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Computational modelling of the masked onset priming effect in reading aloud

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The masked onset priming effect (MOPE) was first defined by Forster and Davis (1991) as the finding that human naming latencies are faster when a target word (e.g., BREAK) is preceded by a briefly presented masked prime word that shares its initial sound with the target (e.g., *belly*) compared to when it does not (e.g., *merry*) or when it rhymes with it (e.g., *stake*). The present paper presents a review of empirical findings on the MOPE in the English language and their simulations by the DRC computational model of reading (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001), which offers an explicit account of how the effect might occur in humans. A new version of DRC, called DRC 1.2, which differs from the previous downloadable DRC version mainly in the way its nonlexical route operates, has been recently developed. The performance of DRC 1.2 on simulating the MOPE is evaluated in this paper.

Keywords: DRC 1.2 computational model of reading; Masked onset priming effect; Reading aloud.

COMPUTATIONAL MODELLING OF READING ALOUD AND THE DRC MODEL

> A computational model of reading aloud is a computer program that is not only capable of generating some kind of phonological output representation from some kind of orthographic input representation but also does so using processing mechanisms considered to be the same as the mechanisms used by human readers as they read aloud. (Coltheart, 2006, p. 98)

The DRC (Dual Route Cascaded) computational model of reading (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001), which is shown in Figure 1, is a computational implementation of the dual-route theory of

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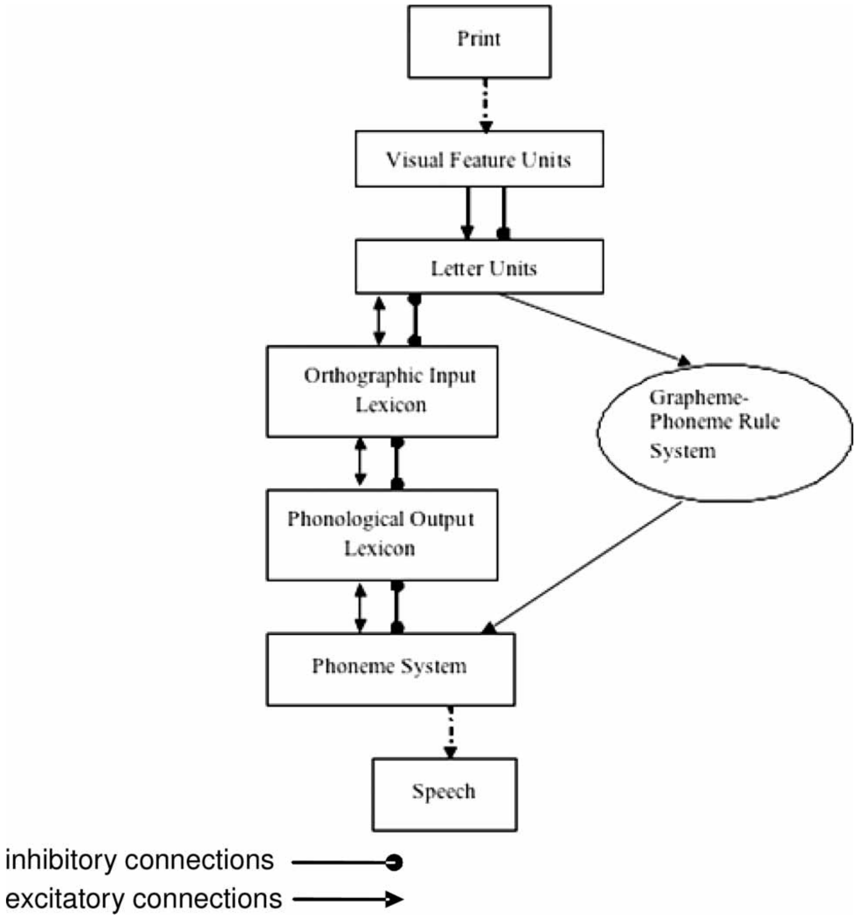

Figure 1. The DRC model (Coltheart et al., 2001).

reading (Coltheart, 1978; Coltheart, Curtis, Atkins, & Haller, 1993; Forster & Chambers, 1973; Marshall & Newcombe, 1973), according to which there are two routes involved in reading aloud: a lexical route, which involves looking up a word in a mental lexicon that contains knowledge about the pronunciation and spelling of letter strings that are real words (either regular or irregular) and a nonlexical route, which applies grapheme-to-phoneme correspondence rules to letter strings in order to convert them to phonology.

The DRC model, which is currently implemented for monosyllables only, determines the pronunciation of a letter string when all of the phonemes of that letter string are activated to some criterion of satisfaction. The cycle on which this criterion is achieved will be the model's naming latency for that particular letter string. In particular, at the end of each processing cycle, each set of phonemes in each position of the letter string, starting from the first set in the first position, is sequentially examined and the phoneme with the highest activation in each set is identified. When the blank phoneme, which indicates the end of the letter string, reaches the minimum naming threshold (which is 0.4 in the simulations reported in the present paper), the model checks if any of the other phonemes in each of the preceding phoneme sets has an activation value that is over the minimum naming threshold, i.e., 0.4. If this is so the model's pronunciation consists of the phonemes with the highest activation in each of the phoneme sets. That is how the DRC model decides when to name a word/nonword and therefore performs the task of reading aloud (see also Coltheart et al., 2001, pp. 217–218).

The current version of the DRC model, which is DRC 1.2, can be downloaded from http://www.maccs.mq.edu.au/~ssaunder/DRC/, where the differences between this version and the original DRC version, i.e., DRC 1.0 (Coltheart et al., 2001), are also fully documented. A document on the same site 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 the simulations of the experiments reported in the present paper the default parameters installed in the downloadable model were used, except where otherwise noted.

For the purposes of our study, the most important difference between DRC 1.2 and the previous downloadable DRC version is the following. In the previous downloadable version a fixed number of cycles, determined by the GPCInterletterInterval parameter, had to elapse before the nonlexical route moved from one letter to another in a serial left-to-right manner. In DRC 1.2 the nonlexical route 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.

Also, it is worth pointing out that the only difference between DRC 1.2 and DRC beta6, a version that has been used for the simulations of all experiments reported in Mousikou, Coltheart, Saunders, and Yen (in press), is that in DRC 1.2 all the units in the orthographic lexicon are connected to every letter unit, whereas in DRC beta6 each lexical unit is connected only to the first *N* letter units, where *N* is the number of letters in the lexical unit, plus one for the blank. This modification was made to correct one failure of simulation by the beta6 version: Its latencies for reading words increased with word length, whereas the naming latencies for words are not affected by length in human readers (Weekes, 1997) and also not in DRC 1.2.

THE MASKED ONSET PRIMING EFFECT (MOPE)

Since the MOPE was defined in the seminal paper of Forster and Davis (1991), it has been observed in different laboratories and in different languages both with word and nonword stimuli (e.g., Grainger & Ferrand, 1996; Kinoshita, 2000; Kinoshita & Woollams, 2002; Malouf & Kinoshita, 2007; Mousikou et al., in press; Schiller, 2004, 2007, 2008). In general terms, the MOPE refers to the finding that target naming occurs faster when the target is preceded by a first letter/phoneme related prime compared to an unrelated one. The reason why this effect has been investigated in detail is because it has been claimed to reflect the operation of the nonlexical route of reading, which forms a component of the dual-route theory of reading. Additionally, the MOPE taps into the early stages involved in the reading aloud process and so it can be a useful tool for studying how the human reading system operates.

THE DRC 1.2 ACCOUNT OF THE MOPE

The DRC 1.2 model explains the MOPE as being due to the functioning of the nonlexical route of reading, which operates serially and from left to right. More specifically, when the prime is briefly presented the nonlexical route has time to process its first letter and translate it into its corresponding phoneme. Then, when the target is presented, if its first phoneme is different from that of its prime (e.g., *merry*-BREAK) there is a pronunciation conflict between the first phoneme of the prime and the first phoneme of the target that delays naming of the target compared to when the target's first phoneme is similar to that of its prime (e.g., *belly*-BREAK). Additionally, in the latter case the preactivation of the first phoneme of the target by its prime speeds up target naming latencies compared to when the prime and the target do not share their first phoneme. The difference in naming latency between the unrelated (e.g., *merry*-BREAK) and the related condition (e.g., *belly*-BREAK) determines the size of the MOPE.

EVIDENCE IN FAVOUR OF THE IMPLEMENTATION OF DRC 1.2

Because the nonlexical route of the previous downloadable DRC version and the current one operate quite differently with respect to how serial processing is implemented, the two models make different predictions about how prime/target letter length will influence the MOPE with nonword items in particular. For the previous downloadable version of DRC, the longer the primes and targets were, the more likely it would be that the conflict between the first phoneme of the prime and the first phoneme of the target would have been resolved by the time the serially operating nonlexical route reached the end of the target. In other words, the longer the items were, the smaller the MOPE would be, and indeed there could even be no MOPE when primes and targets were long enough. In contrast, with DRC 1.2 the nonlexical route will not be able to move on to the processing of the second letter until activation of the first phoneme has reached the critical level, and this will be true regardless of target length: So for DRC 1.2 the size of the MOPE will be independent of length. An experiment that was carried out with humans in our laboratory showed a MOPE both for three-letter long and five-letter long nonword stimuli. Also, the size of the MOPE was independent of target length (for a detailed description of this study see Mousikou et al., in press, Exp. 3). Such a finding provided evidence in favour of the implementation of DRC 1.2.

