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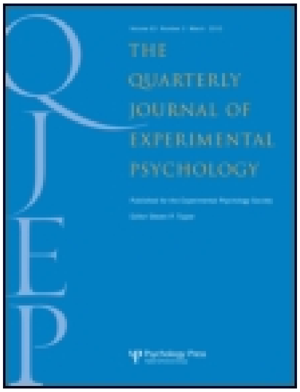

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Can the dual-route cascaded computational model of reading offer a valid account of the masked onset priming effect?

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The masked onset priming effect (MOPE) refers to the empirical finding that target naming is faster when the target (SIB) is preceded by a briefly presented masked prime that starts with the same letter/phoneme (*suf*) than when it does not (*mof*; Kinoshita, 2000, Experiment 1). The dual-route cascaded (DRC) computational model of reading (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001) has offered an explanation for how the MOPE might occur in humans. However, there has been some empirical discrepancy regarding whether for nonword items the effect is limited to the first-letter/phoneme overlap between primes and targets or whether orthographic/phonological priming effects occur beyond the first letter/phoneme. Experiment 1 tested these two possibilities. The human results, which were successfully simulated by the DRC model, showed priming beyond the first letter/phoneme. Nevertheless, two recent versions of the DRC model made different predictions regarding the nature of these priming effects. Experiment 2 examined whether it is facilitatory, inhibitory, or both, in order to adjudicate between the two versions of the model. The human results showed that primes exert both facilitatory and inhibitory effects.

Keywords: Reading aloud; Masked onset priming effect; Dual-route cascaded computational model of reading.

Reading aloud consists of transforming print to speech. This print-to-sound transformation has been explained within a dual-route framework (Coltheart, 1978; Coltheart, Curtis, Atkins, & Haller, 1993; Forster & Chambers, 1973; Marshall & Newcombe, 1973) and within a connectionist framework (Plaut, McClelland, Seidenberg, & Patterson, 1996; Seidenberg & McClelland, 1989). According to the dual-route theory of reading, reading aloud consists of a lexical route and a nonlexical route. The lexical route involves looking up a word in a mental lexicon that contains knowledge about the pronunciation and spelling of letter strings that are real words, and the nonlexical route involves decoding letter strings from print to speech using

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letter–sound rules. According to the connectionist approach, there is no distinction between a lexical and a nonlexical procedure; instead, the same mechanism is used to convert print into sound for words and for nonwords. This mechanism is based on connections between orthographic input units and phonological output units.

An empirical finding, which has been explained by the dual-route theory of reading but has not been explained by connectionist theories, is the masked onset priming effect (hereinafter MOPE). In the masked priming three-field paradigm, a series of hash marks (#####) is presented first for approximately 500 ms; these are then replaced by a prime word/nonword that is presented in lower-case letters for between 50 and 60 ms, after which the prime is replaced by a target word/nonword that is presented in upper-case letters for 500 ms or until a response is generated by the participants (Forster & Davis, 1984). The MOPE, in particular, refers to the finding that target naming is faster when the targets are preceded by first-letter/phoneme related primes than when they are preceded by unrelated ones. The explanation that the dual-route theory of reading offers for this effect is that it occurs due to the functioning of the nonlexical route, which operates serially and from left to right. More specifically, during prime presentation the nonlexical reading route processes the first letter of the prime and translates it into its corresponding phoneme. Therefore, when the target is presented, the first phoneme of the prime has already been activated. If the target's first phoneme is different from that of its prime (e.g., *merry*–BREAK), there is a pronunciation conflict that delays target naming in comparison with when the target's first phoneme is similar to that of its prime (e.g., *belly*–BREAK). Also, in the latter case, the preactivation of the first phoneme of the target by its prime can facilitate the naming of the target in comparison with the unrelated condition.

The dual-route interpretation of the MOPE has been particularly supported by a study carried out by Kinoshita (2000, Experiment 1). In that study, three-letter-long CVC (in which C is consonant and V is vowel) nonword targets (e.g., SIB) were preceded by three types of prime that overlapped with the targets in a left-to-right manner—one-letter overlap (*suf*–SIB), two-letters overlap (*sif*–SIB), all-letters different (*mof*–SIB)—and also in a right-to-left manner—one-letter overlap (*mub*–SIB), two-letters overlap (*mib*–SIB), all-letters different (*mof*–SIB). Participants were instructed to read aloud the nonwords in upper-case letters, while no mention about the prime was made to them. The prime duration used in that experiment was 56 ms. The results showed that participants' naming reaction times to the nonword targets were significantly faster in the one-letter and two-letters overlap conditions than in the all-letters-different condition only when the letter/phoneme overlap between the prime and the target was either in the first or the first and the second positions (that is, *suf*–SIB, *sif*–SIB), confirming the dual-route hypothesis that left-to-right processing of the prime via a nonlexical serial mechanism causes the MOPE to occur. Additionally, the naming latency difference between the *suf*–SIB and the *sif*–SIB conditions was not significant, indicating that the second letter/phoneme of the prime does not have an influence on target naming. Such a result could be explained by the dual-route theory of reading on the basis that, at a brief prime duration (below 60 ms), participants' nonlexical route has time only to process the first letter of the prime and translate it into its corresponding phoneme.

The validity of the verbal dual-route account of the MOPE can be explicitly tested using the dual-route cascaded (DRC) computational model of reading (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001), which is a computational implementation of the dual-route theory of reading (see Figure 1).

In an attempt to simulate Kinoshita's (2000) finding with the DRC 1.1.4 version (Biedermann, Coltheart, Nickels, & Saunders, 2009; Nickels, Biedermann, Coltheart, Saunders, & Tree, 2008), we presented first a three-letter long CVC nonword prime to the model for a number of cycles so that the nonlexical route would have time to process at least its first letter, and also the activation of its first phoneme at the

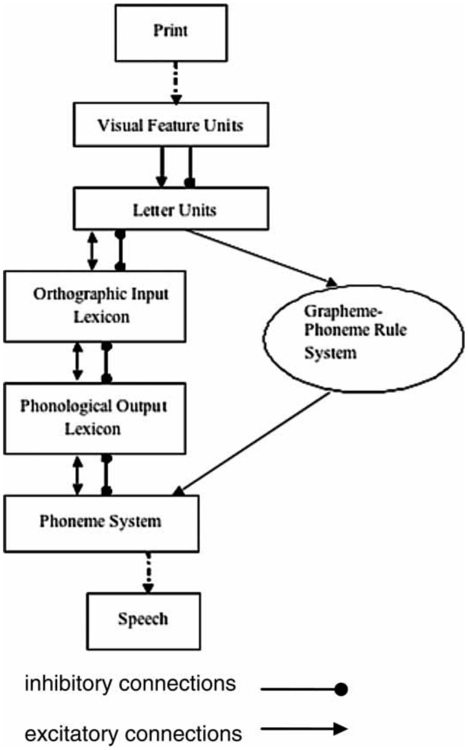

Figure 1. *The dual-route cascaded (DRC) model. From "DRC: A Dual Route Cascaded Model of Visual Word Recognition and Reading Aloud", by M. Coltheart, K. Rastle, C. Perry, R. Langdon, and J. Ziegler, 2001,* Psychological Review, 108, *pp. 204–256. Copyright 2001 by Max Coltheart. Adapted with permission.*

phoneme level would have time to build up and have an effect thus (either facilitatory in the onset-related conditions, or inhibitory in the unrelated condition) on the first phoneme of the target;[1] we then replaced the prime with a three-letter-long CVC nonword target, while we applied decay at the letter level in order to simulate backward masking.[2] The DRC 1.1.4 model showed a target naming-latency advantage in the onset-related conditions in comparison with the all-letters-different condition (*suf*–SIB and *sif*–SIB < *mof*–SIB), but no priming beyond the first letter/phoneme (*suf*–SIB = *sif*–SIB), confirming the theoretical dual-route explanation of the Kinoshita data (2000, Experiment 1)—namely, that at a specific prime duration participants' nonlexical route has time only to process the first letter of the prime and translate it into its corresponding phoneme.

