this would indicate scope in the DRC model for a simulation of fast phonological priming effects. We foreshadow that such a pattern of activation is obtained following a number of major modifications to the model. Our final simulation thus explores the implications of these modifications for other aspects of the model's performance.

6.2. *Simulation 1*

Preliminary study of the DRC model yielded optimism regarding its ability to capture fast phonological priming effects on visual lexical decision: Coltheart and Rastle (1994) demonstrated that the orthographic unit COAT was activated more strongly and more rapidly by presentation of the pseudohomophone KOAT than by presentation of the graphemic control stimulus FOAT. However, Coltheart and Rastle's simulation strategy during the development of the DRC model was less rigid than would be desirable at the current stage of evaluation. They wrote, "These simulations are done by varying the parameters of the model until a parameter set is found (if one can be found) under which the model's behavior exhibits the effect that human subjects have been found to exhibit." (p. 1200). A more desirable strategy is, of course, to ascertain whether a single set of parameters can simulate a wide range of human data. This is exactly the approach advocated by Coltheart et al. (2001): "…we would in any case not be interested in an approach in which each set of human data is simulated with a different set of DRC parameters. Our aim instead…has been to find just one set of parameters that, unchanged, simulate a wide variety of sets of human data." (p. 218). Thus, the purpose of Simulation 1 was to discover whether there is scope in the DRC model to simulate a fast phonological priming effect, when the model is controlled by the set of parameters already shown to simulate other benchmark effects in visual word recognition.

6.2.1. Parameter set

Simulation 1 used the standard set of DRC parameters for lexical decision, as described by Coltheart et al. (2001). The lexical decision parameters are identical to the parameters used for reading aloud (Coltheart et al., 2001, Table 1), except that the parameter controlling inhibition from the letter units to the orthographic units is reduced to −0.300 from −0.435. Coltheart et al. (2001) justified this very minor modification as a strategic variation adopted specifically for the lexical decision task.

6.2.2. Results

6.2.2.1. Total activation in the orthographic lexicon. The total orthographic activation produced by each graphemic control (at each of the 100 processing cycles) was subtracted from the total orthographic activation produced by each phonological prime (at each processing cycle). A positive value reflected more total orthographic activation produced by phonological primes than by graphemic controls (indicating scope for simulating a phonological priming effect); a negative value reflected the reverse relationship. These activation difference values at 25, 50, and 100 cycles were then subjected to one-sample t tests. Results showed an effect on total activation in the opposite to desired direction: Greater total activation was produced by graphemic controls than by phonological primes. This effect was marginally significant at 25 cycles ($M = -.0193$, $t(111) = -1.66$, $p < .10$), 50 cycles ($M = -.1342$, $t(111) = -1.72$, $p < .10$), and 100 cycles ($M = -.1763$, $t(111) = -1.70$, $p < .10$).

6.2.2.2. Activation of target units in the orthographic lexicon. The activation produced in each target orthographic unit during presentation of each graphemic control was subtracted from that produced during presentation of each phonological prime. A positive value reflected more activation in target orthographic units produced by phonological primes than by graphemic controls and a negative value reflected the reverse relationship. These activation difference values at 25, 50, and 100 cycles were then subjected to one-sample t tests. Results showed no statistical difference in the amount of activation produced in target orthographic units from phonological primes and graphemic controls at 25 cycles ($M = -.0002$, $t < 1$), 50 cycles ($M = .0005$, $t < 1$), or 100 cycles ($M = .0227$, $t(111) = 1.23$, n.s.).

6.2.3. Discussion

Simulation 1, which used the standard parameters for lexical decision, showed no scope for producing a phonological priming effect at any of the time points sampled. Phonological and graphemic control primes had an equivalent influence on the activation of target orthographic units; further, graphemic control primes actually yielded more total orthographic activation than did phonological primes (a result in the opposite to desired direction). This influence on total activation is likely due to the fact that graphemic control primes had slightly greater neighborhood sizes ($M = 3.86$ neighbors) than did phonological primes ($M = 3.42$ neighbors), although this difference was not statistically significant, $t(111) = -1.12$.

To understand how the model's performance might be improved, we examined the items for which phonological primes produced greater activation in target orthographic units than did graphemic control primes (i.e., the pattern needed to simulate a phonological priming effect). At 25 cycles, 10/112 items yielded this pattern; at 50 cycles, 14/112 items yielded this pattern; and at 100 cycles, 16/112 items yielded this pattern. In all of these cases, phonological primes were orthographic neighbors of their targets (e.g., ryp–RIP). When prime stimuli were not neighbors of their targets—and this was the case for the vast majority of our stimuli—they produced no activation whatsoever in target orthographic units at any cycle of the time period monitored. The reason for this result is clear. When primes are orthographically very different from their targets (e.g., kaik–CAKE), letters of the prime that do not overlap letters of the target (in a position-specific manner) exert massive inhibition on the activation of target orthographic units.

While a phonological prime had to be a neighbor of its target to produce a pattern of activation consistent with phonological priming, this condition was not by itself sufficient to produce such a pattern. The reason for this was that graphemic controls in these cases were usually also neighbors of their targets (e.g., ryp–RIP versus rop–RIP), and often activated the orthographic units corresponding to their targets to the same degree as did the phonological primes. Further analysis of these neighboring prime–target pairs revealed that a pattern consistent with phonological priming (i.e., more activation in target orthographic units produced by phonological primes than by graphemic controls) emerged only when phonological primes had fewer neighbors (and neighbors of lower frequency) than their matched graphemic controls. When graphemic controls had fewer neighbors (and neighbors of lower frequency) than their matched phonological primes, the effect was reversed (i.e., more activation in target orthographic units produced by graphemic controls than by phonological primes). We suggest that this pattern of data is the result of lateral inhibition in the orthographic lexicon: When primes activate many orthographic neighbors, those neighbors can inhibit the rise of activation in target orthographic units.

6.3. Simulation 2

The standard set of parameters for lexical decision in the DRC model showed no scope for simulating a phonological priming effect on lexical decision. It appears as if the orthographic aspects of primes (e.g., their orthographic similarity to targets, their neighborhood size) influenced both total activation and activation in target orthographic units too greatly relative to the phonological aspects of primes to result in a pattern of activation consistent with phonological priming. One likely explanation for the undesirably meagre influence of phonology in Simulation 1 is that phonological assembly operates in a serial left-to-right manner under the standard DRC parameterization. Indeed, nonlexical phonology is assembled letter by letter in the model (with 17 processing cycles intervening the computation of phonology for each letter), and does not even begin until Cycle 10 of processing. It thus takes a full 61 processing cycles to assemble the phonology of a 4-letter prime such as KAKE. Given this characterization, it is perhaps not so difficult to understand why phonology had such a limited influence on early visual word recognition in the model.