Additionally, the previous downloadable version of the DRC model could show a MOPE with word items at a relatively short prime duration (28 cycles), but 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). This was because at the shorter prime duration, the activation of the first phoneme of the prime was weak and this would allow competition with the first phoneme of the target (when these were different) to have been resolved (via lateral inhibition between the competing phonemes) by the time the nonlexical route reached the last letter of the target. Because words are named faster via the lexical route, by the time naming of the target words occurs, the competition between the first phoneme of the prime and the first phoneme of the target has not been resolved yet and so a MOPE was observed even at a relatively short prime duration (28 cycles). Nevertheless, because nonwords can only be named via the nonlexical route, by the time naming of the target nonwords occurs, the competition between the first phoneme of the prime and the first phoneme of the target has already been resolved, therefore for the MOPE to occur with nonwords a very long prime duration was needed (at least 40 cycles for three-letter long nonwords and over 40 cycles for longer nonwords). Given that the nonlexical route of DRC 1.2 does not move to the next letter of the target string until the previous phoneme has reached some critical activation, even with a relatively short prime duration, an unrelated nonword prime is able to delay the naming of a nonword target compared to a related nonword prime, because processing of all of the target's letters is going to be delayed in the unrelated condition compared to the related condition. Similarly, an onset-related nonword prime is able to facilitate the naming of a nonword target, because processing of all of the target's letters is going to speed up in the onset-related condition where the target's first phoneme will reach the critical activation earlier than in the unrelated condition. Empirical studies on the MOPE have shown that independently of the items' lexical status, the effect occurs at similar prime durations (see, for example, Forster & Davis, 1991; Grainger & Ferrand, 1996; Kinoshita, 2000; Kinoshita & Woollams, 2002; Malouf & Kinoshita, 2007; Mousikou et al., in press; Schiller, 2004, 2007, 2008). The results from these studies provide thus further evidence in favour of the implementation of DRC 1.2.

COMPUTATIONAL MODELLING OF THE MOPE WITH DRC 1.2

In the typical three-field masked priming paradigm, a forward mask (#####) is first presented for approximately 500 ms, followed by the prime, which is briefly presented in lowercase letters for between 50 and 60 ms, followed by the target, which is in turn presented in uppercase letters for 500 ms or until a response is generated by the participants. The target acts as a backward mask to the prime. The participants' task is to read aloud the target word/nonword, while no mention about the presence of the prime is made to them. We accordingly simulated masked priming in DRC 1.2 by presenting the prime for a small number of cycles (e.g., 26)[1] and then by switching off the activation of the prime's letters at the letter level in order to simulate backward masking. We then presented the target until a naming response was generated by the model.

The present paper consists of seven sections, where each section contains the empirical data of one particular study or of different interrelated studies and their simulations with the DRC 1.2 model.

[1] The choice of using a prime duration of 26 cycles in order to simulate a MOPE with word and nonword stimuli with the DRC 1.2 computational model of reading was made on the basis that the default value for the GPCOnset parameter in this model is 26, which means that the nonlexical route of the model will start operating after 26 cycles of stimulus presentation have elapsed. In other words, in order to obtain a MOPE with nonword items in DRC 1.2 the minimum prime duration used should be 26 cycles. According to the literature, in experiments with humans the minimum prime duration at which a MOPE has been observed with nonword items is 50 ms. At this prime duration a MOPE with word items has also been reported, therefore the equivalent prime duration in the model had to be the minimum that could be used for a significant MOPE to occur with nonword items and also a valid one for a significant MOPE to occur with word items. Such prime duration in the DRC 1.2 model corresponded to the value of 26 cycles.

SECTION 1: WHAT CAUSES THE MOPE TO OCCUR?

Empirical data

Forster and Davis (1991) carried out a masked priming experiment (Exp. 1) where a forward mask (######) was presented first for 500 ms. This was immediately followed by a prime word presented in lowercase letters for 60 ms, which was in turn immediately followed by a target word presented in uppercase letters for 500 ms. Three conditions were included in that experiment: In the first condition, there was no phonetic or orthographic overlap between the prime and the target, e.g., *merry*-BREAK; this condition served as a baseline. In the second condition, the only overlap between the prime and the target was in the initial sound (it was also the case that the initial letter was the same), e.g., *belly*-BREAK; in the third condition, the prime rhymed with the target, but the number of common letters in the same position never exceeded two, e.g., *stake*-BREAK. The results showed that participants' target naming latencies were faster when the initial sound of the prime matched that of the target compared to the rhyming and baseline conditions that did not differ significantly from each other (the human results are shown in Table 1). Forster and Davis explained this effect in terms of a response competition hypothesis where the tendency to pronounce both the prime and the target leads to longer reaction times in the all different condition (*merry*-BREAK) compared to the same initial sound condition (*belly*-BREAK).

Computational data

Twenty-six monosyllabic pairs of primes and targets selected from the experimental stimuli used in Experiment 1 of Forster and Davis (1991) were submitted to the DRC 1.2 model.[2] The simulation results are presented in Table 1.

With a prime duration of 26 cycles the DRC 1.2 naming latencies were significantly faster in the rhyming condition compared to the all different condition, $t(21) = 2.29$, $p = .032$, and the same initial sound condition, $t(21) = 2.15$, $p = .043$, whereas the difference between the same initial sound condition and the all different condition was not significant, $t(21) = 1.47$, $p > .05$. Additionally, DRC 1.2 regularised the pronunciation of the target item PEAR when it was preceded by the unrelated prime *take* and it named the primes instead of the targets in three cases: when the target word RAID was preceded by the prime *made*, when the target word BOW

[2] A list of all the stimuli used in the simulations reported in the present paper can be found at http://www.maccs.mq.edu.au/~ssaunder/MOPE

TABLE 1
Human reaction times (in milliseconds) and percent errors and DRC 1.2 reaction times (in cycles) and percent errors from Experiment 1 (Forster & Davis, 1991)

Type of prime	*All different* (*merry*-BREAK)	*Same initial sound* (*belly*-BREAK)	*Rhyming* (*take*-BREAK)
Human RTs	470	446	464
Human errors	6.1	5.6	11.7
DRC 1.2 RTs (*SD*s)	75.4 (18.6)	71.4 (9.3)	65.6 (8.4)
DRC 1.2 errors	3.9	7.7	3.9

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

was preceded by the prime *but*, and when the target word KNEE was preceded by the prime *know*.[3]

On one hand, the reason why DRC 1.2 showed faster target naming latencies in the rhyming condition compared to the other two is because in this condition primes and targets share on average more letters and phonemes in the same position. Therefore, at a prime duration of 26 cycles the primes' entries are activated (most of the times) in the orthographic lexicon (and sometimes in the phonological lexicon too) and the more letters/phonemes they share with their targets in the same position, the more they will speed up the activation of their targets' phonological entries and subsequently the targets' phonemes at the phoneme layer.

On the other hand, the reason why DRC 1.2 did not show a significant MOPE is because many of the prime stimuli used in the Forster and Davis (1991) study were words of very high frequency that would get highly activated in the orthographic lexicon during prime presentation and would then compete very strongly with their targets. Because of such a strong competition between these very high frequency primes and their targets, any other prime type effects (e.g., onset relatedness) were easily wiped out. One way of overcoming this problem is by increasing the inhibitory component in the model so that the unrelated primes will interfere more with their targets causing thus some further delay in their naming. This was achieved by increasing the value of the GPCCriticalPhonology parameter from .05 to .08 and by decreasing the value of the PhonemeUnsupportedDecay parameter from .05 to .02. With these parameter changes the DRC 1.2 model showed a significant MOPE, $t(21) = 2.08$, $p = .05$.

[3] For all of the simulations reported in the present paper the naming latencies that corresponded to the items that the model mispronounced were excluded from the analyses.

Conclusion

The DRC 1.2 model was unable to simulate the human data from Experiment 1 of Forster and Davis (1991), because on one hand, primes that rhymed with their targets significantly facilitated target naming compared to primes that shared their first letter/phoneme with their targets or to unrelated primes, whereas in the human data there was no such facilitation; in fact, in the human data primes that rhymed with their targets yielded similar target naming latencies to unrelated primes. On the other hand, the model was unable to simulate the human data from Experiment 1 of Forster and Davis, because due to its sensitivity to the frequency of the primes, it did not show a MOPE with the default parameters. Nevertheless, the human data did show a significant MOPE, indicating no sensitivity to the frequency of the primes. When the inhibitory component of the model was enhanced, DRC 1.2 showed a MOPE; however, we do acknowledge that there is no justification for this parameter modification and so a change to the way frequency scaling is implemented in the model, which will make the frequency of the primes have no effect on the targets, is currently being pursued.[4]

Such a change could possibly solve the problem in the rhyming condition too, because if the frequency scaling is implemented differently in the model any lexical activation of the primes (including those that rhyme with their targets) during their presentation might be significantly reduced. In that case, lexical processing of the primes might not affect target naming latencies as much as nonlexical processing does. If that were true primes that rhyme with their targets should yield similar target naming latencies to primes that are unrelated to their targets.[5]

SECTION 2: IS THE MOPE DUE TO LEFT-TO-RIGHT PROCESSING OF THE PRIME?

Empirical data

As was mentioned in the introduction, the MOPE has been found to occur both with words and nonwords (for a review, see also Kinoshita, 2003). With regard to nonwords, Forster and Davis (1991) carried out a masked priming experiment (Exp. 4) using four-letter long items. The same conditions of presentation were used as in their Experiment 1 (described in Section 1), except that a dummy word in lowercase letters of the same length as the

[4] It is worth mentioning here that four experiments on reading aloud that were carried out in our laboratory and tested whether in masked priming conditions prime frequency affects target naming latencies showed no trend for a prime frequency effect.

[5] This is indeed the case when the lexical route is turned completely off in the model.

target was used as a forward mask rather than a row of hash marks. The human data showed a significant MOPE, so that FENT preceded by *fosk* was named faster than when preceded by *jisk*. These results were interpreted within a dual-route framework of reading where left-to-right processing of the prime by the nonlexical route causes the effect to occur.