However, Kinoshita's (2000) results do not agree with the results from other studies of reading aloud that investigated orthographic/phonological priming effects with nonword items (Horemans & Schiller, 2004; Masson & Isaak, 1999).[3] In the Masson and Isaak study (1999, Experiment 1), nonword targets (e.g., NUMP) were preceded by three types of prime: repetition primes (*nump*), orthographic primes (*nurp*), and first-letter/phoneme related primes (*nalk*), which were presented for 50 ms. The results revealed a masked orthographic priming effect—that is, NUMP preceded by *nurp* was named faster than NUMP preceded by *nalk*, indicating that more letters of the prime than the first have an influence on the target.[4]

In the Horemans and Schiller (2004) study, nonword target items (e.g., KATROEN) were preceded by five types of prime: first-syllable (e.g., %%*ka*%%%%%%), first-segment (e.g., %%*k*%%%%%%%),

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[1] For the DRC 1.1.4 model to show a MOPE with three-letter-long CVC nonword prime–target pairs, the minimum prime duration had to be 40 cycles.

[2] In human experiments that use the three-field paradigm masking procedure, which is the procedure used in the studies that we tried to simulate with the DRC model in the present study, a forward mask is presented first, followed by the prime, followed by the target. The target acts as a backward mask to the prime so that the prime's letters are not visible to the participants at target onset. In order to simulate backward masking effects with the DRC model in the same way as they occur with humans, the activation of the prime's letters at the letter level was completely switched off at target onset so that the letters of the prime would not be available to the model when the target was presented.

[3] Given that different components of the human reading system are likely to be involved in word versus nonword reading (e.g., lexical vs. nonlexical route for word and nonword reading, respectively) we only refer here to the discrepancies among empirical studies of masked priming that used nonword stimuli.

[4] It is worth noting that although the orthographic priming effect in that study was significant in the subject analysis, it was not significant in the item analysis, and therefore the effect was not consistent across items.

first-segment plus second-syllable (e.g., `%%k%troen%`), second-syllable (e.g., `%%%%troen%`), and control (e.g., `%%%%%%%%%%`) primes, which were presented for 50 ms. The results showed small priming effects both in the first-segment condition and in the second-syllable condition in comparison with the control condition. These priming effects were significant by items and marginally significant by participants. Most importantly though, human naming latencies were faster in the first-syllable condition and the first-segment plus second-syllable condition than in the other three conditions, indicating form priming beyond the initial letter/phoneme.[5]

The discrepancy of the data in the three studies mentioned above led us to carry out a new study that was similar to Kinoshita's (2000) Experiment 1, but with a more powerful experimental design so as to increase the statistical power of the analyses. Our Experiment 1 consisted of three-letter-long CVC nonword targets (e.g., SIB) that were preceded by three types of prime that overlapped with the targets in a left-to-right manner: one-letter overlap (*suf*–SIB), two-letters overlap (*sif*–SIB), zero-letter overlap (*mof*–SIB). If at a relatively short prime duration (below 60 ms) participants do not process more than the first letter/phoneme of the prime we should be able to replicate Kinoshita's findings. Such a result would be correctly simulated by the DRC model and would therefore fully agree with the dual-route explanation of the effect. Nevertheless, if participants are capable of nonlexically processing more letters/phonemes of the prime than the first during prime presentation, our results should show priming beyond the first letter/phoneme—that is, *sif*–SIB < *suf*–SIB, and therefore a different interpretation of the human data should be sought. Most importantly though, any empirical result and its possible explicit interpretation by a computational model of reading would enhance our knowledge of how the human reading system operates.

But how does the MOPE arise in the DRC model? Why does the model show faster target-naming latencies in the onset-related conditions than in the unrelated one? We sought the answer to these questions by examining the behaviour of the DRC 1.1.4 version when nonword prime–target pairs were presented to the model. In particular, DRC 1.1.4, which differs from the original DRC version reported in the 2001 Psychological Review paper (Coltheart et al., 2001), known as DRC 1.0,[6] shows a MOPE because when the prime and the target do not share their first phoneme (unrelated condition), and the activation of the prime's first phoneme at the phoneme level has been built up sufficiently so as to compete strongly with the target's first phoneme and therefore delay its naming, targets are named slower than in the onset-related conditions, where prime and target share their first phoneme, and therefore there is no competition in the first-phoneme position. According to DRC 1.1.4, then, the MOPE is inhibitory in nature.

Nevertheless, a new version of the DRC model has recently been developed, because it was observed that although DRC 1.1.4 showed a MOPE with three-letter-long nonwords, it failed to show the effect with five-letter-long nonwords, while the results from an experiment that was carried out with humans in our laboratory showed a MOPE for nonword stimuli of both letter lengths (see Mousikou, Coltheart, Saunders, & Yen, in press, Experiment 3). Also, although DRC 1.1.4 showed a MOPE with word items at a relatively short prime duration (28 cycles), it could only show a MOPE with nonword items at a significantly longer prime duration (from 40 cycles onwards depending on the items' letter length), and this is not the case in humans where, independently of the items' lexical status, a MOPE has been found at similar prime durations (Forster & Davis, 1991; Grainger & Ferrand, 1996; Kinoshita, 2000; Kinoshita & Woollams,

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[5] The results from this experiment also show an advantage of initial over final overlap between the prime and the target, which agrees with the idea that a nonlexical serial mechanism must be processing the prime in a left-to-right manner.

[6] The differences between the two versions are fully documented at: http://www.maccs.mq.edu.au/~ssaunder/DRC/DRC-Differences.pdf

2002; Malouf & Kinoshita, 2007; Mousikou et al., in press; Schiller, 2004, 2007, 2008).

The reason that DRC 1.1.4 behaves as it does in the two cases mentioned above is that its nonlexical route's left-to-right movement is controlled by a rule of the form: move on to the next letter after a fixed number (17 in the model's standard parameters) of processing cycles have elapsed (for a detailed explanation of how such a rule affects the model's behaviour in the above two situations see Mousikou et al., 2009). As a result, the newer version of the model, called DRC 1.2, which can be downloaded from http://www.maccs.mq.edu.au/~ssaunder/DRC/,[7] has a nonlexical route that operates differently from that of DRC 1.1.4. In particular, the nonlexical route of DRC 1.2 moves on to the next letter (in a serial left-to-right manner) when any phoneme in the right-most phoneme unit excited by the nonlexical route on the previous cycle reaches an activation level that is greater than or equal to the value of a new parameter implemented in the model: the GPCCriticalPhonology parameter. In combination with this new parameter, decay is applied to unsupported phoneme units so that if a phoneme is no longer receiving excitation from any source, its activation will decrease in value across cycles. The strength of this decay is controlled by a new parameter called PhonemeUnsupportedDecay.

According to this new rule implemented in the model, the MOPE is both facilitatory and inhibitory in nature. In particular, when the prime and the target share their first phoneme (onset-related condition) target naming occurs faster than when they do not (unrelated condition), because in the onset-related condition the preactivation of the prime's first phoneme at the phoneme level facilitates the activation of the target's first phoneme, which reaches the GPCCriticalPhonology parameter earlier than in the unrelated condition, where the prime's first phoneme competes with the target's first phoneme causing delay in target naming.

Given that the 1.1.4 and 1.2 versions of the DRC model make different predictions with regard to the nature of priming effects in humans, it was of particular interest to us to determine whether priming effects are facilitatory, or inhibitory, or both, in order to further adjudicate between the two versions of the DRC model. However, is there any empirical evidence to date regarding the nature of priming effects?