The aim of Simulation 2 was therefore to investigate whether a DRC model that assembles phonology more rapidly and in parallel provides any scope for simulating a fast phonological priming effect on lexical decision. Before proceeding, however, it should be noted that serial phonological assembly allows the standard DRC model to explain a number of effects on human reading aloud performance including the position of irregularity effect (Coltheart & Rastle, 1994; Rastle & Coltheart, 1999; Roberts, Rastle, Coltheart, & Besner, 2003), the whammy effect (Rastle & Coltheart, 1998), the position-sensitive Stroop effect (Bibi, Tzelgov, & Henik, 2000; Coltheart et al., 1999), the onset effect on masked priming (Forster & Davis, 1991; Kinoshita, 2003), the position of bivalence effect (Havelka & Rastle, 2005) and the length by lexicality interaction (Weekes, 1997; see Rastle & Coltheart, in press for a review). No model of reading that operates solely in parallel has been able to provide any account of this body of effects (Rastle & Coltheart, in press; Rastle, Harrington, Coltheart, & Palethorpe, 2000). Thus, if this simulation of fast phonological priming is successful, then some other credible explanation for this substantial body of empirical effects would need to be developed.

6.3.1. Parameter set

Simulation 2 altered the standard set of parameters for lexical decision in two ways: (a) the GPC offset parameter (controlling the time at which the assembly of phonology begins) was changed from 10 cycles to 1 cycle; and (b) the GPC inter-letter interval parameter (controlling the time elapsed between the processing of each letter) was changed from 17 cycles to 1 cycle. Although these changes do not yield fully parallel assembly of phonology, they do provide a very close approximation. The implementation of the DRC model made publicly available by Coltheart et al. (2001) does not allow these two parameters to be set to 0 cycles.

6.3.2. Results

We carried out the analyses of total orthographic activation and of the activation of target orthographic units in the same manner as was reported in Simulation 1. Results again showed greater total orthographic activation produced by graphemic controls than by phonological primes, although this difference was not statistically significant at 25 cycles ($M = -.0156$, $t(111) = -1.47$), 50 cycles ($M = -.1064$, $t(111) = -1.43$), or 100 cycles ($M = -.1744$, $t(111) = -1.57$). Further, as in Simulation 1, results showed no difference in the extent to which phonological primes and graphemic controls activated target orthographic units at 25 cycles ($M = -.0002$, $t < 1$), 50 cycles ($M = .0029$, $t < 1$), or 100 cycles ($M = .0253$, $t(111) = 1.31$).

6.3.3. Discussion

Simulation 2 revealed that altering the DRC model such that it assembles phonology more rapidly and in a near-parallel manner produces no real benefit in terms of its ability to simulate a fast phonological priming effect. Phonological primes and graphemic controls yielded a statistically equivalent influence on both total orthographic activation and activation of target orthographic units. As in Simulation 1, we examined the cases in which phonological primes yielded more activation in target orthographic units than did graphemic controls. At 25 cycles, 10/112 items yielded this pattern; at 50 cycles, 18/112 items yielded this pattern; and at 100 cycles, 17/112 items yielded this pattern. Our analyses of these items revealed once again that the orthographic properties of primes determined their influence on target orthographic units. Primes produced activation in target orthographic units only when they were neighbors of their targets, and the direction of the priming effect (i.e., whether phonological primes or graphemic controls produced more activation in target orthographic units) depended upon the neighborhood sizes (or neighborhood frequencies) of the phonological primes and their matched graphemic controls.

6.4. Simulation 3

We found it surprising that the DRC model tested in Simulation 2 yielded so little improvement in the model's ability to capture phonological priming effects on lexical decision. To understand better the contribution that assembled phonology makes to the information from which visual lexical decisions are made in the DRC model (given the standard parameter values controlling the direct route to the orthographic lexicon), we conducted a third simulation in which we disabled the nonlexical phonological assembly procedure entirely. We did not, of course, expect to observe a pattern resembling a phonological priming effect under these conditions. Our purpose was simply to compare performance under these conditions with performance in Simulations 1 and 2.

6.4.1. Parameter set

Simulation 3 altered the standard set of parameters for lexical decision (i.e., those used in Simulation 1) by reducing the GPC excitation parameter from 0.055 to 0.00.

6.4.2. Results

We carried out the analyses of total orthographic activation and of the activation of target orthographic units in the same manner as was reported in Simulation 1. Results revealed greater total activation produced by graphemic controls than by phonological primes, although this difference was not significant at 25 cycles ($M = -.0156$, $t(111) = -1.47$), 50 cycles ($M = -.1087$, $t(111) = -1.47$), or 100 cycles ($M = -.1576$, $t(111) = -1.43$). Further, results showed no difference in the extent to which phonological primes and graphemic controls activated target orthographic units at 25 cycles ($M = -.0002$, $t < 1$), 50 cycles ($M = .0003$, $t < 1$), or 100 cycles ($M = .0119$, $t < 1$).

6.4.3. Discussion

As expected, Simulation 3 revealed no evidence for a pattern of activation consistent with a phonological priming effect. We examined the cases in which phonological primes yielded more activation in target orthographic units than did graphemic controls: At 25 cycles, 10/112 items yielded this pattern; at 50 cycles, 13/112 items yielded this pattern; and at 100 cycles, 11/112 items yielded this pattern. As in Simulations 1 and 2, these items were neighbors of their target words, and had fewer neighbors (and neighbors of lower frequency) than their matched graphemic controls.

By comparing Simulations 1–3, we can observe that given the standard parameters controlling the strength of the direct route from print to the orthographic lexicon, the assembly of phonological information makes only a miniscule contribution to the activation of orthographic lexical entries. The number of cases in which phonological primes yielded more activation in target orthographic units than did graphemic controls was only marginally greater in the model in which phonology was assembled rapidly and in a near-parallel manner than in the model in which phonology was not assembled at all. Instead, what determined the activation of target orthographic units was largely the orthographic characteristics of primes (e.g., their orthographic overlap with targets their neighborhood structures).

6.5. Simulation 4

Simulations 1–3 indicated that a simulation of phonological priming on lexical decision may not be achieved in the DRC model through simple alterations to the parameters controlling phonological assembly. Rather, more significant changes affecting the balance of the two pathways are needed. To be specific, we require a set of parameters that will not only substantially increase the contribution of assembled phonology to the activation of target orthographic units but also substantially decrease the influence of orthographic characteristics of primes (in particular, their orthographic similarity to targets) on the activation of target orthographic units. Simulation 4 tests the DRC model under a set of parameters that meets these criteria.

6.5.1. Parameter set

Following preliminary study of the influence of different parameter changes on the performance of the model, we made two fairly radical alterations to the set of parameters used in Simulation 2. First, to increase the contribution of assembled phonology to the activation of orthographic units, we increased the value of the parameter controlling excitation from phoneme units to phonological units from 0.04 to 0.30. Second, to enable phonological primes to activate orthographic units of nonneighboring targets, the parameter controlling inhibition from letter units to orthographic units was changed from −0.30 to −0.01 (i.e., this set of parameters virtually eliminates the inhibition from letter units to orthographic units). As in Simulation 2, the nonlexical route of this parameterization of the DRC model was set to operate in a rapid and near-parallel manner.

6.5.2. Results

We carried out the analyses of total orthographic activation and of the activation of target orthographic units in the same manner as was reported in Simulation 1. Results showed significantly greater total activation produced by graphemic controls than by phonological primes at 25 cycles ($M = -.1777$, $t(111) = -3.40$), 50 cycles ($M = -.3273$, $t(111) = -4.45$), and 100 cycles ($M = -.4072$, $t(111) = -4.02$). Conversely, results showed greater activation of target orthographic units by phonological primes than by graphemic controls at 50 cycles ($M = .0477$, $t(111) = 4.03$) and at 100 cycles ($M = .1274$, $t(111) = 5.05$), but not at 25 cycles ($M = -.0028$, $t < 1$).