In a different masked priming experiment carried out by Kinoshita (2000, Exp. 1) three-letter long CVC (where C is a consonant and V is a vowel) nonword targets (e.g., SIB) were preceded by three types of primes 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 in a right-to-left manner: one letter overlap (*mub*-SIB), two letters overlap (*mib*-SIB), all letters different (*mof*-SIB). In Kinoshita's experiment, a forward mask (#######) was presented first for 500 ms, followed by a prime presented in lowercase letters for 56 ms, followed by a target presented in uppercase letters for a maximum of 2000 ms, or until a response was generated by the participants. The main aim of this experiment was to test whether the theoretical assumption that the MOPE is due to left-to-right processing of the prime is correct.

According to the dual-route interpretation of the effect, where the MOPE occurs due to the functioning of the nonlexical route of reading that moves serially from left to right, priming should be observed in the one letter overlap and two letters overlap conditions only when there is left-to-right overlap between the prime and the target (i.e., *suf*-SIB and *sif*-SIB named faster than *mof*-SIB), but not when there is right-to-left overlap (i.e., *mub*-SIB and *mib*-SIB named as fast as *mof*-SIB). The human data from Kinoshita's study showed indeed that participants' target naming latencies were significantly faster in the one letter and two letters overlap conditions compared to 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 (i.e., *suf*-SIB, *sif*-SIB) (see Table 2). The difference between the latter two conditions was not significant, indicating that the second letter/phoneme of the prime does not have an influence on the target. Thus, the results from this experiment suggested that left-to-right processing of the prime causes the MOPE, a finding that is consistent with the dual-route interpretation of the effect.

Computational data

A number of the stimuli that Kinoshita used in her study (2000, Exp. 1)[6] were real words in DRC's 1.2 vocabulary (for the complete list of these

[6] We would like to thank Sachiko Kinoshita for kindly providing us the whole set of experimental stimuli used in her study.

TABLE 2
Human reaction times (in milliseconds) and percent errors and DRC 1.2 reaction times (in cycles) and percent errors from Experiment 1 (Kinoshita, 2000)

Type of data	*Type of prime*	*Examples*	*RTs*	*SDs*	*Errors*
Human	Left-to-right overlap				
	One letter	*suf*-SIB	542	38	1.9
	Two letters	*sif*-SIB	539	35	3.4
	All letters different	*mof*-SIB	554	37	1.5
	Right-to-left overlap				
	One letter	*mub*-SIB	551	32	2.5
	Two letters	*mib*-SIB	548	37	3.4
	All letters different	*mof*-SIB	555	34	4
Computational	Left-to-right overlap				
	One letter	*suf*-SIB	128.7	1.8	0.0
	Two letters	*sif*-SIB	128.7	1.8	0.0
	All letters different	*mof*-SIB	129.6	1.8	0.0
	Right-to-left overlap				
	One letter	*mub*-SIB	129.5	1.5	0.0
	Two letters	*mib*-SIB	129.6	1.1	3.7
	All letters different	*mof*-SIB	129.6	1.1	0.0

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

stimuli see footnote 1 of the document that reports the results from the simulations of the benchmark effects at http://www.maccs.mq.edu.au/~ssaunder/DRC/). However, these words were very low in frequency and would have probably been treated as nonwords by the participants in that study. Therefore, just for this simulation, we removed these items from DRC's 1.2 vocabulary so that the model would also treat them as nonwords. The rest of the stimuli were submitted to the model. With a prime duration of 26 cycles the DRC 1.2 target naming latencies were faster in the one letter and two letters overlap condition compared to 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, i.e., *suf*-SIB and *sif*-SIB < *mof*-SIB (see Table 2).

DRC 1.2 made no errors in any of the left-to-right overlap conditions, but it made two errors in the two letters overlap condition when the overlap was from right to left. Both errors consisted of pronouncing the prime instead of the target, i.e., *fug* instead of YUG and *ref* instead of PEF. The results from the *t*-tests showed that when the overlap between the prime and the target was from left to right target naming occurred faster in the one letter and two letters overlap condition compared to the all letters different condition, $t(53) = 22.79$, $p < .001$, whereas target naming latencies in the former two conditions were identical. However, when the overlap was from right to left no significant differences were observed between any of the conditions. Therefore, the simulation results completely agreed with the human data.[7]

Conclusion

DRC 1.2 showed a MOPE only when the overlap between the prime and the target was from left to right (*suf*-SIB and *sif*-SIB < *mof*-SIB), but not when it was from right to left (*mub*-SIB = *mib*-SIB = *mof*-SIB), confirming the hypothesis that the MOPE must be due to a nonlexical, serial, left-to-right processing of the prime since this was exactly the pattern of results that the human data showed in Kinoshita's study (2000). Additionally, when the overlap was from left to right DRC 1.2 showed no difference in naming latency between the one letter and two letters overlap conditions (*suf*-SIB = *sif*-SIB). This result was consistent with the human data and indicated that at a relatively short prime duration participants' nonlexical route must not have time to process more letters of the prime than the first.

SECTION 3: DOES ORTHOGRAPHIC OVERLAP BETWEEN THE PRIME AND THE TARGET PRODUCE PRIMING BEYOND THE FIRST LETTER/PHONEME?

Empirical data

As was mentioned in Section 2, target naming latencies in the one letter and two letters overlap conditions in Kinoshita's study (2000) were faster than in the all letters different condition; however, naming latencies in the former two conditions did not differ significantly from each other, indicating that the second letter/phoneme of the prime has no influence on the target. These results were in disagreement with the results from a masked priming study carried out by Masson and Isaak (1999, Exp. 1). In that study, a row of uppercase Xs equal in length to the upcoming target item was presented first for 500 ms. These were immediately replaced by a prime stimulus presented in lowercase letters for 50 ms, which was in turn replaced by the target item presented in uppercase letters until a response was generated by the participants. In particular, the Masson and Isaak study used nonword targets that were preceded by three types of nonword primes: *nump*-NUMP (repetition primes), *nurp*-NUMP (orthographic primes), and *nalk*-NUMP (first letter/phoneme related primes). The human results revealed a masked orthographic priming effect, i.e., NUMP preceded by *nurp* was named faster

[7] Simulations of the Forster and Davis data from Experiment 4 (1991) were not carried out with DRC 1.2, because the stimuli used in that experiment were not available.

TABLE 3
Human reaction times (in milliseconds) and percent errors and DRC 1.2 reaction times (in cycles) from Experiment 1 (Masson & Isaak, 1999)

	Human data			*Computational data*		
Type of prime	*RTs*	*SDs*	*Errors*	*RTs*	*SDs*	*Errors*
Repetition (*nump*-NUMP)	596	84	6.1	137.4	3.4	0.0
Orthographic (*nurp*-NUMP)	597	89	7.9	137.4	3.4	0.0
First letter/ phoneme related (*nalk*-NUMP)	613	85	6.6	137.4	3.4	0.0

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

compared to when preceded by *nalk*, indicating that more letters of the prime than the first have an influence on the target.[8] Also, target naming latencies in the repetition priming condition were significantly faster than in the first letter/phoneme related condition; the orthographic and repetition priming conditions yielded similar target naming latencies (see Table 3).

Computational data

The original stimuli that Masson and Isaak used in their study (1999, Exp. 1), except for those pairs that contained disyllabic primes were submitted to the DRC 1.2 model. Three of the primes (drub, kips, pard) and one target (pule) were words in DRC's 1.2 vocabulary, therefore we followed the same procedure as in Kinoshita's study and removed these items from DRC's 1.2 vocabulary before running the simulations. With a prime duration of 26 cycles DRC 1.2 yielded identical target naming latencies in the three conditions (see Table 3), indicating that no letters of the prime beyond the first have an influence on target naming.

As mentioned in Section 2, Kinoshita (2000, Exp. 1) failed to find a significant orthographic priming effect with three-letter long nonword items. Nevertheless, Masson and Isaak (1999, Exp. 1) did find such effect with four-letter long nonwords. In an experiment that we carried out using similar items to those used by Kinoshita and a similar prime duration (55.6 ms) a significant orthographic priming effect was present (Mousikou, Coltheart, Finkbeiner, & Saunders, 2010) even though the target naming latency

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

difference between the two letters (*sif*-SIB) and the one letter (*suf*-SIB) overlap conditions was just 4 ms (subject analysis). Given that in our study two-thirds of the participants and 47 out of 81 items showed an orthographic priming effect, we assumed (based on the dual-route theory of reading) that at a specific prime duration (below 60 ms) some participants' nonlexical route might operate fast enough to process more letters of the prime than the first, whereas other participants' nonlexical route might operate slower and so the latter participants would not be able to process more letters of the prime than the first during prime presentation. In the Masson and Isaak study, as has been pointed out in footnote 8, there was a significant orthographic priming effect in the subject analysis, but not in the item analysis, so it could also be the case that only sometimes and for some participants in that study processing of more letters of the prime than the first occurred during prime presentation. If that were the case, by increasing the speed of the nonlexical route in the DRC 1.2 model so as to simulate the faster participants' performance, the model should be able to show an orthographic priming effect.

We did that by decreasing the value of the GPCOnset parameter to 18 cycles (from its default value of 26) so that the nonlexical route of the model would start operating on an earlier cycle, and also by decreasing the value of the GPCCriticalPhonology parameter to .02 (from its default value .05) so that the nonlexical route would move from one letter to another at a faster speed. The simulation results showed indeed a significant orthographic priming effect, $t(42) = 2.73$, $p = .009$, so that *nurp*-NUMP < *nalk*-NUMP. Similarly to the human data, target naming occurred faster in the repetition priming condition compared to the first letter/phoneme related condition, $t(42) = 4.04$, $p < .001$, but the model also showed a naming latency advantage in the repetition priming condition compared to the orthographic priming condition, $t(42) = 2.50$, $p = .016$; in the human data these two conditions did not differ significantly from each other.