The MOPE in particular was originally interpreted by Forster and Davis (1991) in terms of a response competition hypothesis, where a pronunciation conflict between the first phoneme of the prime and the first phoneme of the target in the unrelated condition causes participants' target-naming latencies to slow down (inhibitory effect). Nevertheless, it could also be that the MOPE is due to participants' target-naming latencies speeding up when the target's first phoneme is preactivated by its prime in the first-letter/phoneme related condition (facilitatory effect). Moreover, the MOPE could be both facilitatory and inhibitory. The Forster and Davis (1991) study did not allow disentangling among these three possibilities though.

Some inferences about the nature of the MOPE were also made in a study that was carried out by Grainger and Ferrand (1996, Experiment 5). In that study, a first-letter/phoneme related condition (*nise*–NERF) was compared to an unrelated condition (*fise*–NERF) and to a condition where the prime consisted of a nonletter symbol in the first position (*%ise*–NERF). The human results showed faster target-naming latencies in the first-letter/phoneme related condition than in the other two, which did not differ significantly from each other. The authors took this result as evidence in

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[7] On the same site the differences between this version and the original DRC version—that is, DRC 1.0 (Coltheart et al., 2001)—are fully documented. Also, a document entitled Incremental Modelling reports results from the simulations (with DRC 1.2) of all the benchmark effects on reading aloud (as listed in Perry, Ziegler, & Zorzi, 2007, p. 301) that DRC 1.0 could simulate. Both for the simulations of these benchmark effects and for the simulations of the experiments reported in the present paper the default parameters installed in the downloadable model were used.

favour of a facilitatory effect and against an inhibitory effect, assuming that the condition containing the *%* sign in the first position of the prime cannot cause response competition. In particular, they argued that since the condition containing the *%* sign is not inhibitory, the unrelated condition could not be inhibitory either, because target-naming latencies in these two conditions did not differ significantly from each other. However, it is questionable whether familiar symbols like percentage signs should be considered as neutral in nature.[8] Therefore, the MOPE found in Grainger's and Ferrand's study, for example, could well be due to an inhibitory effect caused both by the *fise*–NERF and the *%ise*–NERF conditions, or to both a facilitatory and an inhibitory effect caused by the onset-related and the unrelated conditions, respectively. Similarly to the Forster and Davis (1991) study then, the Grainger and Ferrand (1996) study did not allow disentangling among these possibilities.

The lack of empirical evidence regarding whether priming effects, and in particular the MOPE, arise due to inhibitory, facilitatory, or both inhibitory and facilitatory processes led us to conduct a study that aimed at determining the nature of priming effects. The empirical finding of such a study could help us adjudicate between two versions of the DRC model that make different predictions about how priming effects arise in humans. In Experiment 2 we used an *incremental priming technique* (see also Jacobs, Grainger, & Ferrand, 1995; Ziegler, Ferrand, Jacobs, Rey, & Grainger, 2000). In particular, we varied prime duration so that the shortest would serve as a within-condition baseline, while prime type served as the traditional across-condition baseline.

To summarize, Experiment 1 was carried out in order to solve the empirical discrepancy regarding whether there is orthographic/phonological priming beyond the first letter/phoneme for nonword items. The result from such a study could be used to test whether the DRC computational model of reading is able to offer a valid explanation for the observed empirical findings. Given that two versions of the DRC model—the previously downloadable DRC version (i.e., DRC 1.1.4) and the currently downloadable DRC version (i.e., DRC 1.2)—make different predictions with regard to how priming effects occur in humans, the aim of Experiment 2 was to determine the nature of priming effects and adjudicate thus between the two versions of the DRC model.

EXPERIMENT 1

Method

Materials

A total of 324 three-letter-long pronounceable nonwords with graphemic and phonological CVC (consonant–vowel–consonant) structure were selected from the ARC nonword database (Rastle, Harrington, & Coltheart, 2002). A total of 81 nonwords served as target items, and the remaining 243 served as their prime pairs. In particular, three groups of 81 prime–target pairs were formed with the targets remaining the same in all three groups. Three types of prime that matched on mean N[9] were used: primes that shared their first letter and phoneme with their targets (e.g., *suf*–SIB; one-letter overlap condition); primes that shared their first two letters and phonemes with their targets (e.g., *sif*–SIB; two-letters overlap condition); primes that shared no letters or phonemes with their targets in the same position[10] (e.g., *mof*–SIB; unrelated condition). The items used in Experiment 1 are listed in the Appendix.

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[8] The findings from a study that Finkbeiner, Almeida, and Caramazza (2006) conducted showed that nonletter distractors (e.g., ^% ~ *#) engage a bilaterally distributed mechanism responsible for detecting letter shapes: the first stage in the reading process, as the authors suggest on page 1098 of the corresponding paper.

[9] Coltheart, Davelaar, Jonasson, and Besner (1977) defined neighbourhood size (N) as the number of words differing by a single letter from the stimulus, preserving letter positions—for example, worse and house are orthographic neighbours of horse.

[10] Due to an oversight, two pairs in the unrelated condition shared the same phoneme in the same position—that is, dys–PIV and pym–VIC.

In addition to the three groups of 81 prime–target pairs that formed the experimental stimuli, 9 more pairs of primes and targets that matched the experimental stimuli on the same criteria were selected as practice items.

Design

Each experimental condition (one-letter overlap, two-letters overlap, unrelated) consisted of 81 prime–target pairs for a total of 243 pairs per participant in a fully counterbalanced design. This meant that every participant saw the 81 targets three times, each time in a different prime-type condition. A mixed design was used so that the three prime-type conditions were presented in a random order across the experiment. Further, the 243 trials were divided into three blocks so that the same target would not appear more than once within the same block. Also, a brief break was administered between the blocks. Last, three lists were constructed to counterbalance the order of block presentation. An equal number of participants ($N = 8$) were tested on each list.

Participants

A total of 24 undergraduate Macquarie University students participated in this experiment for course credit. All participants were native speakers of Australian English.

Procedure

Participants were tested individually, seated approximately 40 cm in front of a Dell 19″ flat CRT (100-Hz) monitor, upon which the stimuli were presented. Participants were instructed (verbally first and then by written instructions on the monitor) that a list of nonwords, preceded by a series of hash marks (###), would be presented on the screen one at a time and that their task was to read aloud the nonword in upper-case letters as quickly and as accurately as possible. The presence of a prime was not mentioned to the participants. Stimuli were presented to each participant in a different random order, following a series of practice trials that matched the experimental stimuli on the same criteria.

Instructions and stimuli were presented, and naming latencies were recorded to the nearest millisecond using the DMDX display system (Forster & Forster, 2003) on a Dell Pentium 4 computer. Reaction time was recorded by a Beyerdynamic microphone fitted to each participant by means of a headset.

Each trial started with the presentation of a forward mask (###) that remained on the screen for 500 ms. The prime was then presented in lower-case letters for 55.6 ms (4 ticks based on the machine's refresh rate of 13.88 ms), followed by the target, which was presented in upper-case letters and acted as a backward mask to the prime. The target words appeared in white on a black background (Courier New, 12 font) and remained on the screen for 2,000 ms or until participants responded. The intertrial interval was 1,000 ms. The order of trial presentation within blocks and lists was randomized across participants.

Results

Participant responses were hand marked using CheckVocal (Protopapas, 2007). To reduce the effects of outliers, any reaction times (RTs) slower than 1,500 ms or faster than 200 ms were discarded from the analyses. Also, any RTs more than 2 standard deviations (*SD*s) units away from the overall mean RT for each participant were trimmed by setting them equal to the default cut-off value. The results are shown on Table 1.