6.5.3. Discussion

The parameter alterations in Simulation 4 enabled assembled phonology to play a greater role in the activation of target orthographic units than was the case in Simulations 1–3. In the analysis of target unit activation, Simulation 4 produced scope for a phonological priming effect (i.e., greater unit activation produced by phonological primes than by graphemic controls) at prime exposure durations of 50 cycles and 100 cycles. As in Simulations 1–3, we examined the cases in which phonological primes yielded more activation in target orthographic units than did graphemic controls: At 25 cycles, 30/112 items yielded this pattern; at 50 cycles, 49/112 items yielded this pattern; and at 100 cycles, 54/112 items yielded this pattern. As expected given our parameter changes, these cases were no longer restricted to instances in which phonological primes were orthographic neighbors of their targets.

Despite improvement in the analysis of target unit activation, however, the analysis of total orthographic activation in Simulation 4 was not so positive. Specifically, it appears as if the reduction in inhibition from letter units to orthographic units exacerbated the consequences of the marginal difference between graphemic controls and phonological primes in neighborhood size—yielding significantly greater total orthographic activation from graphemic controls than from phonological primes. Although we acknowledge that this is an undesirable outcome, we also posit that it is possible to construct a lexical decision rule that does not take into account total orthographic activation. For this reason, we focus in particular in Simulation 5 on improving the model's performance with regard to the analysis of the activation of target orthographic units.

6.6. Simulation 5

Simulation 4 revealed scope for simulating a phonological priming effect on lexical decision at prime exposure durations of 50 cycles and 100 cycles. At these time points, phonological primes yielded greater activation in target orthographic units than did graphemic controls. The purpose of Simulation 5 was to explore whether there is a parameter set that would enable to the model to support a fast phonological priming effect (i.e., whether greater activation of target orthographic units could be obtained from phonological primes than from graphemic controls at 25 cycles).

6.6.1. Parameter set

We adopted the parameter set used in Simulation 4 with one alteration: The parameter controlling the strength of GPC excitation was increased from 0.055 to 0.30. As in Simulations 2 and 4, the nonlexical route of this parameterization of the DRC model operates in a rapid and near-parallel manner.

6.6.2. Results

The analyses of total activation and of target orthographic unit activation were carried out in the same manner as in Simulation 1. As in Simulation 4, results showed significantly greater total orthographic activation produced by graphemic controls than by phonological primes at 25 cycles ($M = -.2043$, $t(111) = -3.67$), 50 cycles ($M = -.2827$, $t(111) = -3.70$), and 100 cycles ($M = -.2592$, $t(111) = -2.51$). Conversely, results showed significantly greater activation of target orthographic units by phonological primes than by graphemic controls at 25 cycles ($M = .0037$, $t(111) = 2.30$, $p < .05$), 50 cycles ($M = .1211$, $t(111) = 7.56$), and 100 cycles ($M = .1725$, $t(111) = 5.89$).

6.6.3. Discussion

Simulation 5 established that there is scope within the DRC model to produce a fast phonological priming effect on lexical decision, when the model is controlled by a parameter set in which (a) the assembly of phonology occurs rapidly and in a near-parallel manner; (b) the contribution of assembled phonology to the activation of orthographic lexical entries is strengthened substantially; and (c) the inhibition between letter representations and orthographic lexical entries is virtually eliminated. Under this parameterization, phonological primes yield greater activation in target orthographic units than do graphemic control primes, and do so relatively early in processing. These successes do come with a cost in terms of total orthographic activation, however, a cost which would have to be taken into account in the reformulation of any lexical decision rule.

Further analyses of the DRC model under this parameterization reveal another very serious cost: These alterations to the model leave it unable to read aloud exception words. The DRC model used in Simulation 5 was presented with the 88 exception words and the 88 matched regular words developed by Rastle and Coltheart (1999) for reading aloud. Though the model read aloud 85/88 regular words correctly, it read aloud 0/88 exception words correctly. These errors comprised regularizations (69/88; e.g., 'books'→/buks/), lexicalizations (3/88; e.g., 'tsar'→/tai/), and other kinds of error (16/88; e.g., 'aft'→/ææt/). Given the massive contribution of assembled phonology required to simulate fast phonological priming effects on lexical decision, it is not surprising that exception words pose such difficulty for the DRC model under this parameterization.

6.7. Simulation 6

These simulations leave us in a difficult position. On the one hand, the DRC model operating under the standard set of parameters for lexical decision (Simulation 1) does not come close to simulating fast phonological priming effects. On the other hand, the DRC parameterization that shows some scope for simulating fast phonological priming effects on lexical decision (Simulation 5) cannot correctly read aloud exception words. If our evaluation of the DRC model requires that it simulate fast phonological priming effects on lexical decision using a set of parameters that can also read aloud, then the model seems almost certainly false. An alternative approach would be to justify using the parameters developed in Simulation 5 for lexical decision while adopting the standard set of parameters (Coltheart et al., 2001; Rastle & Coltheart, 1999) for reading aloud. Indeed, Coltheart et al. (2001) used a parameter set for simulating lexical decision that differed very slightly (on a single parameter) from that used for reading aloud—justifying this small parameter change as a strategic response to the specific demands posed by the lexical decision task.

In Simulation 6, we investigated quantitatively whether we could offer a specific justification for adopting the parameter set used in Simulation 5 for lexical decision. Our logic was simple. We reasoned that the lexical decision task requires readers to discriminate between word and nonword stimuli. As such, any strategic variation in the parameters used for lexical decision should maximize—not minimize—the model's ability to perform this discrimination. If the parameters used in Simulation 5 are to be justified in terms of a strategic variation due to the demands posed by the lexical decision task, then words and nonwords should produce a larger difference in the sources of activation used to make a lexical decision when the model is controlled by the parameters used in Simulation 5 than when it is controlled by the standard parameters for reading aloud (Coltheart et al., 2001; Rastle & Coltheart, 1999). We therefore presented two parameterizations of the DRC model with the 112 word targets and the 112 nonword targets used in Experiment 1, and monitored the two sources of activation currently used to make a lexical decision (i.e., the total activation of the orthographic lexicon and the maximum activation of any single unit; see Coltheart et al., 2001) for a 100 cycle period within each parameterization. If the parameters developed in Simulation 5 are to be justified for use in lexical decision on strategic grounds, then they should work to maximize the model's ability to discriminate between words and nonwords.

6.7.1. Parameter set

Simulation 6 compared the performance of two models: One controlled by the set of parameters developed in Simulation 5 and one controlled by the standard set of parameters used for reading aloud (Coltheart et al., 2001; Rastle & Coltheart, 1999).

6.7.2. Results

Fig. 2 depicts the influence of target type (word or nonword) on the activation of information used to make a lexical decision when the model is running under (a) the parameters used in Simulation 5; and (b) the standard parameters for reading aloud.