Conclusion

Masson and Isaak (1999) found an orthographic priming effect with nonword stimuli, which indicated that humans process more letters of the prime than the first during prime presentation. However, such an effect does not seem to occur always and for all participants; Kinoshita (2000), for example, failed to find a second letter/phoneme priming effect using three-letter long nonword items (see Section 2). Also, the orthographic priming effect found in the Masson and Isaak study was only consistent across subjects, but not across items. In a study that we carried out using similar nonword items as those used by Kinoshita (2000, Exp. 1) and a similar prime duration (Mousikou et al., 2010), we observed a significant orthographic priming effect, but our data also showed that although a number of participants showed the effect, others did not. We assumed thus that the speed at which each participant's nonlexical route operates might vary from one person to another and so it could be that at a relatively short prime duration some participants are fast enough to process more letters of the prime than the first, whereas others can only get to the first letter of the prime.

This idea is also 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 than 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) compared to 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 nonword reading aloud and so individual differences in adult readers should be expected in this task.

We simulated the performance of the participants with the presumed faster nonlexical route by speeding up the operation of the nonlexical route of DRC 1.2. The simulation results revealed an orthographic priming effect, confirming the dual-route interpretation of the Masson and Isaak (1999) human data.

SECTION 4: IS THE MOPE MODULATED BY TARGET FREQUENCY?

Empirical data

Malouf and Kinoshita (2007) carried out a reading aloud experiment which tested whether target frequency modulates the presence of the MOPE.[9] In their experiment, each trial started with the presentation of a forward mask (#######), centred on the screen for 500 ms. The prime was then presented

[9] We are not going to refer to Malouf's and Kinoshita's (2007) Experiment 2, which tried to replicate Forster's and Davis' (1991) Experiment 5, because these two experiments did not include a condition where the prime and the target shared just their initial letter/phoneme and so they did not specifically address the MOPE.

in lowercase letters for 58.5 ms, followed by the target displayed in uppercase letters. The target remained on the screen for a total of 2000 ms or until a response was generated by the participants. The results from their study showed that naming latencies both for the high frequency and the low frequency monosyllabic target words were faster when these were preceded by onset-related primes (e.g., *hark*-HEAT, *hark*-HEEL) compared to unrelated primes (e.g., *pork*-HEAT, *pork*-HEEL). Additionally, there was no interaction between the size of the MOPE and the frequency of the targets. Last, a significant frequency effect was observed so that the high frequency targets were named significantly faster than the low frequency targets (see Table 4).

Computational data

The same set of monosyllabic stimuli that Malouf and Kinoshita (2007) used in Experiment 1 were submitted to the DRC 1.2 model.[10] With a prime duration of 26 cycles DRC 1.2 showed a significant MOPE both for the high frequency (HF) and the low frequency (LF) targets; it made no errors (see Table 4).

In particular, the main effect of prime type was significant, with target naming in the onset-related condition being significantly faster than in the unrelated condition, $F(1, 150) = 23.68$, $p < .001$. However, the interaction between the size of the MOPE and the frequency of the targets was not significant, $F(1, 150) < 1$. *T*-tests for each type of target items showed a significant MOPE both for the HF, $t(75) = 3.20$, $p = .002$, and the LF targets, $t(75) = 4.33$, $p < .001$. Last, LF targets were read by the model faster than HF targets. Even though this difference was not significant, $F(1, 150) = 2.86$, $p > .05$, it was surprising that with the stimuli used in the Malouf and Kinoshita study the model could not show a frequency effect in the same direction that people do, although it successfully did so with the stimuli used by Weekes (1997) (see list of benchmark effects that DRC 1.2 successfully simulated at the Incremental Modelling document found at the following website: http://www.maccs.mq.edu.au/~ ssaunder/DRC/).

When we looked closely at the experimental stimuli used by Malouf and Kinoshita (2007), we realised that there was a confounding between target regularity and frequency. Twelve out of seventy-six HF targets were irregular words (hall, hold, last, mind, month, rise, rose, view, wall, word, world, young), and there was only one irregular LF target (jolt). Therefore, we removed these items and we reran the simulations. The DRC 1.2 model made no errors, and showed the results presented in Table 5.

[10] We would like to thank Sachiko Kinoshita for kindly providing us the pairs of primes and targets used in their study.

TABLE 4
Human reaction times (in milliseconds) and percent errors and DRC 1.2 reaction times (in cycles) from Experiment 1 (Malouf & Kinoshita, 2007)

	Human data				*Computational data*			
	Onset[a]		*Control*[b]		*Onset*[a]		*Control*[b]	
Condition	*RTs*	*Errors*	*RTs*	*Errors*	*RTs*	*SDs*	*RTs*	*SDs*
High frequency targets	553	3.0	564	2.6	72.5	16.0	74.9	18.0
Low frequency targets	571	2.8	584	3.6	69.4	6.1	71.1	5.2
Frequency effect	18	−0.2	20	1.0	−3.1	0.0	−3.8	0.0

Note: DRC = dual-route cascaded; RT = reaction time; *SD* = standard deviation.
Examples[a]: *hark*-HEAT, *hark*-HEEL. Examples[b]: *pork*-HEAT, *pork*-HEEL.

TABLE 5
DRC 1.2 reaction times (in cycles) from Experiment 1 (Malouf & Kinoshita, 2007) after the irregular word targets were removed

	Computational data			
	Onset		*Control*	
Condition	*RTs*	*SDs*	*RTs*	*SDs*
High frequency targets	66.0	2.6	67.6	2.1
Low frequency targets	68.8	2.7	70.6	2.4
Frequency effect	2.8		3.0	

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

In particular, the DRC 1.2 model showed a significant main effect of prime type, $F(1, 137) = 39.33$, $p < .001$, with target naming in the onset-related condition occurring significantly faster than in the unrelated condition. The interaction between the size of the MOPE and the frequency of the targets was not significant, $F(1, 137) < 1$. *T*-tests for each type of target items showed a significant MOPE both for the HF, $t(63) = 4.22$, $p < .001$, and the LF targets, $t(74) = 4.69$, $p < .001$. Last, there was a significant frequency effect, with the HF targets being read by the model faster than the LF targets, $F(1, 137) = 87.78$, $p < .001$.

Conclusion

The DRC 1.2 model successfully simulated a MOPE both for the high frequency and the low frequency targets. Additionally, the model showed no interaction between the size of the MOPE and the frequency of the targets. These results were consistent with the results obtained from the human data. However, the model could not show a frequency effect, but it read instead the LF targets faster than the HF targets. Such a result did not agree with the human data, but a close look at the stimuli used by Malouf and Kinoshita (2007) revealed that there was a confounding between regularity and frequency; a substantial number of HF targets were irregular words, and only one LF target was irregular. Such a confounding made DRC's 1.2 target naming latencies slower for the HF targets compared to the LF targets, but when this confounding was eliminated by removing all irregular word targets from the simulations, the model was able to show overall a pattern of results that corresponded to the pattern of results that the human data showed.

SECTION 5: IS THE MOPE MODULATED BY TARGET REGULARITY?

Empirical data

Forster and Davis (1991, Exp. 4) tested participants both on nonword prime–target pairs (see Section 2) and on word prime–target pairs that consisted of irregular word targets (e.g., *fish*-FETE vs. *spot*-FETE). The two types of items were presented in separate blocks (Davis, personal communication). As mentioned in Section 2, Experiment 4 of Forster and Davis had the same conditions of presentation as their Experiment 1 (see Section 1), except that a dummy word in lowercase letters of the same length as the target was used as a forward mask rather than a row of hash marks. The human results revealed a significant MOPE for the nonword items (see Section 2), but not for the word items. Because a significant MOPE was observed in Experiment 1 that also used word items, Forster and Davis attributed the absence of the effect for the word items in Experiment 4 to the irregularity of the targets. In particular, their claim was that when the targets are irregular words the nonlexical route of reading is prevented from operating, because irregular words can only be read correctly via the lexical route, whereas they are mispronounced if read via the nonlexical route. As a result, because the MOPE occurs due to the functioning of the nonlexical route of reading, it will not be present when the targets are irregular words.

Although this explanation was formed within a dual-route framework of reading, according to the dual-route interpretation of the MOPE, target naming might well occur via the lexical route of reading (as it is the case when the targets are irregular words, for example); however, this doesn't stop the nonlexical route from being operative, which means that it is still able to process the first letter of the prime during prime presentation and therefore cause a MOPE to occur. In fact, if the nonlexical route was "prevented from operating" in irregular word reading, as Forster and Davis (1991) suggested, there should be no regularity effect, i.e., naming latencies for irregular words should not be slower than for regular words, because the dual-route theory of reading assumes that what delays the naming of irregular words compared to regular words is the conflict between the incorrect regularised pronunciation of the irregular words produced by the nonlexical route and their correct irregular pronunciation produced by the lexical route, whereas such a conflict does not exist for regular words which are read correctly via both routes. Given that a number of studies have reported a significant regularity effect (Jared, 2002; Kinoshita & Woollams, 2002; Rastle & Coltheart, 1999), the idea that humans can "prevent their nonlexical route from operating" when reading irregular words is inconsistent with the presence of the effect in these studies.

More specifically, the dual-route account of the MOPE claims that nonlexical processing of the first letter of the prime during prime presentation results in the activation of its corresponding phoneme which will either compete with the first phoneme of the target if they are different and hence delay naming of the target, or facilitate its activation if they are the same and hence speed up target naming, or both. This should occur independently of whether the targets are regular or irregular words, nonwords or even pictures (for a MOPE found in the picture naming task in the Dutch language, see Schiller, 2008).

But then, how would the dual-route account of the MOPE explain the absence of the effect for the irregular word targets in the Forster and Davis (1991) study? What is specific to irregular word reading that prevents the first phoneme of the prime from having any effect on the first phoneme of the target?