In the RT analysis, a repeated measures analysis of variance (ANOVA) with prime type (one-letter overlap, two-letters overlap, unrelated) as a within-subjects factor and block of presentation (List A, List B, List C) as a between-subjects factor showed that the main effect of prime type was significant, $F_1(1.19,\ 25.06) = 154.19, p < .001$ (Greenhouse–Geisser correction), $F_2(2,\ 720) = 94.09,\ p < .001$.[11] There was no

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[11] In the item analysis prime type was a between-groups factor, and therefore a univariate analysis of variance was carried out with prime type (one-letter, two-letters, unrelated) and list (A, B, and C) as fixed factors.

Table 1. *Mean reaction times and mean errors from Experiment 1*

	RT (SD)	*Errors (SD)*
suf–SIB	480 (61.8)	4.1 (3.8)
sif–SIB	476 (62.0)	3.4 (3.4)
Average *suf*–SIB & *sif*–SIB	478 (61.8)	3.8 (3.4)
mof– SIB	513 (56.0)	6.7 (7.5)

Note: RT = reaction time (in ms); *SD* = standard deviation.

interaction between prime type and block of presentation, $F_1(2.39, 25.06) < 1$ (Greenhouse–Geisser correction), $F_2(4, 720) < 1$. Planned comparisons tested whether RTs in the unrelated condition were significantly slower than those in the onset-related conditions by calculating the average of the mean RTs in the related conditions and comparing it to the mean RTs in the unrelated condition—that is, *suf*–SIB and *sif*–SIB/2 versus *mof*–SIB. The *t* test from this comparison was significant, $t_1(23) = 13.22$, $p < .001$, $t_2(80) = 15.60$, $p < .001$, indicating that letter(s)/phoneme(s) overlap between the prime and the target causes faster target-naming latencies than no letter(s)/phoneme(s) overlap. Further planned comparisons between the one-letter and the two-letters overlap condition also showed that target-naming latencies in the latter condition were significantly faster than those in the former, $t_1(23) = 4.19$, $p < .001$, $t_2(80) = 2.16$, $p = .034$.

The error analysis was carried out in the same way as the RT analysis. The results showed that the main effect of prime type was significant, $F_1(1.30, 27.26) = 5.68$, $p = .017$ (Greenhouse–Geisser correction), $F_2(2, 720) = 10.09$, $p < .001$. The interaction between prime type and block of presentation was not significant, $F_1(2.59, 27.26) = 1.28$, $p > .05$ (Greenhouse–Geisser correction), $F_2(4, 720) = 2.25$, $p > .05$. Planned comparisons tested whether participants made more errors in the unrelated condition than in the related conditions. The *t* test from this comparison was significant, $t_1(23) = 2.50$, $p = .02$, $t_2(80) = 4.24$, $p < .001$. However, the difference in error rate between the one-letter and two-letters overlap conditions was not significant, $t_1(23) = 1.20$, $p > .05$, $t_2(80) < 1$.

Discussion

An experiment on reading aloud investigated whether for nonword items orthographic/phonological overlap between primes and targets affects target-naming latencies beyond a first-letter/phoneme overlap. The results showed that it does. In particular, a robust MOPE was found in Experiment 1, so that target-naming latencies were significantly faster in the conditions where primes and targets shared their first letter/phoneme than in the condition where primes and targets shared no letters/phonemes in the same position. Most importantly though, target naming was faster in the condition where primes and targets shared their first two letters/phonemes than in the condition where primes and targets shared just their first letter/phoneme. This difference was just 4 ms in the subject analysis and almost 5 ms in the item analysis, but it was statistically significant in both, indicating that at a prime duration of 55.6 ms information about the second letter/phoneme of the prime becomes available to the participants (at least sometimes or for some participants).[12]

Our finding was inconsistent with Kinoshita's finding (2000, Experiment 1), where no priming beyond the first letter/phoneme was observed; however, it is worth noting that in Kinoshita's study, target naming in the two-letters overlap condition occurred 3 ms faster than in the one-letter overlap condition; hence Kinoshita's results were in the same direction as ours. The reason why the difference between the one-letter and the two-letters overlap condition was significant in our study but not in Kinoshita's study could be either the increased power in our study

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[12] When we looked at the individual RTs we noticed that 16 out of 24 participants showed a naming-latency advantage in the two-letters overlap condition in comparison with the one-letter overlap condition. Similarly, 47 out of 81 targets yielded faster naming latencies in the two-letters overlap condition than in the one-letter overlap condition.

(more experimental stimuli and trials in each of the three experimental conditions, repeated measures design), or the increased accuracy in reaction time measuring that is achieved by hand marking our participants' naming responses. Most importantly, our finding was consistent with the findings from the other two studies mentioned above, which also found that for nonword prime–target pairs there is priming beyond the first letter/phoneme (Horemans & Schiller, 2004; Masson & Isaak, 1999).

So can the DRC computational model of reading offer an explanation for our results? The two most recently downloadable versions (DRC 1.1.4 and DRC 1.2) make different predictions with regard to whether the priming effects observed in humans are due to competition between the first letter(s)/phoneme(s) of the unrelated prime and the first letter(s)/phoneme(s) of the target, to facilitation from the first letter(s)/phoneme(s) of the related prime to the first letter(s)/phoneme(s) of the target, or to both processes. Therefore, Experiment 2 was carried out to investigate these possibilities in order to adjudicate between the two versions of the DRC model.

EXPERIMENT 2

In Experiment 2 we examined the nature of the priming effects observed in Experiment 1 by crossing the factors prime type and prime duration. In particular, if the priming effects observed in Experiment 1 were solely inhibitory in nature, when prime duration is increased naming latencies should increase in the unrelated condition (*mof*–SIB) but remain constant in the two related conditions (*suf*–SIB and *sif*–SIB). This is because the more the first letter/phoneme (or it could also be the second and the third depending on the number of letters that participants are able to process at each prime duration) of the unrelated prime (*mof*) becomes available to the participants by increasing its exposure, the more interference it should cause to the target (SIB) and therefore delay its naming. However, if the effects observed in Experiment 1 were solely facilitatory in nature, when prime duration is increased naming latencies should decrease in the one-letter and two-letters overlap conditions (*suf*–SIB and *sif*–SIB), but remain constant in the unrelated condition (*mof*–SIB). This is because the more the first letter/phoneme (or the first two in the two-letters overlap condition) of the related primes (*suf* or *sib*) becomes available to the participants by increasing its exposure, the more it should activate the first letter/phoneme of the target (SIB; or the first two in the case of the two-letters overlap condition) and therefore speed up its naming. Last, if the effects were both inhibitory and facilitatory in nature, as prime duration is increased naming latencies should decrease in the one-letter and two-letters overlap conditions (*suf*–SIB and *sif*–SIB) and increase in the unrelated condition (*mof*–SIB).

Moreover, given that our findings from Experiment 1 indicated that information about the second letter/phoneme of the prime becomes available to the participants at a relatively short prime duration (that is, 55.6 ms), at least sometimes or for some participants (see Footnote 12), in Experiment 2 we should observe clear orthographic/phonological priming effects as a function of prime duration, because if primes are exposed to the participants for longer durations, their nonlexical route will have sufficient time to process more letters of the prime than just the first.

Method

Materials

The same stimuli as those in Experiment 1 were used in Experiment 2 (see Appendix).

Design

The design of Experiment 2 was similar to that of Experiment 1; however, prime duration was now added as an extra factor. In particular, three prime durations were used: 50.1, 70.14, and 90.18 ms (5, 7, and 9 ticks based on the machine's refresh rate of 10.02 ms).[13] A total of 81 pairs of primes and targets were presented in three prime-type and prime-duration conditions for a total of 243 pairs per participant. Therefore, every participant saw the 81 targets three times, each time preceded by a different type of prime and a different prime duration. The three prime durations were equally represented across the total number of trials that corresponded to each participant.