A statistical analysis is not necessary to demonstrate that the DRC model's ability to discriminate between words and nonwords is seriously compromised under the parameter set adopted in Simulation 5.

6.7.3. Discussion

Simulation 5 yielded a parameter set that shows scope for producing a fast phonological priming effect. However, the DRC model running under that parameter set was totally unable to read aloud exception words correctly. In Simulation 6, we asked whether we could justify using the standard set of parameters for reading aloud (Coltheart et al., 2001; Rastle & Coltheart, 1999) and the set of parameters developed in Simulation 5 for lexical decision. This simulation was unambiguous. It revealed that the discrimination between word and nonword stimuli is far more difficult when the model is running under the parameters used in Simulation 5 than when it is running under the standard parameters for reading aloud. We therefore consider that adopting the parameters used in Simulation 5 could *not* be justified in terms of a strategic variation arising due to the demands of the lexical decision task.

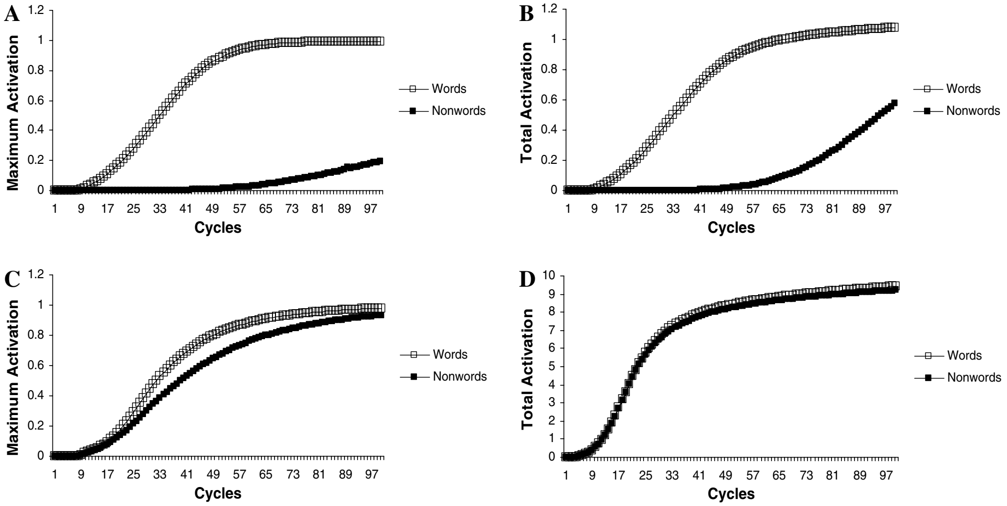

Fig. 2. Maximum orthographic activation (A and C) and total orthographic activation (B and D) produced by words and nonwords. The top panels (A and B) reflect the DRC model's performance under the standard parameters for reading aloud, and the bottom panels (C and D) reflect the DRC model's performance under the parameters used in Simulation 5.

7. General discussion

The empirical and computational research reported in this article had two aims. Our first aim was to settle the empirical issue of whether or not there is a masked phonological priming effect on English visual word recognition. To meet this aim, we first conducted an exhaustive meta-analytic literature review that examined the evidence for these effects in each of the five experimental paradigms in which they have been studied. We followed our meta-analysis by conducting two new experiments, which investigated whether these effects emerge in the lexical decision task, and which addressed various methodological issues identified in our analysis of previous research. Our second aim was to contribute to a firmer assessment of the theoretical implications of masked phonological priming effects than has so far been possible. In particular, we wished to discover the extent to which these effects actually pose difficulties for weak phonological theories of visual word recognition. To meet this aim, we studied the DRC model of visual word recognition (Coltheart et al., 2001) in the context of masked phonological priming effects, under several parameterizations that varied the strength of the contribution of assembled phonology to the recognition process.

7.1. Masked phonological priming effects: Are they real?

In respect of our first aim, our meta-analytic literature review and the new experiments that we report not only demonstrate the reality of masked phonological priming effects, but also establish for the first time their size. Our analysis of the published literature revealed small but significant masked priming effects in all five of the paradigms in which these effects have been studied. This analysis revealed an effect in forward-masked perceptual identification averaging 9%, an effect in backward-masked perceptual identification averaging 4%, an effect in forward-masked reading aloud averaging 10 ms, an effect in forward-masked lexical decision averaging 10 ms, and an effect in text reading averaging 8 ms. Effect-size calculations taking into account the magnitude and variability of the effect yielded r values (e.g., Rosnow & Rosenthal, 1996; Rosnow et al., 2000) of between .20 and .30, indicating a small- to medium-sized effect. Our own empirical work confirmed the existence of the phonological priming effect in forward-masked visual lexical decision. We observed a 13-ms effect ($r = .40$) when there was a correlation between the pseudohomophone status of the prime and the response (as there has been in previous studies). The effect persisted when this correlation was removed and when participants may have been biased against phonological recoding of the visual input—though the size of the effect was reduced, at 9 ms ($r = .19$). This dataset provides a benchmark for consideration in future computational modelling of visual word recognition. Given the low effect sizes that we observed in our own studies and in previous literature, we believe that the null effects cited in the introduction to this article (e.g., Coltheart & Woollams, unpublished; Forster & Mahoney, unpublished; Holyk & Pexman, 2004) were probably due to a lack of sufficient power.

These empirical findings enable us to make some important generalizations about the nature of visual word processing. First, our findings suggest that a phonological code is assembled quickly from the visual stimulus, and influences the recognition process from its earliest stages. Our findings also suggest that phonological assembly occurs without intention (i.e., under conditions in which the visual stimulus is consciously imperceptible) and, at least in the brief exposure conditions explored in our research, in a manner that is not subject to strategic control (i.e., it cannot be 'turned off' in response to the demands of the stimulus environment). Thus, our findings appear to vindicate claims by strong phonological theorists that phonological assembly is a process that operates rapidly and automatically. However, it is our position that neither our findings nor those of previous investigators (e.g., Drieghe & Brysbaert, 2002; Ferrand & Grainger, 1992; Lukatela & Turvey, 1994b; Xu & Perfetti, 1999) can be used to argue that phonological assembly is an *obligatory* component of visual word recognition. Such an argument could be lodged only on the basis of neuropsychological studies or intervention studies (e.g., transcranial magnetic stimulation) demonstrating that visual word recognition is impossible in the absence of phonological recoding.

7.2. Masked phonological priming effects: Do they matter?

Many leading researchers have argued that the characterization of phonological assembly provided by masked phonological priming effects, and supported by our own empirical investigation, is at odds with theories that consider visual word recognition to be a process that is driven primarily by the analysis of orthographic form (i.e., weak phonological theories). Thus, in respect of our second aim, we studied several parameterizations of the DRC model of visual word recognition (Coltheart et al., 2001) in the context of these effects. The DRC model posits that words are recognized (in e.g., lexical decision) on the basis of activation in orthographic lexical representations. Crucially, these representations are activated not only via direct input from letter-level representations but also via indirect input from a phonological assembly procedure (see Fig. 1). It is this indirect input that has been thought to provide a basis for simulating fast phonological priming effects on lexical decision (Coltheart & Rastle, 1994).