Kinoshita and Woollams (2002) further investigated this issue by carrying out a study that particularly looked at how the MOPE interacts with the regularity of the target items, both when regular and irregular targets are presented in separate blocks (blocked design, Exp. 1) and when they are randomised (mixed design, Exp. 3).[11] Their results showed a significant MOPE for the regular targets in the blocked design, but not in the mixed design.[12] For the irregular targets, no MOPE was observed in either design. Also, there was a significant regularity effect both in the blocked and mixed designs, so that regular word targets (preceded by either onset-related or unrelated primes) were named significantly faster than irregular word targets. However, the size of the regularity effect was bigger in the blocked design (70 ms) compared to the mixed design (31 ms).

The dual-route theory of reading can offer an explanation for the regularity effect observed in the Kinoshita and Woollams (2002) study (see second paragraph of this subsection). Also, it could presumably explain why there was no significant MOPE for the regular word targets in the mixed design; when regular and irregular word targets are presented in a mixed random order, participants' nonlexical route might not operate as fast as it could when regular words are presented in a blocked design, because if it did so they would end up mispronouncing many of the irregular word targets. Therefore, if participants substantially slowed down their nonlexical route in the mixed design, the MOPE for the regular words could be eliminated. Additionally, if participants' nonlexical route operated at a slower pace in the mixed design compared to the blocked design a decrease in the size of the regularity effect would be expected in the former design compared to the latter, because in the mixed design the competition between the correct pronunciation of an irregular word produced by the lexical route and its incorrect regularised pronunciation produced by the nonlexical route would be weaker than in the blocked design.

Although the dual-route theory of reading seems to offer a plausible explanation for most of the results obtained from the study of Kinoshita and Woollams (2002), it is not yet apparent how it could explain the absence of the effect for the irregular word targets. Simulations of the human data with the DRC 1.2 computational model of reading could possibly offer an explicit account of the relevant empirical findings. However, given that the MOPE for the regular word targets in the mixed design was nonzero and it even

[11] For the purposes of the present paper, where simulations of the empirical findings on the MOPE in the speeded reading aloud task are performed, we are not going to refer to Kinoshita's and Woollams' Experiment 2 that used the conditional naming task.

[12] It is worth noting here that the MOPE for the regular word targets in the mixed design was 10 ms and only approached significance ($p = .08$), whereas in the blocked design it was 14 ms and significant.

approached significance (see footnote 12), it was unclear whether for the simulations this effect should be considered as present or absent. Such an ambiguity in the empirical data led us to carry out a new study that tried to replicate Kinoshita's and Woollams' results from Experiments 1 and 3. In particular, the aim of our study was to establish the facts about the MOPE with regular and irregular items in order to carry out the simulations of the theoretically interesting effects with the DRC 1.2 computational model of reading and determine thus whether the dual-route theory of reading can offer a valid explanation for all of these effects.

In our study the type of design was manipulated within subjects. However, the order of presentation of the designs was counterbalanced across subjects so that half of the subjects ($N = 12$) were presented the blocked design first, and the other half were presented the mixed design first. Also, while half of the subjects ($N = 6$) in the blocked design were presented the block of regular items first followed by the block of irregulars; the other half were presented these two blocks in the reverse order.

The other difference between our study and Kinoshita's and Woollams' (2002) study was that all target items in our study appeared twice (i.e., both in the onset related and the unrelated condition) and this was so for both designs. To make this explicit, each participant saw, for example, the target PEAR preceded both by the onset-related prime *pill* and the unrelated prime *tick* in the irregulars block of the blocked design and then the same participant also saw the target PEAR preceded by the primes *pill* and *tick* in the mixed design. Since participants saw each of the targets four times, we ensured that the same target item would only reappear after at least 20 trials of its first appearance in the blocked design and after at least 40 trials of its first appearance in the mixed design. Two lists were constructed (lists A and B) both in the blocked and the mixed design in order to counterbalance the order of prime type presentation so that if for example the onset related pair *pill*-PEAR was presented first in List A, the unrelated pair *tick*-PEAR would be presented first in List B and vice versa. An equal number of participants ($N = 12$) were tested on each list.

With regard to the experimental stimuli used in our study, most of them were similar to those used by Kinoshita and Woollams (2002) in Experiments 1 and 3; however, some of them (mainly primes) were replaced, because of being very high frequency words and according to the description of the materials used in their study all items were intended to be low to medium frequency words. Also, some target items that were used as irregulars in the Kinoshita and Woollams (2002) study were replaced, because according to the DRC 1.2 GPC (grapheme–phoneme correspondence) rules they were regulars (e.g., pour, hoof, dose, lure), and the target item "bolt" was replaced, because it was used as regular in the Kinoshita and Woollams (2002) study, but according to the DRC 1.2 GPC rules, it is irregular. Then, the target item "fuel" was replaced, because although in CELEX (Baayen, Piepenbrock, & van Rijn, 1993) it has both a monosyllabic and a disyllabic pronunciation, according to the Macquarie Dictionary (Yallop et al., 2005), it is disyllabic and so not included in the DRC 1.2 vocabulary. Last, many of the primes in the Kinoshita and Woollams study were repeatedly used; therefore, we replaced them with new prime words. The experimental stimuli consisted then of 30 regular and 30 irregular word targets in two prime type conditions each (onset vs. control). Because each participant was tested both on the blocked and the mixed design, the total number of experimental trials per participant were 240. Five additional prime–target pairs in each design served as practice trials. A total number of 24 participants were tested individually in a dimly lit room.

Each trial started with the presentation of a forward mask (#####), which remained on the screen for 501 ms. The prime was then presented in lowercase letters for 50.1 ms followed by the target that was presented in uppercase letters and acted as a backward mask to the prime. The target words appeared in white on a black background (Courier New, 14 font) and remained on the screen for 2000 ms or until subjects responded. The intertrial interval was 1002 ms. The order of trial presentation within blocks and lists was randomised across participants.

We carried out the analyses of the human data in the same way that Kinoshita and Woollams (2002) did. In particular, we performed planned comparisons instead of the omnibus *F*, because at the outset of our study we had a number of particular questions that we wanted to answer separately (for the logic of using planned comparisons see Abelson, 1995; Hays, 1973; Loftus & Loftus, 1988; Rosenthal & Rosnow, 1985). In a preliminary planned contrasts analysis by subjects, where we added order of presentation as a factor, given that in our experiment participants saw each target item in each design twice, we observed that there were carryover effects. In particular, participants showed a significant MOPE for the regular word targets both at first and second presentation in both designs, however, they did not show a significant MOPE for the irregular word targets at first presentation, but they did show the effect at second presentation. As a result, we analysed the data at first presentation only. The results are shown in Table 6.

Participants' naming responses were analysed using CheckVocal (Protopapas, 2007). The target items "wail", "debt", "beau", "pint", and "lieu" were removed from the analyses, because both in the blocked and the mixed design they caused an average error rate of over 20%. Similarly to Kinoshita and Woollams (2002), we performed planned contrasts testing (1) the regularity effect, (2) the MOPE for regular words, and (3) the MOPE for irregular words.

In the blocked design, averaged across prime type, the regularity effect was 28.75 ms and significant, $F1(1, 16) = 21.0$, $p < .001$, $F2(1, 212) = 34.39$,

TABLE 6
Human reaction times (in milliseconds) and percent errors from our experiment on the MOPE with regular and irregular words

	Human data					
	Regular targets		*Irregular targets*		*Regularity effect*	
Prime type	*RTs (SDs)*	*Errors*	*RTs (SDs)*	*Errors*	*RTs*	*Errors*
Blocked design						
Onset	445.8 (43.8)	3.2 (4.9)	481.5 (64.1)	5.5 (5.8)	35.7	2.3
Control	468.9 (42.8)	8.4 (8.7)	490.7 (54.7)	4.5 (5.0)	21.8	−3.9
MOPE	23.1	5.2	9.2	−1.0		
Mixed design						
Onset	456.8 (55.5)	0.9 (2.3)	475 (69.1)	8 (11.2)	18.2	7.1
Control	479.5 (51)	4.6 (6.2)	486.6 (55.9)	10.6 (11.3)	7.1	6.0
MOPE	22.7	3.7	11.6	2.6		

Note: RT = reaction time; *SD* = standard deviation; MOPE = masked onset priming effect.

$p < .001$.[13] The 23.1 ms of MOPE for the regular words was significant, $F1(1, 16) = 40.29$, $p < .001$, $F2(1, 224) = 17.16$, $p < .001$. The 9.2 ms of MOPE for the irregular words was not significant, $F1(1, 16) = 3.32$, $p > .05$, $F2(1, 199) = 2.0$, $p > .05$.[14]

The same planned contrasts were carried out for the error data. In the blocked design, averaged across prime type, the regularity effect was not significant, $F1(1, 16) < 1$, $F2(1, 212) = 1.07$. There was a significant MOPE for the regular words, $F1(1, 16) = 9.50$, $p = .007$, $F2(1, 224) = 8.86$, $p = .003$. The MOPE for the irregular words was not significant, $F1(1, 16) < 1$, $F2(1, 199) = 1.42$, $p > .05$.

Similarly, in the mixed design, averaged across prime type, the regularity effect was 12.65 ms and significant, $F1(1, 20) = 25.90$, $p < .001$, $F2(1, 106) =$

[13] In the subject analysis (repeated-measures), type of target item (regular vs. irregular) was a within-subjects factor, and list (A vs. B), order of block (block of regulars first vs. block of irregulars first), and order of design (blocked first vs. mixed first) were between-subjects factors. In the item analysis, a univariate analysis of ANOVA was carried out with type of target item, order of block, and order of design as fixed factors (given that the data were analysed at first presentation only, in the item analysis the factor list overlapped with the factor prime type). As a note, in most analyses of the human data there were significant interactions driven by the factors of either list, or order of block, or order of design, both for naming latencies and errors in both designs; however, these interactions were neither theoretically interesting nor relevant to the simulations by the model, and therefore were not included in the text for the sake of simplicity.