In Experiment 2 we were only interested in the effects of the variable of prime duration and not in the effects of the variable of prime type, because the latter effects had already been identified in Experiment 1, which used a masked-priming procedure. Therefore, if we presented the three levels of each of the two independent variables (prime type and prime duration) in a mixed design, it was very likely that the effect of the variable we were interested in—that is, prime duration—would be smaller in size (and maybe unidentifiable) than that in a blocked design (see Los, 1996, p. 146). As a result, we decided to block the items by prime type, while the three prime durations were randomly mixed across the experiment.[14]

Similarly to Experiment 1, the 243 trials were divided into three blocks so that the same target would not appear more than once within the same block, but now each of the three blocks represented a different prime-type condition. A brief break was administered between the blocks. Three lists were constructed to ensure a totally counterbalanced order of block presentation, and an equal number of participants ($N = 8$) were tested on each list.

Participants

A total of 24 undergraduate Macquarie University students participated in this experiment for course credit. All participants were native speakers of Australian English.

Procedure

Overall, the procedure in Experiment 2 was similar to that of Experiment 1 except for minor differences in display times. Due to the different refresh rate used in Experiment 2, each trial started with the presentation of a forward mask (###), which remained on the screen for 501 ms. The prime was then presented in lower-case letters for 50.1, 70.14, or 90.18 ms (5, 7, and 9 ticks based on the machine's refresh rate of 10.02 ms), followed by the target, which was presented in upper-case letters and acted as a backward mask to the prime. The target words appeared in white on a black background (Courier New, 12 font) and remained on the screen for 2,000 ms or until participants responded. The intertrial interval was 1,002 ms. The order of trial presentation within blocks and lists was randomized across participants.

Results

Similarly to Experiment 1, participant responses were hand marked using CheckVocal

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[13] The reason we used a prime duration of 50 ms as a within-condition baseline is that, to our knowledge, all studies in the literature that reported a MOPE with nonword items used prime durations no shorter than 50 ms. Therefore, it is unknown whether the effect would still be present at shorter prime durations. We are aware of the fact that at prime durations as long as 70 and 90 ms, there is the possibility that primes become visible to the participants, and therefore the priming effects observed at such long prime durations, as well as their underlying mechanisms, might well be strategically affected. However, we would like to remind the reader that the only aim of Experiment 2 was to compare the trend (facilitatory, inhibitory, or both) of the three prime-type conditions as they develop in time between the human data and the computational data in order to adjudicate between two versions of the DRC model that offer a different explanation for how priming effects arise in humans. Given that consciousness does not affect the model's performance, if conscious perception of the primes at the long prime durations affects human behaviour in a way that would particularly influence the nature of the observed priming effects, then we should not be able to find a pattern of results in the computational data that could possibly match that of the human data.

[14] The reason we blocked the items by prime type and not by prime duration was that, in a different experiment that we carried out in our laboratory in order to investigate whether the MOPE is orthographic or phonological in nature, we used three prime durations (30, 50, and 70 ms), which were presented in pure blocks in a within-subjects design. The results showed that the priming effects observed at the prime duration of 50 ms, in particular, were greatly influenced by whether the prime duration of the preceding block of trials was short (30 ms) or long (70 ms), indicating carry-over effects between the blocks.

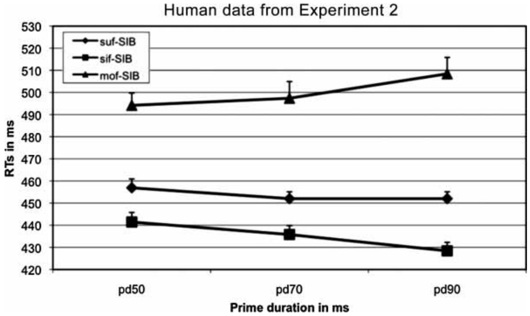

Figure 2. *Human naming latencies and error bars from Experiment 2.*

(Protopapas, 2007). Also, the same data rejection and trimming criteria as those in Experiment 1 were applied. The results are shown in Figure 2.

In terms of RTs, a trend analysis of the one-letter overlap condition showed a nonsignificant linear, $F_1(1,\ 23) = 1.80$, $p > .05$, $F_2(1,\ 80) < 1$, and quadratic component, $F_1(1,\ 23) < 1$, $F_2(1,\ 80) < 1$.[15] In the two-letters overlap condition the linear component was significant, $F_1(1,\ 23) = 8.29$, $p = .008$, $F_2(1,\ 80) = 6.25$, $p = .014$, and this was also the case in the unrelated condition, $F_1(1,\ 23) = 11.47$, $p = .003$, $F_2(1,\ 80) = 19.90$, $p < .001$. The quadratic component was not significant in either.[16] In the error analysis, both by participants and by items, no significant trends (either linear or quadratic) were observed across prime duration for any of the three prime-type conditions.

Discussion

The aim of Experiment 2 was to examine the time course of the one-letter overlap, two-letters overlap, and unrelated conditions so as to determine the nature of priming effects in humans. Our results showed that it is both facilitatory and inhibitory, because as prime duration increased the two-letters overlap condition showed a significant facilitatory linear trend, but at the same time the unrelated condition showed a significant inhibitory trend. With regard to the one-letter overlap condition, no significant trends were observed. Nevertheless, the 5 ms of facilitation observed in this condition when prime duration increased from 50 to 70 ms in combination with the flat effect observed from 70 to 90 ms perhaps merits some discussion, because it could be that one-letter overlap primes exert simultaneously both facilitatory and inhibitory effects (facilitatory due to the letter/phoneme match between the prime and the target in the first position, i.e., *suf*–SIB, and inhibitory due to the letter/phoneme mismatch between the prime and the target in the second and/or third positions, i.e., *suf*–SIB). That would explain why in this condition some minor facilitation was only observed at the shorter prime durations, while at the longer prime durations such facilitation was cancelled out due to inhibition from the mismatching letters/phonemes between the prime and the target. Another possible explanation for the almost flat effect observed in the one-letter overlap condition as prime duration increased is that when there is only one phoneme that overlaps, 50 ms is long enough for the participants' nonlexical route to handle the onset, and therefore having a longer prime duration will not lead to any further benefit.[17] What these results indicate is that the MOPE observed in humans is probably due to contribution of both facilitatory and inhibitory processes that are involved in the reading-aloud process. Therefore, if the DRC model were to offer an explicit account of the effect, it would also have to show that it is both facilitatory and

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[15] Although this effect was not statistically significant it is worth pointing out that some minor facilitation (5 ms) was observed as prime duration increased from 50 to 70 ms, while the effect remained flat between 70 and 90 ms. The reason why this effect deserves some attention is discussed in the Discussion section.

[16] Due to our experimental design, where each participant saw each target three times, each time preceded by a different type of prime and a different prime duration, the item analysis could only be carried out across participants.

[17] We would like to thank Ken Forster for pointing out this alternative explanation of the flat effect observed in the one-letter overlap condition.

inhibitory in nature, as seems to be the case in humans.

Even though an analysis of the differences among the three prime-type conditions is beyond the scope of Experiment 2, it is worth pointing out that at the shortest prime duration (50 ms) the naming-latency difference between the one-letter and the two-letters overlap conditions was 15.5 ms, while in Experiment 1 this same difference at a slightly longer prime duration (i.e., 55.6 ms) was just 4 ms. One possible explanation for this discrepancy could be that in Experiment 2 participants were aware of the presence of a prime stimulus preceding the target (because very long prime durations were used in that experiment), and so they were strategically paying attention to it. As a result, their performance would be expected to increase in the condition with the maximum orthographic/phonological overlap between the prime and the target, which would make the naming-latency difference between the one-letter and the two-letters overlap condition bigger than that in Experiment 1. Moreover, the task per se in Experiment 2 was easier than that in Experiment 1, because in Experiment 2 the three prime-type conditions were presented in separate blocks; therefore in the two conditions where participants could benefit from the prime (one-letter and two-letters overlap conditions), there were no unrelated primes that could interfere with their responses to the targets, and so participants could make maximum use of the information provided from the related primes. As a result, their performance would be expected to substantially increase in the two-letters overlap condition in comparison with the one-letter overlap condition.