The results of our simulations were unambiguous. These simulations demonstrated (a) that the DRC model running under the standard set of parameters for lexical decision shows no scope whatsoever for simulating our findings and (b) that alterations to the operation of the phonological assembly procedure (e.g., making it operate in a rapid and near-parallel manner) do not improve the situation. Further alterations to the model designed to (a) strengthen the contribution of the indirect phonological pathway to the activation of orthographic units and (b) weaken the influence of the orthographic characteristics of our stimuli on the activation of orthographic units yielded a parameter set that did show scope for simulating a fast phonological priming effect. However, these alterations were so radical that they rendered the model unable to read aloud exception words. Furthermore, these alterations could not be justified strategically with respect to the demands of the lexical decision task, since they impaired considerably the model's ability to perform that task (i.e., discriminate between words and nonwords). These simulations appear to indicate that, at least at the specific level of the DRC model, masked phonological priming effects do matter: Some aspect of the DRC model must be false. Exactly which aspect of the DRC model is falsified by these effects is an issue that we will return to in the following section.

The implications of masked phonological priming effects extend much further than the DRC model, however. Indeed, our simulations reveal that these effects present one half of a general dilemma that must be faced by *any* theory of English skilled reading. That dilemma is to account, simultaneously, for both the masked phonological priming effect on lexical decision and the correct reading aloud of irregular words. On the one hand, the degree of spelling-sound irregularity in English appears to require a phonological assembly procedure that is weak and that operates relatively slowly. If a phonological assembly procedure is too strong or operates too quickly, regularization errors will result (as demonstrated in Simulation 5). The indirect phonological pathway of the English DRC model under the standard parameterization is, in fact, so weak and must operate so slowly relative to the direct orthographic pathway that Ziegler et al. (2003) had to speed it up to simulate reading aloud adequately in the more spelling-sound regular French language. On the other hand, the existence of masked phonological priming effects appears to require a phonological assembly procedure that operates quickly and that is strong enough to make a substantial contribution to the activation of the lexical entries monitored in lexical decision (again, as demonstrated in Simulation 5).

Not surprisingly, theorists from weak phonological and strong phonological perspectives have to date focused on different aspects of this fundamental dilemma. Weak phonological theorists including the DRC modellers have paid particular attention to the problem of reading aloud irregular words, and have proposed to deal with the problem of masked phonological priming effects by doubting their empirical basis. The empirical contribution of this article demonstrates that these doubts cannot be sustained. Conversely, strong phonological theorists have paid particular attention to the problem of masked phonological priming effects, and have dealt with the problem of reading irregular words by proposing a procedure whereby the initial phonological representation is "...shaped (whether serially or in parallel) through top-down lexical knowledge to yield a final correct pronunciation" (Frost, 1998, p. 89). Exactly how such a procedure is meant to operate has, however, never been described in any kind of detail; and there is no guarantee that it could even be implemented as a working computational model. To our knowledge, no weak or strong phonological theory has yet been proposed that postulates a phonological assembly procedure that is rapid and/or strong enough to influence the earliest stages of word recognition, but also slow and/or weak enough to retain the ability to read aloud English exception words correctly.

7.3. Reconciling weak and strong phonological theories

Our view is that bringing together the commitments from weak and strong phonological perspectives may provide a solution to this fundamental dilemma. Our starting point is the idea that phonological codes are generally regarded as far more stable and retrievable than orthographic codes, hence their importance in short-term memory (e.g., Baddeley, 1986) and in text reading (e.g., Brysbaert, Grondelaers, & Ratinckx, 2000; Rayner & Pollatsek, 1987). Phonological representations also develop far earlier in life than reading begins, and thus provide an anchor onto which corresponding orthographic codes can develop (see Kello & Plaut, 2003, for discussion). Despite the relative importance of phonological codes in the cognitive system, implemented models of skilled reading (e.g., Coltheart et al., 2001; Grainger & Jacobs, 1996) have generally assumed that visual word recognition (as indexed by the lexical decision task) is based on the analysis of orthographic codes. Neuropsychological research has certainly demonstrated that it is wholly possible to recognize words solely on the basis of an analysis of orthographic representations (see Coltheart, 2004, for a review). However, we submit that it is *not impossible* that visual word recognition in normal skilled readers is based largely on an analysis of phonological representations. Could a theory that retained the commitment to direct orthographic and indirect phonological pathways, but that made lexical decisions on the basis of an analysis of phonological representations, provide a means of reconciling the dilemma outlined above?

To investigate this possibility, we conducted an additional simulation with the DRC model identical to that described in Simulation 1 (i.e., standard parameters for lexical decision; Coltheart et al., 2001), except that we monitored the activation of target phonological units instead of target orthographic units in response to the phonological prime and graphemic control stimuli. This simulation revealed significantly greater activation produced in target phonological units by phonological primes than by graphemic controls at 50 cycles, $t(111) = 2.05$, $p < .05$, and at 100 cycles, $t(111) = 3.74$, $p < .01$. This outcome is considerably better than that achieved in Simulation 1, and indeed, is similar to that achieved in Simulation 4 following radical changes the model's parameters.[4] Mindful that further (though, we believe, relatively minor) parametric alterations are necessary to demonstrate the small but significant *fast* phonological priming effect found in human readers, we feel confident on the basis of this simulation in suggesting that masked phonological priming effects are problematic for the DRC model only with respect to its assumption that orthographic codes provide the sole basis for lexical decisions. On a more general note, the compromise approach that we have adopted in this simulation has come closer than any other theory to resolving the dilemma created by masked phonological priming effects in a language characterized by a substantial degree of spelling-sound irregularity.

One immediate objection to this approach is that lexical decisions based solely on information at a phonological level would not allow discrimination between words and pseudohomophones (e.g., brain versus brane). Indeed, it is exactly this problem that has required strong phonological theorists (e.g., Frost, 1998; Lukatela & Turvey, 1994a, 1994b) to postulate a spelling check, presumed to follow the activation of lexical entries by the assembled phonological code. This objection is fallacious, however, because it misses the subtle point that in theories that postulate a direct orthographic pathway (such as the DRC model), the activation of phonological representations *is already constrained* by orthographic information. While 'brain' and 'brane' both activate the phonological unit for /braen/ via assembled phonology, only 'brain' activates the phonological unit for /braen/ via the direct orthographic pathway. The result is greater activation for the stimulus 'brain' than the stimulus 'brane' in the phonological unit /braen/.

To confirm this verbal description, we conducted a simulation with the DRC model running under the standard parameters for lexical decision, which was similar to Simulation 6. Two sources of phonological information—total activation in the phonological lexicon and maximum activation of any phonological unit—were monitored while the DRC model processed each of the 112 word targets and 112 pseudohomophone targets used in Experiment 2. The results of this simulation, shown in Fig. 3, demonstrate clearly that activation in phonological lexical entries alone provides a reliable source of information with which to discriminate between words and pseudohomophones. Lexical decisions

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[4] The DRC model was relatively successful in this instance for two reasons. First, there are no inhibitory connections between the orthographic lexicon and the phonological lexicon in the DRC model. Thus, the massive inhibition faced at the orthographic level when phonological primes and targets are visually dissimilar is not transmitted to the phonological level. Second, activation from the phonological assembly procedure both arrives at the phonological lexicon more quickly than it arrives at the orthographic lexicon and suffers a much lesser reduction in magnitude when it is transmitted to the phonological lexicon than when it is transmitted to the orthographic lexicon.