[14] In the subject analysis (repeated-measures), prime type was a within-subjects factor, and list, order of block, and order of design were between-subjects factors. In the item analysis, a univariate analysis of ANOVA was carried out with prime type, order of block, and order of design as fixed factors.

7.15, $p = .009$.[15] The 22.7 ms of MOPE for the regular words was significant, $F1(1, 20) = 92.17$, $p < .001$, $F2(1, 112) = 17.53$, $p < .001$. The 11.6 ms of MOPE for the irregular words was not significant in the subject analysis, $F1(1, 20) = 2.57$, $p > .05$, although it approached significance in the item analysis, $F2(1, 100) = 3.77$, $p = .055$.[16]

The same planned contrasts were carried out for the error data. In the mixed design, averaged across prime type, the regularity effect was significant, $F1(1, 20) = 15.42$, $p = .001$, $F2(1, 106) = 22.39$, $p < .001$. Also, there was a significant MOPE for the regular words, $F1(1, 20) = 6.39$, $p = .020$, $F2(1, 112) = 8.08$, $p = .005$. The MOPE for the irregular words was not significant, $F1(1, 20) = 1.06$, $p > .05$, $F2(1, 100) = 1.11$, $p > .05$.

In summary, the most important findings of our study, in terms of reaction times, were the significant regularity effect that was observed both in the blocked and the mixed design with the size of the effect being bigger in the blocked design compared to the mixed design. This difference was significant in the subject analysis, $F1(1, 20) = 8.29$, $p = .009$, but not in the item analysis, $F2(1, 212) = 2.54$, $p > .05$. Also, the MOPE for the regular word targets was significant in both designs, but not significant for the irregular word targets in neither design. In terms of errors, a significant MOPE for the regular word targets was found both in the blocked and the mixed design and also a significant regularity effect was observed in the mixed design.

Computational data

We have assumed that when humans are presented regular and irregular words randomly (mixed design) they read them using their "standard" reading parameters, which would correspond to the default parameters that we used in the DRC 1.2 model in order to simulate regular and irregular word reading in the mixed design. The reason for making this assumption is that the default parameters were originally chosen so that DRC 1.2 could correctly read all words, including all irregular words in its vocabulary (for DRC's 1.2 performance on regular and irregular word reading see the Incremental Modelling document found at the following website: http://www.maccs.mq.edu.au/~ ssaunder/DRC/).

However, when humans are presented regular words in a pure block, they can afford to read at a faster pace compared to the mixed design, because

[15] In the subject analysis (repeated-measures) type of target item was a within-subjects factor, and list and order of design were between-subjects factors. In the item analysis a univariate analysis of ANOVA was carried out with type of target item and order of design as fixed factors.

[16] In the subject analysis (repeated-measures) prime type was a within-subjects factor, and list and order of design were between-subjects factors. In the item analysis a univariate analysis of ANOVA was carried out with prime type and order of design as fixed factors.

since irregulars are not present within the same block, participants are not at risk of making regularisation errors (as it is the case in the mixed design for example). Therefore, we simulated reading of regular word targets in the blocked design by increasing (compared to the mixed design) the speed at which naming occurs in the system.[17] As for when humans are presented irregular words in a pure block, it is obvious why they could not speed up their reading pace compared to the mixed design: if they did that, they would mispronounce most of them. Therefore, we have assumed that the speed at which participants perform the task of irregular word reading in the blocked design is the same as that of the mixed design. As a result, we simulated reading of irregular word targets in the blocked design by using the same parameters as in the mixed design.

More specifically, the same stimuli that we used in our study were submitted to the DRC 1.2 model. With the default parameters and a prime duration of 26 ms, which would correspond to the simulation of the mixed design in the human experiment, the DRC 1.2 model made no errors with regular words, and it regularised the pronunciation of three irregular words; the words "feud" and "wasp" both in the onset-related and unrelated conditions and the word "palm" in the unrelated condition. The simulation results are presented in the mixed design part of Table 7.[18]

In particular, the model showed a significant regularity effect of 46.45 cycles, $F(1,\ 55) = 406.90$, $p < .001$, and also a significant MOPE for the regular words, $t(29) = 3.04$, $p = .005$, but no MOPE for the irregular words, $t(26) < 1$. The reason why the model showed no MOPE for the irregular word targets was because in irregular word reading, the last phoneme to reach the Minimum Reading Phonology parameter, which is the phoneme that in other words will determine the cycle at which the irregular word will be named by the model, is always the irregular phoneme (= the phoneme, which if read according to the GPC rules, will be incorrectly pronounced/regularised).[19] This occurs independently of whether the irregular word targets are preceded by onset-related or unrelated primes. That is why in the DRC 1.2 model target naming latencies for irregular words are not affected by whether the primes share their initial letter/phoneme with the targets or not.

[17] This can be done in many ways in the DRC 1.2 model; the different options are described in a later paragraph.

[18] As mentioned in the Empirical Data subsection, some of the target items were removed from the human analyses because they caused an error rate of over 20%. When these same items were removed from the computational data analyses no differences were observed in the results.

[19] In the only cases where the irregular phoneme was not the last to reach Minimum Reading Phonology, the model mispronounced the targets.

TABLE 7
DRC 1.2 reaction times (in cycles) from our experiment on the MOPE with regular and irregular words

	Word type				
	Regular		*Irregular*		*Regularity effect*
Prime type	*RTs*	*SDs*	*RTs*	*SDs*	*RTs*
Mixed design					
Onset	67.8	2.1	114.9	17.2	47.1
Control	69.2	1.4	115.0	16.0	45.8
MOPE	1.4		0.1		
Blocked design					
Onset	60.8	2.1	114.9	17.2	54.1
Control	62.3	1.4	115.0	16.0	52.7
MOPE	1.5		0.1		

Note: DRC = dual-route cascaded; RT = reaction time; *SD* = standard deviation; MOPE = masked onset priming effect.

With the default parameters then, which would correspond to the simulation of the mixed design in the human data, the DRC 1.2 model showed a pattern of results that was similar to the pattern of results that the human data showed.

As mentioned earlier, we have proposed that when humans are presented regular words in the blocked design they increase their reading speed, so we simulated that in the DRC 1.2 model by decreasing the value of MinReadingPhonology, which is the parameter that controls the speed of naming in the model, from 0.4 to 0.3. The results from the simulations, which are presented in the blocked design part of Table 7, showed a significant MOPE for the regular words, $t(29) = 3.06$, $p = .005$, and the model made no errors. As already predicted, when a value of 0.3 was used for the MinReadingPhonology parameter to simulate irregular word reading in the blocked design, the model produced a lot of errors. In fact, it mispronounced 28 out of 60 irregular words, confirming our hypothesis with regard to why humans could not be speeding up their pace in the blocked design compared to the mixed design when reading irregular word targets. Thus, we assumed that participants read irregular words in the blocked design as fast as in the mixed design and so the default parameters of DRC 1.2 were used again to simulate the blocked design with irregular word targets. As reported in the mixed design subsection, these parameters showed no MOPE for irregulars and this was also what the human data showed. Additionally, the regularity effect in the blocked design was significant, $F(1, 55) = 538.86$, $p < .001$, and significantly bigger in size (53.4 cycles) than in the mixed design, $F(1, 110) = 4.61$, $p = .034$.

Thus, by increasing the speed at which naming occurs in the DRC 1.2 model in order to simulate regular word reading in the blocked design and by using the default parameters in order to simulate irregular word reading in the blocked design, the simulations captured the human data. Nevertheless, it is worth pointing out that the same simulation results were obtained when either the nonlexical route of the model was speeded up (by increasing the value of the GPCPhonemeExcitation parameter from .051 to .061) or the lexical route of the model was speeded up (by increasing the value of the PhonlexPhonemeExcitation parameter from .09 to .1) or when both the nonlexical and lexical routes were speeded up. Such a result indicates that any method of the above could be valid for simulating the human data and so further empirical work would be required to discriminate between these different possibilities.

Conclusion

Similarly to Kinoshita and Woollams (2002), a significant regularity effect was observed both in the blocked and the mixed design of our human data, with the effect in the blocked design being significantly bigger in size than in the mixed design (only by subjects).[20] Also, both in our study and in Kinoshita's and Woollams' study no significant MOPE was observed for the irregular word targets neither in the blocked nor in the mixed design. However, although we observed a significant MOPE for the regular word targets both in the blocked and the mixed design, Kinoshita and Woollams only found the effect in the blocked design. Given that the MOPE in their mixed design was nonzero (10 ms) though and it even approached significance ($p = .08$), the discrepancy between our results and their results could just be due to the finer data analysis achieved by hand-marking participants' naming responses in our study.

With regard to the computational data, DRC 1.2 successfully simulated a significant regularity effect both in the blocked and the mixed design, with the effect in the former design being significantly bigger in size than in the latter design. Additionally, the model successfully simulated the absence of a MOPE for irregular word targets both in the blocked and the mixed design. This was explained in terms of a competition process between the incorrect regularised pronunciation of the irregular phoneme of the target and its correct irregular pronunciation which is not resolved until the letter string is

[20] We would like to note here that this difference was not statistically tested in the Kinoshita and Woollams study.

named by the model; by this time, any other effects that the prime could have on the target, such as the onset effect for example, have already been wiped out. Similarly to the human data from our study, the model showed a significant MOPE for the regular words both in the blocked and the mixed design.

Overall then, the DRC 1.2 model simulated successfully the major findings about the MOPE with regular and irregular word items.

SECTION 6: IS IT THE COMMON ORTHOGRAPHIC/ PHONOLOGICAL ONSET OR THE COMMON LETTER/ PHONEME BETWEEN THE PRIME AND THE TARGET THAT CAUSES THE MOPE TO OCCUR?