Last, as was already predicted from our findings in Experiment 1, slightly bigger orthographic/phonological priming effects were observed as prime duration increased (see Figure 2), indicating that at the longer prime durations participants' nonlexical route had sufficient time to process more letters of the prime than just the first.

With regard to the main aim of Experiment 2 though, the important finding was that priming effects in humans arise due to both facilitation and competition processes that are involved in the reading-aloud process.

SIMULATIONS

We ran the simulations of Experiments 1 and 2 both with DRC 1.1.4 and with DRC 1.2 in order to see which version fitted best the human data from both experiments.

Simulations of Experiment 1

Simulations of Experiment 1 with DRC 1.1.4

The experimental stimuli listed in the Appendix were submitted to DRC 1.1.4. With a prime duration of 40 cycles and the MinReadingPhonology parameter[18] set to 0.3 to simulate speeded naming, the model made no errors and additionally showed that for every target the unrelated condition was two cycles slower than the other two (see Table 2). Thus, the DRC model did not show priming beyond the first letter/phoneme, while the human data from Experiment 1 did. Nevertheless, as we have already pointed out, the difference between the one-letter and the two-letters overlap condition in Experiment 1 was numerically very small, but significant both by participants and by items; such a result could indicate that at a particular prime duration, at least sometimes, or for some participants, the second letter/phoneme of the prime is processed. Indeed, as was mentioned at Footnote 12, two thirds of the participants showed a naming-latency advantage in the two-letters overlap condition in comparison with the one-letter overlap condition. In dual-route terms this could

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[18] This parameter serves for simulating different levels of speed in reading aloud. In particular, when the value of this parameter is high, self-paced reading is simulated, while when it is low, speeded naming is simulated.

Table 2. *Mean reaction times from simulations of Experiment 1*

		RT (SD)	
Model		*Standard parameters*	*Faster nonlexical route*
DRC 1.1.4	*suf*–SIB	126 (0.0)	123 (0.0)
	sif–SIB	126 (0.0)	121 (0.0)
	mof–SIB	128 (0.0)	134 (0.0)
DRC 1.2	*suf*–SIB	129 (0.0)	113 (0.0)
	sif–SIB	129 (0.0)	112 (0.0)
	mof–SIB	130 (0.0)	116 (0.0)

Note: Mean reaction times in cycles. DRC = dual-route cascaded; RT = reaction time; *SD* = standard deviation.

be explained as result of the variance in the speed of the nonlexical route of the participants; namely, some participants' nonlexical route could be operating faster than that of others. This hypothesis could be easily tested with the DRC model.

In particular, in order to simulate the performance of the participants with the faster nonlexical route we decreased the value of the GPCOnset parameter from 22 to 15 cycles so that processing via the nonlexical route would start earlier in the model. With this parameter modification DRC 1.1.4 made no errors and additionally showed that for every target the unrelated condition was 11 cycles slower than the one-letter overlap condition and 13 cycles slower than the two-letters overlap condition. Therefore, there was a naming-latency advantage of 2 cycles for the two letters-overlap condition in comparison with the one-letter overlap condition (see Table 2), a result that agreed with the human data from Experiment 1 and additionally confirmed the dual-route interpretation of our findings.

Simulations of Experiment 1 with DRC 1.2

The same experimental stimuli were submitted to DRC 1.2. With a prime duration of 26 cycles (this was the minimum prime duration that could be used for the 1.2 version in order to show a MOPE with nonwords) and the default parameters of the downloadable version, the model made no errors and additionally showed that for every target the unrelated condition was 1 cycle slower than the other two (see Table 2). Given that the nonlexical route of DRC 1.2 operates differently from the nonlexical route of DRC 1.1.4, we simulated the performance of the participants with the fast nonlexical route in DRC 1.2 by decreasing the value of the GPCOnset parameter from 26 to 15 cycles, the value of the GPCCriticalPhonology parameter from 0.05 to 0.02, and the value of the PhonemeUnsupportedDecay parameter from 0.05 to 0.04. With these parameter modifications DRC 1.2 made no errors, while it showed that for every target the unrelated condition was 3 cycles slower than the one-letter overlap condition and 4 cycles slower than the two-letters overlap condition. Thus, the DRC 1.2 model showed a naming-latency advantage of 1 cycle for the two-letters overlap condition in comparison with the one-letter overlap condition (see Table 2). This simulation result is consistent with the idea that what causes some participants to show priming beyond the first letter/phoneme might be the faster operation of their nonlexical route.

Simulations of Experiment 2

The simulations of Experiment 2 were run in order to determine whether the priming effects in the DRC model arise in the same way as they do in humans. In particular, we compared the pattern of results that the human data showed in each of the three prime-type conditions as prime duration increased with the pattern of results that the computational data of both DRC 1.1.4 and DRC 1.2 showed as each of the three prime type conditions developed in time. We ran the simulations with DRC 1.1.4 using the default parameters and a value of 0.3 for the MinReadingPhonology parameter in order to simulate speeded naming. Similarly we ran the simulations with DRC 1.2 using the default parameters, while we did not have to alter the value of the MinReadingPhonology parameter in this version of the model, because the

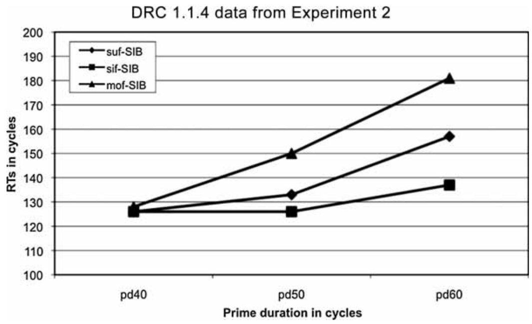

Figure 3. *DRC 1.1.4 simulations from Experiment 2.*

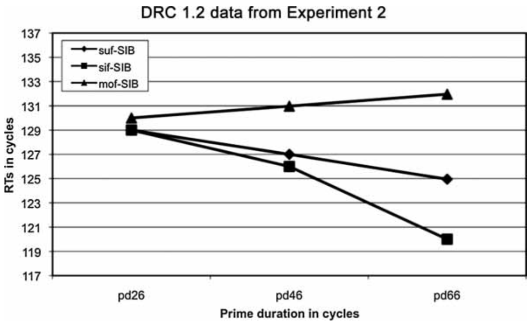

Figure 4. *DRC 1.2 simulations from Experiment 2.*

default one was chosen with the aim to simulate speeded naming.[19]

Simulations of Experiment 2 with DRC 1.1.4

Three equally spaced prime durations (40, 50, and 60 cycles) were used to run the simulations with DRC 1.1.4. The simulation results, which are shown in Figure 3, showed interference as prime duration increased in all three prime-type conditions, while the model made no errors.[20]

In particular, the model showed no variance across items (within any prime duration) in any of the three prime-type conditions, and therefore statistical analyses could not be carried out. However, both linear and quadratic components were present in the relationship between RT and prime duration, because for all three prime-type conditions, RTs increased monotonically as a function of prime duration (linear trend) even though the difference between short and medium prime duration was not the same as the increase between medium and long prime duration for any of the three prime-type conditions (quadratic trend).

Overall then, the increase in RT as a function of increasing prime duration in the unrelated condition agreed with the human data, but the increase in RT as a function of increasing prime duration in the onset-related conditions did not.