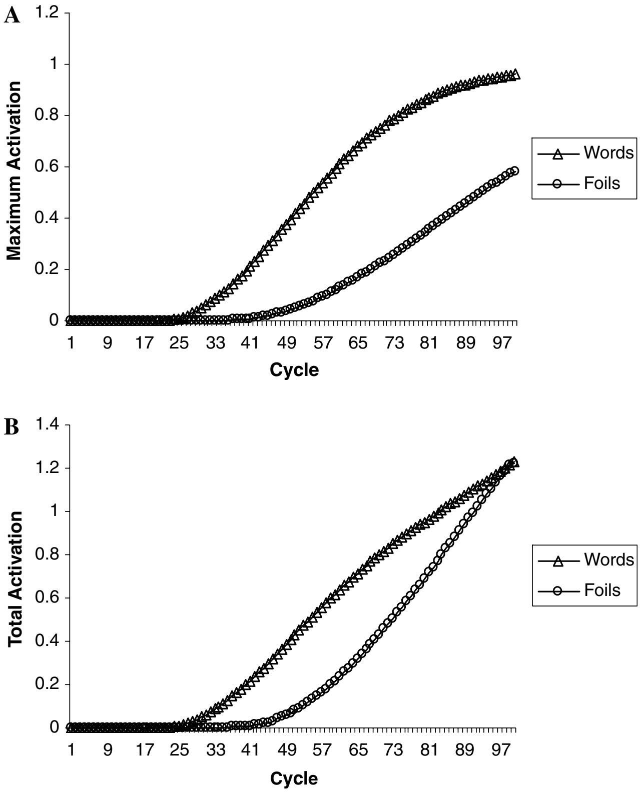

Fig. 3. Maximum phonological activation (A) and total phonological activation (B) for words and pseudohomophone foils using the standard lexical decision parameters of the DRC model.

can be made solely on the basis of phonological information; and doing so in the context of a weak phonological architecture totally eliminates the need to propose an additional spelling check.

On the basis of these simulations, we submit that the recognition of printed words in lexical decision (and perhaps in other tasks too; e.g., perceptual identification) is based largely on the analysis of phonological representations, the activation of which is constrained by orthographic information.

8. Conclusions

The research in this article began with two investigators sitting on opposite sides of the fence separating weak phonological and strong phonological theories of visual word recognition. One of us had argued on the basis of reading aloud data (e.g., Havelka & Rastle, 2005; Rastle & Coltheart, 1999) that phonological assembly is a slow and serial process, but had not considered how such a process could be reconciled with masked phonological priming effects (the empirical basis of which she questioned; Coltheart et al., 2001). The other of us had argued on the basis of masked phonological priming data (e.g., Brysbaert, 2001; Drieghe & Brysbaert, 2002) that phonological assembly is a rapid and automatic process in word recognition, but had not considered how such a process could be reconciled with reading aloud data. These divergent positions on the role of phonology in visual word recognition provide a good characterisation of the past 15 years of theoretical debate in this area. The empirical and computational investigations of masked phonological priming presented in this article led us to a new position, supported by simulations from an implemented model, which integrates these opposing perspectives in a relatively successful manner.

To end on a broader note, in considering the nature of debate in this area over the past 15 years, we have been struck by the fact that researchers too easily think in terms of yes or no distinctions (e.g., is there as masked phonological priming effect or not?) and do not realize how often they are making assumptions that are based on 'common sense' (e.g., that it is not possible to distinguish words and pseudohomophones on the basis of phonological information). If our research has any very general implications to impart, it is that the two of us could not have come to an agreement about the role of phonology in visual word recognition if we had not conducted a quantitative review of the literature, carried out new well-designed experiments, and evaluated our ideas in the context of a working computational model.

Appendix A

Item RT and error data, Experiments 1 and 2

Target	Prime	Control	Condition	E1: RT primed	E1: RT control	E1: error primed	E1: error control	E2: RT primed	E2: RT control	E2: error primed	E2: error control
coarse	korce	roipe	DDD	630	659	0.10	0.20	679	763	0.10	0.08
fade	phayed	dearch	DDD	622	593	0.05	0.00	638	654	0.05	0.08
foes	phoze	chonn	DDD					862	762	0.12	0.26
ford	phawed	droith	DDD	633	566	0.05	0.05	637	681	0.15	0.03
gaze	gheighs	gnolled	DDD	610	561	0.00	0.10	641	594	0.00	0.03
goes	ghoze	gnopp	DDD	644	608	0.05	0.20	662	657	0.07	0.00
norse	gnauce	snieve	DDD								
raid	wreighed	droigues	DDD	676	561	0.15	0.05	724	689	0.15	0.08
raise	wraze	berne	DDD	533	609	0.00	0.00	612	592	0.08	0.02
roars	wrauze	tharts	DDD	680	794	0.15	0.30	736	763	0.13	0.18
use	yuice	douke	DDD	593	594	0.10	0.00	610	608	0.03	0.07
wade	whayed	wreach	DDD	716	689	0.10	0.21	799	788	0.08	0.15
wall	whawl	wraig	DDD	647	624	0.00	0.05	652	634	0.08	0.00
ways	wheize	wreets	DDD	614	723	0.00	0.15	623	676	0.03	0.12
whores	hauze	dophe	DDD	693	817	0.15	0.25	886	905	0.23	0.22
work	whirque	wribbed	DDD	575	599	0.20	0.25	618	601	0.05	0.00
cone	koan	voon	DDS	664	697	0.10	0.35	686	681	0.17	0.08
face	phaice	plauce	DDS	581	577	0.00	0.00	557	580	0.02	0.00
file	phyle	cheal	DDS	631	595	0.15	0.00	627	618	0.07	0.05
folk	phoak	thoik	DDS	674	624	0.00	0.10	618	604	0.02	0.13
nail	gnale	koarl	DDS	581	591	0.00	0.00	567	661	0.00	0.00
noise	gnoys	chons	DDS	542	554	0.00	0.00	548	565	0.00	0.00
nurse	gnerse	roinse	DDS	546	661	0.00	0.00	588	605	0.00	0.03
phone	foan	jorn	DDS	562	598	0.05	0.00	571	622	0.02	0.05
rate	wrait	thart	DDS	687	653	0.05	0.20	685	638	0.08	0.05
root	wrute	chert	DDS	572	589	0.10	0.00	627	610	0.00	0.05
seam	ceme	relm	DDS	667	680	0.05	0.15	726	890	0.26	0.07
seat	cete	dest	DDS	555	567	0.00	0.00	577	578	0.00	0.03
walk	whauk	wraik	DDS	558	596	0.05	0.00	621	606	0.08	0.00
wise	whyes	wrees	DDS	562	582	0.00	0.00	637	612	0.03	0.00
with	whyth	wruth	DDS	614	628	0.05	0.00	629	632	0.05	0.05
write	rhight	moight	DDS	606	548	0.00	0.00	616	590	0.03	0.02