Empirical data

An interesting question that arises regarding the MOPE is whether it is due to the shared letter/phoneme between the prime and the target or to the shared orthographic/phonological onset. In fact, there has been a lot of discrepancy among different empirical studies that investigated whether the human reading system represents the orthographic/phonological onset as a single unit or as separate letters/phonemes (for a review see Mousikou et al., in press). As a result of this discrepancy, no theoretical consensus has been reached among computational models of reading regarding the implementation of a common coding scheme that could be considered representative of the human visual word recognition system; instead, different coding schemes have been adopted by the most recently developed computational models of reading: the PDP model (Harm & Seidenberg, 1999; Plaut, McClelland, Seidenberg, & Patterson, 1996), the DRC model (Coltheart et al., 2001), and the CDP+ model (Perry et al., 2007).

In a reading aloud study that we carried out using both word and nonword stimuli (see Mousikou et al., in press, for a detailed description of that study) we tested whether complex-onset targets (e.g., DRUM) are named faster when preceded by simple-onset first letter/phoneme related primes (e.g., *disc*) compared to when preceded by unrelated primes (e.g., *melt*). Similarly, we tested whether simple-onset targets (e.g., DISC) are named faster when preceded by complex-onset first letter/phoneme related primes (e.g., *drum*) compared to when preceded by unrelated primes (e.g., *melt*). The human results revealed a significant MOPE both for the simple-onset and the complex-onset targets and this was so both for words and nonwords (for the human results of this study see Mousikou et al., in press). This finding clearly indicated that the human reading system represents the orthographic/phonological onset as separate letters/phonemes and not as a single unit.

Computational data

The same stimuli that we used in our study were submitted to the DRC 1.2 model. With a prime duration of 26 cycles DRC 1.2 showed a significant MOPE for both types of target items (simple onset vs. complex onset) and for both types of stimuli (words vs. nonwords); the model made no errors. The simulation results are shown in Table 8.[21]

DRC 1.2 showed consistently a difference of one cycle for the nonword items (Exps. 1a and 1b). A Wilcoxon test that was carried out showed a highly significant MOPE in both experiments, $z = -8.367$, $p < .001$. Similarly, the MOPE was significant for the word items, $t(59) = 5.12$, $p < .001$ in Experiment 2a, and $t(59) = 2.26$, $p = .027$ in Experiment 2b.[22]

TABLE 8
DRC 1.2 reaction times (in cycles) from Experiments 1a, 1b, 2a, and 2b (Mousikou et al., in press)

Experiments	*Prime type*	*Mean RTs (SDs)*
Experiment 1a	*biln*-BREV	135.96 (0.36)
	kalt-BREV	136.96 (0.36)
	MOPE	1.0
Experiment 1b	*brev*-BILN	134.83 (2.6)
	kalt-BILN	135.83 (2.6)
	MOPE	1.0
Experiment 2a	*disc*-DRUM	68.03 (1.9)
	melt-DRUM	69.52 (1.8)
	MOPE	1.5
Experiment 2b	*drum*-DISC	68.22 (2.4)
	melt-DISC	69.03 (2.5)
	MOPE	0.8

Note: DRC = dual-route cascaded; RT = reaction time; *SD* = standard deviation; MOPE = masked onset priming effect.

[21] The simulation results reported in the Mousikou et al. (in press) paper slightly differ (in terms of arithmetic values only) from the simulation results shown in Table 8 of the present paper, because the DRC beta6 version of the DRC model was used for the simulations of the former paper.

[22] It should be noted here that in Experiment 2b 8 items were removed from the analyses of the human data, because they caused an average of more than 20% of errors in the two prime type conditions. When these items were removed from the analyses of the computational data, the naming latency difference between the onset related and the unrelated condition missed significance, $t(51) = 1.92$, $p = .061$ (two-tailed), even though the difference between the two conditions only decreased by 0.047 cycles compared to when these items were not removed from the analyses.

Conclusion

A study of reading aloud that consisted both of word and nonword stimuli used the MOPE in order to investigate whether the human reading system represents complex onsets as whole units or as separate letters/phonemes. The human results from this study provided evidence for the latter. The DRC 1.2 model that uses a letter-coding scheme successfully simulated the human data. However, it remains to be seen whether a whole-onset coding scheme as that implemented in the Plaut et al. (1996) model, for example, would be able to simulate these results. With regard to other computational models of reading, such as the Harm and Seidenberg model (1999) or the CDP+ (Perry et al., 2007) model, which do not contain complex onsets as input units, only simulations could determine whether they can simulate the human results or not (see also Conclusions in Mousikou et al., in press).

SECTION 7: IS THE MOPE ORTHOGRAPHIC OR PHONOLOGICAL IN NATURE?

Empirical data

Forster and Davis (1991, p. 7) first defined the MOPE as the finding that target naming occurs faster when the target (e.g., BREAK) is preceded by a prime with the same initial sound (e.g., *belly*), compared to an unrelated or rhyming prime (e.g., *merry* or *stake* respectively). However, in Forster's and Davis' (1991) study, primes and targets in the same initial-sound condition also shared their initial letter; therefore the effect could be due to the initial letter rather than to the initial phoneme.

In order to investigate whether the nature of the MOPE is orthographic or phonological we carried out a reading aloud study using nonword stimuli.[23] In our experiment the target items started with any of the four letters: K, F, P, or T that corresponded to the phonemes /k/, /f/, /p/, and /t/, respectively. The primes, which were matched with their targets on *N*,[24] either shared their first phoneme and letter with their targets, e.g., *kalt*-KEMP, *fich*-FERF, *pymn*-PAZZ, *tinc*-TALM (phonologically and orthographically congruent condition, i.e., P+O+), or their first phoneme, but not their first letter, e.g., *calc*-KEMP, *phal*-FERF (phonologically congruent, but orthographically incongruent condition, i.e., P+O−), or their first letter, but not their first

[23] Another study that investigated the same issue using words and was carried out in Dutch (Schiller, 2007) provided evidence in favour of the MOPE being phonological rather than orthographic.

[24] Neighbourhood size (*N*) is the number of words differing by a single letter from the stimulus, preserving letter positions, e.g., worse and house are orthographic neighbours of horse (Coltheart, Davelaar, Jonasson, & Besner, 1977).

phoneme, e.g., *pheb*-PAZZ, *thef*-TALM (phonologically incongruent, but orthographically congruent condition, i.e., P – O +), or shared no phonemes or letters with their targets in the same position, e.g., *diff*-KEMP, *sisp*-FERF, *neff*-PAZZ, *bes*k-TALM (unrelated condition, i.e., P – O –).

In particular, three groups of target items were formed: 20 K-onset, 20 F-onset, and 40 P/T-onset (half of which were P-onset and the other half T-onset). The targets in each of these groups were preceded by three different types of primes:

1. 20 P + O + primes (*kalt*-KEMP), 20 P + O – primes (*calc*-KEMP), and 20 P – O – primes (*diff*-KEMP).
2. 20 P + O + primes (*fich*-FERF), 20 P + O – primes (*phal*-FERF), and 20 P – O – primes (*sisp*-FERF).
3. 40 P + O + primes (*pymn*-PAZZ or *tinc*-TALM), 40 P–O + primes (*pheb*-PAZZ or *thef*-TALM), and 40 P – O – primes (*neff*-PAZZ or *besk*-TALM).

The reason why we considered the K-onset and the F-onset targets as different groups of items, even though they were preceded by the same types of primes, was because for the F-onset targets, the combination of the first two letters of the prime corresponded to the first phoneme of the target in the P + O – condition (*phal*-FERF), whereas for the K-onset target items, the first letter of the prime mapped onto the first phoneme of the target in that same condition (*calc*-KEMP). According to the literature (see Sections 2 and 3 of the present paper), at a prime duration of 50 ms participants could be processing either just the first letter of the prime or the first two; therefore, these two types of target items in the P + O – condition could yield different results and so we classified them into different groups.

Additionally, 60 prime – target pairs which started with all letters but K, F, P, and T and all phonemes but /k/, /f/, /p/, and /t/ were used as fillers. Half of the fillers formed related pairs (e.g., *basp*-BELK); the remaining half formed unrelated pairs (*belm*-ZOOP).

In the first group of target items (K-onset), each experimental condition (P + O +, P + O –, and P – O –) consisted of 20 prime – target pairs for a total of 60 pairs per participant. In the second group of target items (F-onset), each experimental condition (P + O +, P + O –, and P – O –) consisted of 20 prime – target pairs for a total of 60 pairs per participant. In the third group of target items (P/T-onset) each experimental condition (P + O +, P – O + and P – O –) consisted of 40 prime – target pairs (20 for each letter onset) for a total of 120 pairs per participant. Therefore, every participant saw the 80 targets three times, each time in a different prime type condition. Overall, each participant was presented 240 experimental trials and 60 trials that consisted of fillers; a total of 300 trials.

The 240 experimental trials were divided into three blocks so that the same target would not appear more than once within the same block. A brief break was administered between the blocks. Each block consisted of target items from all three groups; in particular, 20 targets from each letter onset (K, F, P, T) that corresponded to a specific prime type condition. Different prime type conditions were presented within each block. Three lists were constructed (List A, List B, and List C) to counterbalance the order of block presentation. An equal number of participants ($N = 12$) were tested on each list, making a total of 36 participants in all three lists. Last, participants were tested individually in a dimly lit room.

Each trial started with the presentation of a forward mask (####) that remained on the screen for 501 ms. The prime was then presented in lowercase letters for 50.1 ms followed by the target that was presented in uppercase letters and acted as a backward mask to the prime. The target words appeared in white on a black background (Courier New, 14 font) and remained on the screen for 2000 ms or until subjects responded. The intertrial interval was 1002 ms. The order of trial presentation within blocks and lists was randomised across participants.