Simulations of Experiment 2 with DRC 1.2

Similarly as with DRC 1.1.4, in DRC 1.2 we used three equally spaced prime durations (26, 46, and 66 cycles). The simulation results, which are shown in Figure 4, showed facilitation in the one-letter and two-letters overlap condition and interference in the unrelated condition as prime duration increased, while the model made no errors.

In the unrelated condition, the linear component was highly significant, $F(1, 80) = 5{,}107.27$,[21] $p < .001$, while the quadratic was not, $F(1, 80) < 1$. In the two-letters overlap condition, the model showed no variance across items (within

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[19] We would like to point out that the only reason we used very long prime durations in the two versions of the DRC model was that we wanted to observe whether the pattern of results that the computational data show in each of the three prime-type conditions as prime duration increases is similar to the corresponding pattern of results that the human data show so as to determine whether priming effects in DRC arise in the same way as they do in humans. Evidently, we do not intend to use such long prime durations for generally simulating priming effects with the DRC model, because if the experimental stimuli consisted of word items, for example, it is very likely that at such long prime durations the model would pronounce the primes instead of the targets in many cases. Thus, the use of long prime durations in the model are limited to the simulations of the human data from Experiment 2.

[20] It is worth pointing out that the RTs in the two-letters overlap condition did not increase between the short and the medium prime durations.

[21] The reason the F values in the reported simulation results are so high is that there was hardly any variance in the model's RTs across items.

any prime duration), and therefore statistical analyses could not be carried out. However, both linear and quadratic components were present in the relationship between RT and prime duration, because RTs decreased monotonically as a function of prime duration (linear trend) even though the difference between short and medium prime duration was not the same as the decrease between medium and long prime duration (quadratic trend). In the one-letter overlap condition, the linear component was highly significant, $F(1, 80) = 1.61$, $p > .05$, while the quadratic was not, $F(1, 80) < 1$.

Overall then, the decrease in RT as a function of increasing prime duration in the two-letters overlap condition and the increase in RT as a function of increasing prime duration in the unrelated condition that DRC 1.2 showed agreed with the human data. Nevertheless, the facilitatory trend that the model showed in the one-letter overlap condition was inconsistent with the human results, where this trend was not significant. As was mentioned in the Discussion section of Experiment 2 though, the minor facilitation that was observed in the one-letter overlap condition as prime duration increased from 50 to 70 ms and the flat effect observed between 70 and 90 ms could indicate that first-letter/phoneme related primes exert simultaneously both facilitatory and inhibitory effects. If our hypothesis was correct, by altering adequately the parameters of DRC 1.2 that control the inhibitory and/or facilitatory components of the model, the model should be able to show the same pattern of results that the human data showed.

Given that with the standard parameters DRC 1.2 showed more facilitation than the human data did in the one-letter overlap condition, we assumed that probably the model's inhibitory component is not as strong as the inhibitory component of the human reading system. Therefore, we increased the inhibition in the model by setting PhonemeLateralInhibition to 0.3 (from its default value 0.147), so that particularly at the long prime durations (from 46 to 66 cycles), where the activation of the second phoneme of the prime will have been built up sufficiently so as to have an effect on the second phoneme of the target, the competition between the mismatching phonemes in the second position (*suf*–SIB) is stronger than before. That way, the model should no longer show facilitation in the one-letter overlap condition as prime duration increases from 46 to 66 cycles. Indeed, with this parameter change DRC 1.2 showed (at least numerically) the same pattern of results that the human data showed (see Figure 5). Also, at a prime duration of 66 cycles the model made one error in the one-letter overlap condition.

In particular, in the unrelated condition, the linear component was highly significant, $F(1, 79) = 53{,}900.91$, $p < .001$, and so was the quadratic, $F(1, 79) = 624.84$, $p < .001$. In the two-letters overlap condition, the model showed no variance across items (within any prime duration), and therefore statistical analyses could not be carried out. However, both linear and quadratic components were present in the relationship between RT and prime duration, because RTs decreased monotonically as a function of prime duration (linear trend), even though the difference between short and medium prime duration was not the same as the decrease between medium and long prime duration (quadratic trend). In the one-letter overlap condition, both the linear and the quadratic components were highly significant, $F(1, 79) = 25{,}921.0$, $p < .001$, and $F(1, 79) = 25{,}281.0$, $p < .001$, respectively. Although

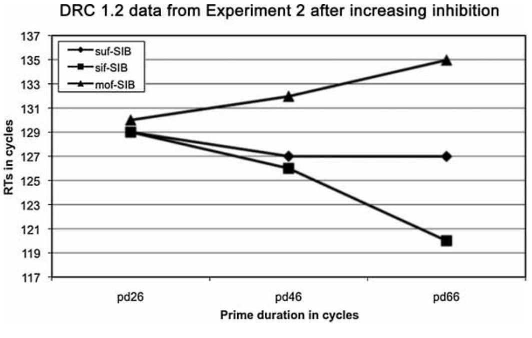

Figure 5. *DRC 1.2 simulations from Experiment 2 after increasing inhibition in the model (prime durations: 26, 46, and 66 cycles).*

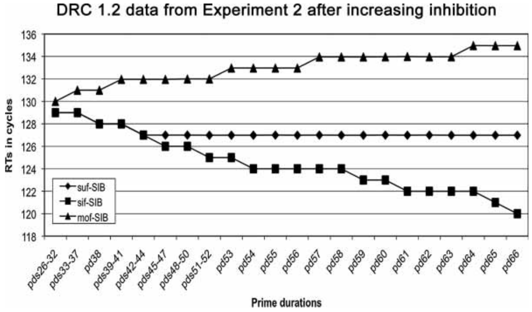

Figure 6. *DRC 1.2 simulations from Experiment 2 after increasing inhibition in the model (prime durations: 26 to 66 cycles).*

the latter result did not statistically agree with the human data, it did so numerically, because when inhibition was increased in the model, DRC 1.2 showed 2 cycles of facilitation at the medium prime duration in comparison with the shortest one, but no further facilitation at the longest prime duration, which was exactly the pattern of results that the human data showed.

Last, in order to observe the behaviour of the model in a continuum, apart from the simulation results at the three prime durations (26, 46, and 66 cycles) that corresponded to the human results at the three prime durations used in the human experiment (50, 70, and 90 ms), we plotted the simulation results at all intermediate prime durations (i.e., from 26 to 66 cycles). The computational data, which are shown in Figure 6, show the same pattern of results as that when just three prime durations were used; namely, RTs increase for the unrelated condition and decrease for the two-letters overlap condition as a function of prime duration. For the one-letter overlap condition RTs decrease at prime durations between 26 and 44 cycles, but then from 45 to 66 cycles they remain steady. That was also the pattern of the results that the human data showed at the three prime durations that were used in the human experiment. However, it might be worth pointing out that within certain prime duration ranges (e.g., 26–32, 33–37, 48–50 cycles) the model's RTs in all three prime-type conditions did not vary with prime duration. Whether humans would show a pattern of results that is similar to that of the model, so that within particular prime duration ranges (e.g., 50–60, 60–70, 70–80, 80–90 ms) their RTs would not vary, is a question that could only be answered if the adequate human experiment was carried out.

Discussion of simulations

The two versions of the DRC model, DRC 1.1.4 and DRC 1.2, successfully simulated a MOPE at a specific prime duration—that is, 40 cycles for DRC 1.1.4 and 26 cycles for DRC 1.2. Nevertheless, with the standard parameters neither of the two versions was able to simulate an orthographic/phonological priming effect beyond the first letter/phoneme as the human data showed. Provided that two thirds of the participants showed a naming-latency advantage in the two-letters overlap condition in comparison with the one-letter overlap condition, we formed the hypothesis (based on the dual-route theory of reading) that the nonlexical route of the participants who showed the above pattern of results would be probably operating faster than the nonlexical route of the rest of the participants. We then tested this hypothesis by increasing the speed of the nonlexical route in the DRC model, and we reran the simulations of Experiment 1. Both versions of the model were able to simulate the human data, confirming their dual-route interpretation.