flu	phlue	slaur	DSD	727	669	0.15	0.25	681	732	0.02	0.18
flaw	phloar	gleare	DSD	666	590	0.05	0.15	677	660	0.12	0.03
catch	kach	dack	DSD	563	552	0.00	0.00	571	577	0.00	0.00
free	phrea	thref	DSD	589	574	0.00	0.10	574	580	0.02	0.05
fry	phrye	throy	DSD	650	569	0.05	0.05	601	628	0.05	0.00
nick	knique	khince	DSD	634	670	0.05	0.11	715	709	0.07	0.05
nose	knoze	thone	DSD	571	594	0.05	0.10	593	611	0.02	0.08
flow	phlo	gloy	DSD	563	549	0.05	0.10	662	571	0.00	0.00
old	oaled	oulch	DSD	545	562	0.00	0.00	584	597	0.08	0.00
coin	koign	noich	DSD	584	618	0.05	0.05	591	602	0.00	0.00
rich	writch	ghicks	DSD	555	653	0.05	0.05	610	618	0.00	0.00
web	whebb	wrell	DSD	598	635	0.00	0.20	570	683	0.08	0.12
nut	knutt	thund	DSD	578	631	0.10	0.00	583	618	0.00	0.05
claw	kloar	plarc	DSD	649	649	0.00	0.10	594	657	0.03	0.08
force	phorse	thorde	DSD	562	607	0.00	0.00	591	594	0.00	0.05
phase	faze	yade	DSD	635	642	0.00	0.10	664	681	0.05	0.02
tomb	toom	toid	SDD	585	589	0.00	0.00	610	650	0.10	0.05
bade	beighed	beaphed	SDD								
bays	beize	broak	SDD	641	687	0.25	0.17	746	731	0.15	0.05
chase	chaice	chauze	SDD	640	589	0.15	0.05	713	655	0.00	0.05
sauce	sourse	scuthe	SDD	608	611	0.05	0.00	646	616	0.00	0.10
towed	tode	toye	SDD	717	680	0.11	0.15	718	754	0.08	0.13
peace	peese	pethe	SDD	541	537	0.00	0.00	597	601	0.00	0.05
showed	shoad	shons	SDD	646	752	0.21	0.05	785	799	0.08	0.13
horse	hauce	heale	SDD	556	562	0.05	0.00	548	588	0.03	0.00
jerk	jirque	jorphe	SDD	605	667	0.05	0.11	694	669	0.03	0.00
base	baice	barle	SDD	652	706	0.00	0.10	683	683	0.08	0.15
thawed	thord	thift	SDD	647	680	0.10	0.35	774	731	0.15	0.15
lace	lais	larc	SDD	613	664	0.10	0.05	602	659	0.03	0.07
dues	dooze	deaps	SDD								
tied	tighed	tirque	SDD	561	695	0.00	0.00	629	725	0.05	0.05
haze	hays	haff	SDD	578	654	0.05	0.05	651	630	0.00	0.10
fob	phob	thob	DSS								
farm	pharm	gharm	DSS	540	604	0.00	0.00	554	581	0.02	0.03
fairs	phairs	ghairs	DSS	740	647	0.30	0.26	833	738	0.24	0.19
fin	phin	slin	DSS					642	731	0.24	0.28

(*continued on next page*)

Appendix A (*continued*)

Target	Prime	Control	Condition	E1: RT primed	E1: RT control	E1: error primed	E1: error control	E2: RT primed	E2: RT control	E2: error primed	E2: error control
fail	phail	chail	DSS	584	544	0.00	0.00	544	517	0.07	0.00
knot	gnot	klot	DSS	588	570	0.05	0.05	681	630	0.07	0.00
fat	phat	wrat	DSS	528	579	0.00	0.00	529	549	0.00	0.00
feared	pheared	sleared	DSS	647	692	0.05	0.10	635	644	0.02	0.10
cage	kage	lage	DSS	529	584	0.00	0.05	683	653	0.03	0.00
couch	kouch	mouch	DSS	569	635	0.05	0.10	635	640	0.00	0.02
set	cet	fet	DSS	575	593	0.00	0.10	570	621	0.05	0.10
fame	phame	thame	DSS	590	553	0.10	0.00	567	624	0.00	0.00
cake	kake	yake	DSS	519	587	0.00	0.10	548	625	0.00	0.07
fan	phan	chan	DSS	594	577	0.00	0.00	549	570	0.03	0.02
side	cide	jide	DSS	551	581	0.05	0.20	615	663	0.13	0.27
coal	koal	noal	DSS	628	637	0.05	0.15	605	660	0.03	0.02
sown	soan	soin	SDS	766	677	0.15	0.20	780	741	0.28	0.32
rip	ryp	rop	SDS	636	596	0.00	0.15	636	596	0.07	0.05
known	knoan	knoin	SDS	588	575	0.00	0.00	579	626	0.05	0.00
gain	gane	garn	SDS	549	590	0.00	0.00	632	576	0.00	0.03
waif	wafe	wauf	SDS								
dame	daim	darm	SDS	608	628	0.10	0.05	739	691	0.05	0.13
line	lyne	lene	SDS	699	699	0.35	0.30	743	675	0.29	0.31
ripe	rype	rupe	SDS	591	551	0.00	0.00	660	625	0.05	0.03
church	cherch	chorch	SDS	585	597	0.00	0.00	628	544	0.00	0.00

nerve	nurve	narve	SDS	563	547	0.10	0.00	671	641	0.05	0.02
paid	pade	pard	SDS	590	588	0.05	0.00	568	574	0.03	0.00
won	wun	wan	SDS	563	708	0.35	0.15	599	638	0.21	0.34
rave	raive	rauve	SDS	637	713	0.10	0.00	666	689	0.08	0.10
weight	wate	weat	SDS	578	580	0.00	0.00	572	644	0.05	0.02
moan	mone	moin	SDS	708	633	0.20	0.11	640	663	0.05	0.02
shine	shyne	shune	SDS	569	562	0.05	0.00	626	622	0.00	0.00
grow	groe	groy	SSD	572	565	0.05	0.05	569	556	0.00	0.00
lease	leace	leame	SSD	608	668	0.05	0.00	592	674	0.05	0.08
cheese	cheeze	cheede	SSD	554	590	0.00	0.00	548	600	0.02	0.00
choice	choise	choife	SSD	533	601	0.00	0.00	537	554	0.00	0.00
ski	skee	skey	SSD	586	601	0.00	0.15	566	720	0.02	0.18
cheque	chec	chem	SSD	631	616	0.05	0.10	626	667	0.00	0.03
dry	drigh	drair	SSD	533	540	0.00	0.00	540	546	0.02	0.00
pork	porque	porthe	SSD	554	557	0.00	0.05	567	566	0.02	0.03
thick	thique	thiphe	SSD	544	544	0.00	0.05	611	556	0.00	0.00
choose	chooze	choone	SSD	563	545	0.00	0.00	557	558	0.00	0.02
brew	brue	bree	SSD	604	650	0.11	0.00	698	634	0.05	0.05
shack	shaque	shaphe	SSD	581	712	0.15	0.20	660	746	0.08	0.02
blur	blirr	blorr	SSD	623	723	0.05	0.05	634	656	0.03	0.10
vat	vatt	vath	SSD								
dark	darque	darthe	SSD	549	511	0.00	0.00	547	554	0.00	0.02
sky	skigh	skorr	SSD	514	517	0.05	0.00	534	550	0.00	0.00

Note: D, Different; S, Same.