With regard to Experiment 2, the simulation results revealed that DRC 1.1.4 was unable to simulate the human data, because it showed that priming effects are only inhibitory in nature, while according to the human data, these are both facilitatory and inhibitory. In contrast, DRC 1.2 successfully simulated both the facilitatory and the inhibitory nature of the two-letters overlap and unrelated conditions, respectively. With regard to the one-letter overlap condition, we assumed (based on the human results) that it consists of both a facilitatory and an inhibitory component. When we increased the strength of the inhibitory component in DRC 1.2, the model successfully simulated the human results, confirming our hypothesis. The results from Experiment 2 provided additional evidence in favour of the implementation of the DRC 1.2 version.[22]

GENERAL DISCUSSION

The present study was carried out to test whether the DRC computational model of reading can offer a valid account of the MOPE. Given the empirical discrepancy as to whether the MOPE is limited to the first-letter/phoneme overlap between nonword primes and targets or whether orthographic/phonological priming effects with nonwords occur beyond the first letter/phoneme, we carried out a study that addressed this issue (Experiment 1). Our results showed that with nonword items, humans (at least sometimes or some of them) do process orthographic/phonological properties of the primes beyond the first letter/phoneme. We suggested that according to the dual-route account, these results could indicate that a nonlexical reading mechanism, which is capable of reading correctly nonwords (nonlexical route), could be operating at a different speed in each individual, so that during prime presentation, participants with a faster nonlexical route would be able to process more letters of the prime than the first, while participants with a slower nonlexical route would not be able to process more than the first letter of the prime.

Such a hypothesis is further supported by a recent study (Thompson, Connelly, Fletcher-Flinn, & Hodson, 2009), which has shown that adults with childhood phonics instruction read nonwords in a different way from adults without childhood phonics instruction. More specifically, when responding to nonwords that can receive alternative legitimate pronunciations, adults with childhood phonics instruction used more regular grapheme–phoneme correspondences that were context free and fewer vocabulary-based contextually dependent correspondences than did adults who had no childhood phonics instruction. In dual-route terms, such a difference in the way the two different groups of participants read nonwords would indicate that the group of participants with childhood phonics instruction would be making more use of their nonlexical route of reading (when reading nonwords) than would the group of participants without childhood phonics instruction. If that were the case the nonlexical route of the former group of participants could well be operating at a faster speed than that of the latter group of participants when the task in question is speeded nonword reading aloud, and so individual differences in adult readers should be expected in this task.

When we tested computationally the dual-route interpretation of our human data using both versions of the DRC model the simulation results were successful, indicating that a nonlexical reading mechanism that operates serially and from left to right is responsible for the MOPE as well as additional orthographic/phonological nonword priming effects occurring in humans. The faster this mechanism operates the more orthographic/phonological information participants will extract from printed letter strings.

Even though the simulation results from Experiment 1 fully agreed with the human data, providing evidence in favour of the dual-route interpretation of the MOPE, the two most recently downloadable versions of the DRC model made different predictions regarding how priming effects occur in humans. In particular, the previously downloadable DRC version (DRC 1.1.4) predicted that priming effects are solely inhibitory in nature, while the currently downloadable version of the model (DRC 1.2) predicted that these are both inhibitory and facilitatory. Therefore, Experiment 2 was particularly designed to adjudicate between the two versions of the model. The human results confirmed DRC 1.2's prediction and additionally indicated that first-letter/phoneme related primes, which form the critical condition in experiments that investigate the MOPE, seem to exert both inhibitory and facilitatory effects. When inhibition in DRC 1.2 was

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[22] Since the priming effects in DRC 1.1.4 only arise because of the interference from the unrelated prime to the target, there was no point in trying to modify any of the parameters in order to simulate the human data from Experiment 2, because the model would still be unable to generate a facilitatory priming effect.

increased so that the model could capture the flat effect of the one-letter overlap condition at the longer prime durations, the pattern of results of the computational data was similar to that of the human data as prime duration increased, indicating that priming effects arise in the DRC 1.2 model in the same way as they do in humans. These results provided further evidence in favour of the implementation of the DRC 1.2 version and fulfilled thus the aim of Experiment 2.

CONCLUSIONS

The results from our study show that the DRC computational model of reading is able to offer a valid account of the MOPE. More specifically, our findings provide evidence for the existence of a nonlexical reading mechanism that operates serially, letter by letter and from left to right. Such a mechanism is used to decode letter strings from print to sound using grapheme-to-phoneme correspondence rules, while its speed is free to vary among skilled readers. Additionally, our data indicate that the human reading system consists of both a facilitatory and an inhibitory component; such a finding is crucial for defining the dynamical properties of computational models of reading, which can offer an explicit account of a number of empirical effects observed in studies on reading, and also it enhances our knowledge of how the human reading system operates.

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APPENDIX

Experimental stimuli used in Experiments 1 and 2

Primes			
One-letter overlap	*Two-letters overlap*	*Zero-letter overlap*	*Targets*
gak	goc	ned	GOS
diz	des	nym	DEG
tiv	tav	doz	TAL
niz	nos	kes	NOM
kal	kiz	zeb	KIF
kiv	kel	huv	KEM
mez	muv	toz	MUP
liz	lem	zav	LEC
fav	fuv	nol	FUD
pif	pef	mof	PEZ
sev	sif	lep	SIZ
nud	nas	zim	NAV
jal	jes	vog	JEK
nal	neb	kim	NEZ
dus	dep	tis	DEV
zev	zos	pav	ZON
pof	piz	dys	PIV
lez	lif	feb	LIL
ruv	rez	jid	RES
bav	bez	hal	BES
nus	nep	boz	NEV
vop	vef	lal	VEB
jic	jav	ked	JAS
mem	mym	seb	MYP
buv	bys	zac	BYM
jiz	joc	seg	JOM
jud	jof	fec	JOZ
jus	jec	tas	JEB
moz	mef	sus	MEP
dup	dis	leb	DIF
vem	vib	poz	VID
zis	zel	dom	ZEC
zag	zob	bev	ZOZ
suv	ses	bof	SEM
zak	zog	keb	ZOM
vos	vel	sal	VED
fif	fev	zif	FEK
vec	vil	fup	VIS
zig	zol	peb	ZOF
vav	vek	fis	VEP
zep	zam	kym	ZAB
ves	voc	fas	VOM
zin	zez	puv	ZEM
vab	viz	pym	VIC
jun	jeg	dav	JEZ
miv	mev	fal	MEG
jev	jup	kev	JUM
kas	kec	von	KEF
mav	mek	fum	MEB
fic	fef	hiv	FES
lel	lus	rys	LUM
biv	beb	loz	BEM
gup	goz	niv	GOM
juv	jif	bal	JIS
hiz	hol	kek	HOF
gof	gav	kez	GAC
nuv	noz	kug	NOF
vez	vig	lub	VIF
div	dak	nis	DAL
voz	val	pem	VAS
tus	teb	vof	TEM
zeg	zid	kun	ZIL
fiv	foc	pev	FOZ
tum	tev	kak	TES
bic	bep	ros	BEF
sym	sez	das	SEF
rem	ral	zek	RAV
roz	rup	hev	RUS
zic	zef	fof	ZES
fep	fom	dez	FOL
zod	zit	tuv	ZIB
riz	rel	tud	REB
mib	mec	kuv	MEL
rof	riv	mub	RIS
sav	sof	kib	SOZ
lis	lof	vip	LOM
lef	lup	ziv	LUN
toc	tef	vam	TEZ
nup	nef	hoz	NEM
lys	lek	sud	LEV
kom	kac	tys	KAV