Appendix B

Prime–target pairs for the “NO” response, Experiments 1 and 2 (*Note.* D, “Different”; S, “Same”)

Relationship	Condition	E1: target	E1: prime	E2: target	E2: prime
Phonological	DDD	neaf	kneeph	roze	wroes
Phonological	DDD	cautch	korch	neas	gneeze
Phonological	DDD	corgue	kaugg	rize	wrighs
Phonological	DDD	knide	nighed	suide	psewed
Phonological	DDD	reace	wreese	whares	wairze
Phonological	DDD	rauce	rhawse	sord	psawed
Phonological	DDD	wheam	weemb	werce	whurse
Phonological	DDD	phease	feece	kares	cairze
Phonological	DDS	werch	whurch	rhume	roome
Phonological	DDS	furve	pherve	fawm	phorm
Phonological	DDS	feen	phean	reak	wreek
Phonological	DDS	ribe	rhybe	nome	knoam
Phonological	DDS	feek	pheak	phine	fighn
Phonological	DDS	gope	ghoap	wurd	wherd
Phonological	DDS	reat	rhete	wrove	roave
Phonological	DDS	nurch	knirch	nune	gnoon
Phonological	DSD	feb	phebb	rhum	rumm
Phonological	DSD	phof	foff	fligh	phly
Phonological	DSD	fid	phidd	fel	phell
Phonological	DSD	rin	rhinn	phib	fibb
Phonological	DSD	phick	fique	ruph	wruff
Phonological	DSD	weff	wheph	caim	kaimm
Phonological	DSD	cice	sise	rimm	rhimn
Phonological	DSD	fuch	phutch	coak	koack
Phonological	SDD	shoof	shuiff	vears	vierze
Phonological	SDD	soys	soize	gize	gighs
Phonological	SDD	loys	loize	shayed	shaid
Phonological	SDD	zays	zaize	tize	tighs
Phonological	SDD	deak	deeck	beas	beeze
Phonological	SDD	hase	haiss	purke	perck
Phonological	SDD	berge	burdge	baws	borze
Phonological	SDD	zake	zaick	heers	hierze
Phonological	DSS	nurk	gnurk	ceap	seap
Phonological	DSS	cig	sig	nooze	knooze
Phonological	DSS	fown	phown	fite	phite
Phonological	DSS	fet	phet	weap	wheap
Phonological	DSS	gert	jert	repe	rhepe
Phonological	DSS	wone	whone	roal	rhoal
Phonological	DSS	roid	wroid	whym	wym
Phonological	DSS	cesh	sesh	feal	pheal
Phonological	SDS	zeat	zeet	koat	kote
Phonological	SDS	veam	veme	tawn	taughn
Phonological	SDS	rause	rourse	shaze	shaize
Phonological	SDS	pode	poad	vise	vighse
Phonological	SDS	gome	goam	mase	maise
Phonological	SDS	wabe	waib	dert	durt
Phonological	SDS	thale	thail	kope	koap
Phonological	SDS	zane	zain	kead	keed
Phonological	SSD	juff	juph	teek	teeck
Phonological	SSD	slee	slea	skore	skoar
Phonological	SSD	pum	pumb	lak	lac

Appendix B (*continued*)

Relationship	Condition	E1: target	E1: prime	E2: target	E2: prime
Phonological	SSD	bick	bique	hed	hedd
Phonological	SSD	sech	setch	stear	stier
Phonological	SSD	lum	lumb	pek	pec
Phonological	SSD	lod	lodd	beaf	beaph
Phonological	SSD	shick	shique	kuff	kuph
Graphemic	DDD	pess	daich	stey	blie
Graphemic	DDD	frew	bleigh	pach	shirl
Graphemic	DDD	yarm	poarb	snoe	frur
Graphemic	DDD	jark	soub	gurl	wheff
Graphemic	DDD	derd	coib	boes	nirl
Graphemic	DDD	yight	fairn	leed	shait
Graphemic	DDD	rarp	veed	beed	marf
Graphemic	DDD	jurse	taid	cill	vach
Graphemic	DDS	bup	meep	kave	soiv
Graphemic	DDS	chupe	vaip	whif	yarf
Graphemic	DDS	mome	hoarm	whove	firv
Graphemic	DDS	yine	woin	whide	broid
Graphemic	DDS	vart	seight	ratt	chett
Graphemic	DDS	leck	dack	rane	gien
Graphemic	DDS	hile	jairl	saive	pheev
Graphemic	DDS	shan	knin	mutch	zatch
Graphemic	DSD	tein	peith	wede	chele
Graphemic	DSD	yome	chope	kub	zum
Graphemic	DSD	nim	thipp	whish	vitt
Graphemic	DSD	lerge	serne	dimb	pidge
Graphemic	DSD	cose	wroke	phole	sofe
Graphemic	DSD	lub	humb	rale	vafe
Graphemic	DSD	thock	jong	pauze	thaule
Graphemic	DSD	louch	thoudd	voat	toadge
Graphemic	SDD	jass	jeeth	laim	leeth
Graphemic	SDD	hade	hoinn	dene	daip
Graphemic	SDD	meem	mairt	whill	whoir
Graphemic	SDD	nush	naid	chude	chait
Graphemic	SDD	sares	searth	kool	kib
Graphemic	SDD	youch	yain	wheek	whain
Graphemic	SDD	tol	teave	trey	taich
Graphemic	SDD	curn	caidd	lide	leedge
Graphemic	DSS	jone	chone	wod	dod
Graphemic	DSS	jave	yave	peech	zeech
Graphemic	DSS	yeared	meared	hirt	lirt
Graphemic	DSS	beve	cheve	mard	thard
Graphemic	DSS	mib	hib	wrood	shood
Graphemic	DSS	gowd	sowd	rhice	sice
Graphemic	DSS	petch	hetch	wrace	hace
Graphemic	DSS	meck	veck	lews	gews
Graphemic	SDS	beash	baish	kap	kep
Graphemic	SDS	zile	zel	buss	biss
Graphemic	SDS	sheed	shad	boch	buch
Graphemic	SDS	shog	sheeg	yooth	yieth
Graphemic	SDS	darred	deighed	whoze	whoiz
Graphemic	SDS	degg	dagg	mame	meim

(*continued on next page*)

Appendix B (*continued*)

Relationship	Condition	E1: target	E1: prime	E2: target	E2: prime
Graphemic	SDS	kive	korve	tole	tuil
Graphemic	SDS	zorgue	zaigue	nise	nais
Graphemic	SSD	dobe	dode	yel	yed
Graphemic	SSD	coob	coom	dait	daich
Graphemic	SSD	vig	vib	rhed	rhell
Graphemic	SSD	paim	paith	boath	boam
Graphemic	SSD	vove	vope	froe	frie
Graphemic	SSD	nuck	nutch	harve	harge
Graphemic	SSD	shace	shafe	bumb	buth
Graphemic	SSD	thutch	thunn	sead	seaph

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