Results

Subject responses were hand-marked using CheckVocal (Protopapas, 2007). The results are shown in Table 9. Each group of target items was analysed separately. For the K-onset targets, a repeated-measures ANOVA was carried out with prime type (P+O+, P+O−, P−O−) as a within-subjects factor and block of presentation (List A, List B, List C) as a between-subjects factor.[25] The results showed a significant main effect of prime type, $F1(2, 66) = 3.83$, $p = .027$, $F2(2, 171) = 5.94$, $p = .003$, and a significant interaction between prime type and block of presentation, $F1(4, 66) = 6.10$, $p < .001$, $F2(4, 171) = 8.16$, $p < .001$. The item analysis also showed a significant main effect of block of presentation, $F2(2, 171) = 10.40$, $p < .001$, with target naming latencies in List B being slower than in the other two lists. Planned comparisons showed that target naming latencies in the P+O+ condition were significantly faster compared to the P−O− condition, $t1(35) = 2.36$, $p = .024$, $t2(19) = 3.48$, $p = .002$. Similarly, target naming latencies in the P+O− condition were significantly faster compared to the P−O− condition, $t1(35) = 2.04$, $p = .049$, $t2(19) = 3.13$, $p = .006$. However, target naming

[25] In the item analysis a univariate analysis of variance was carried out with prime type (P+O+, P+O−, P−O−) and block of presentation (List A, List B, List C) as fixed factors. This analysis also applied to the F-onset and the P/T-onset targets.

TABLE 9
Human reaction times (in milliseconds) and percent errors and DRC 1.2 reaction times (in cycles) from our Experiment 1

Type of targets	*K-onset items*			*F-onset items*			*P/T-onset items*		
Condition	P+O+	P+O−	P−O−	P+O+	P+O−	P−O−	P+O+	P−O+	P−O−
Examples	*kalt*-KEMP	*calc*-KEMP	*diff*-KEMP	*fich*-FERF	*phal*-FERF	*sisp*-FERF	*tinc*-TALM	*thef*-TALM	*besk*-TALM
Human									
RTs	485.6	486.7	499.2	461.1	481.6	483.3	501.9	504.3	513.7
(*SDs*)	(64.7)	(65.9)	(60.2)	(61.2)	(62.5)	(57.8)	(66.2)	(60.7)	(57.8)
Errors	4.4	3.5	4.6	5.7	7.4	7.9	5.9	6.2	5.3
DRC 1.2									
RTs	136.05	136.05	137.05	134.5	135.5	135.5	134.98	134.8	135.98
(*SDs*)	(0.22)	(0.22)	(0.22)	(3.0)	(3.0)	(3.0)	(2.7)	(2.8)	(2.7)
Errors	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

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

latencies in the P+O+ and P+O− conditions did not differ significantly from each other, $t1(35) < 1$, $t2(19) < 1$.

For the F-onset targets, the results showed a significant main effect of prime type, $F1(2, 66) = 7.59$, $p = .001$, $F2(2, 171) = 15.94$, $p < .001$, and also a significant interaction between prime type and block of presentation, $F1(4, 66) = 5.41$, $p = .001$, $F2(4, 171) = 11.03$, $p < .001$. The item analysis also showed a significant main effect of block of presentation, $F2(2, 171) = 8.60$, $p < .001$, with target naming latencies in List B being slower than in the other two lists. Planned comparisons showed that target naming latencies in the P+O+ condition were significantly faster compared to the P−O− condition, $t1(35) = 2.82$, $p = .008$, $t2(19) = 6.65$, $p < .001$, and the P+O− condition, $t1(35) = 2.81$, $p = .008$, $t2(19) = 5.18$, $p < .001$. However, target naming latencies in the P−O− and P+O− conditions did not differ significantly from each other, $t1(35) < 1$, $t2(19) < 1$.

In the P/T-onset targets, the target item "paif" was removed from the analyses, because of causing an average error rate of over 20% in the three prime type conditions. The results showed a significant main effect of prime type, $F1(2, 66) = 5.83$, $p = .005$, $F2(2, 342) = 4.46$, $p = .012$, and also a significant interaction between prime type and block of presentation, $F1(4, 66) = 5.62$, $p = .001$, $F2(4, 342) = 4.90$, $p = .001$. The item analysis also showed a significant main effect of block of presentation, $F2(2, 342) = 17.71$, $p < .001$, with target naming latencies in List B being slower than in the other two lists. Planned comparisons showed that target naming latencies in the P+O+ condition were significantly faster compared to the P−O− condition, $t1(35) = 2.75$, $p = .009$, $t2(38) = 3.30$, $p = .002$. Similarly, target naming latencies in the P−O+ condition were significantly faster compared to the P−O− condition, $t1(35) = 2.38$, $p = .023$, $t2(38) = 2.08$, $p = .044$. However, target naming latencies in the P+O+ and P−O+ conditions did not differ significantly from each other, $t1(35) < 1$, $t2(38) < 1$.[26]

The error analysis was carried out in the same way as the RT analysis. Only for the F-onset targets, the main effect of block of presentation was significant in the items analysis, $F2(2, 171) = 6.14$, $p = .003$, with more errors occurring in List B compared to the other two lists. For each group of targets, planned comparisons of the prime type conditions showed no significant error differences between them.

[26] The reason why the interaction between prime type and block of presentation was significant for all types of target items was because participants' target naming latencies in all prime type conditions that were presented in the first block of trials were much slower compared to those presented in the second and third blocks of trials. However, if block order was the main factor affecting participants' target naming latencies then planned comparisons between the critical prime type conditions would not have been significant. Nevertheless, for all types of target items, pairwise comparisons between the critical prime type conditions resulted in significant two-tailed $t1$ and $t2$ values.

Summarising the most important findings of our study, the reaction time analysis showed a significant phonological MOPE for the K-onset targets, i.e., *kalt*-KEMP = *calc*-KEMP < *diff*-KEMP, but not for the F-onset or P/T-onset targets, i.e., *fich*-FERF < *phal*-FERF = *sisp*-FERF and *tinc*-TALM = *thef*-TALM < *besk*-TALM, indicating that at a prime duration of 50 ms participants do not have time to process both the first and the second letter of the prime and apply grapheme-to-phoneme correspondence rules to multiletter graphemes in order to translate them into their corresponding phoneme.

Computational data

The same stimuli that we used in our study were submitted to the DRC 1.2 model. With a prime duration of 26 cycles, the DRC 1.2 model successfully simulated the human data. The simulation results are shown in Table 9.

In particular, for the K-onset targets the model showed identical target naming latencies in the P+O+ and P+O− conditions that were significantly faster than in the P−O− condition, $z = -4.472$, $p < .001$. For the F-onset targets, target naming latencies in the P+O+ condition were significantly faster than in the P+O− and P−O− conditions, $z = -4.472$, $p < .001$, and the latter two conditions yielded similar target naming latencies. Last, for the P/T-onset targets, target naming latencies in the P+O+ and P−O+ conditions were significantly faster than in the P−O− condition, $z = -6.325$, $p < .001$, and $t(39) = 6.71$, $p < .001$, respectively, whereas the P−O+ and P−O− conditions yielded naming latencies that did not differ significantly from each other, $t(39) = 1.0$, $p > .05$.[27] Therefore, the simulation results, which are completely consistent with the human data, indicate that the MOPE is phonological in nature and that at a relatively short prime duration the nonlexical route of the model processes the first letter of the prime and translates it into its corresponding phoneme, which then has an effect on the first phoneme of the target.

Conclusion

In a reading aloud study that investigated whether at a relatively short prime duration (i.e., 50 ms) it is the first letter or the first phoneme of the prime that causes the MOPE to occur, the results provided evidence for the latter, because in prime–target pairs where the first letter of the prime corresponded to the first phoneme of the target (e.g., *calc*-KEMP) target

[27] When the target item "paif" was also removed from the computational data analyses no differences were observed in the results.

naming occurred faster than in unrelated pairs (e.g., *diff*-KEMP). However, when the combination of the first two letters of the prime corresponded to the first phoneme of the target (e.g., *phal*-FERF) target naming occurred as fast as in unrelated pairs (e.g., *sisp*-FERF); similarly, in prime–target pairs where the first letter of the prime corresponded to the first phoneme of the target, but the combination of the first two letters of the prime corresponded to a phoneme that was different from the first phoneme of the target (*pheb*-PAZZ or *thef*-TALM), target naming occurred as fast as in the P+O+ condition (*pymn*-PAZZ or *tinc*-TALM) and significantly faster than in the unrelated condition (*neff*-PAZZ or *besk*-TALM), indicating that at a relatively short prime duration participants do not have time to translate multiletter graphemes of the prime into their corresponding phoneme. The dual-route account of the MOPE can explain this finding by appealing to the nonlexical route of reading, which at a relatively short prime duration translates the first letter of the prime into its corresponding phoneme that has then an effect on the first phoneme of the target.

CONCLUSIONS

A series of findings from empirical studies on the MOPE and their simulations with the DRC 1.2 computational model of reading have been reported in the present paper. The DRC 1.2 model, which is a computational implementation of the dual-route theory of reading, has explained the MOPE as being due to the functioning of the nonlexical route of reading that operates serially and from left to right. Given that the model has been able to simulate most of the empirical findings on the MOPE reported in the English language to date (see the Appendix for a list of the human studies on the MOPE that the DRC 1.2 model has successfully—or not—simulated), the dual-route interpretation of the effect is strongly supported. With regard to the human data of the Forster and Davis (1991) study that the DRC 1.2 model was unable to simulate, a change to the way frequency scaling is implemented in the model has been proposed as a solution and is currently under investigation.

Concluding then, the masked onset priming effect is an empirical phenomenon that can be used as a tool to investigate the cognitive processes involved in the reading aloud process. To date, only one theory of reading, namely the dual-route theory, has offered an explanation for this effect. The present research has convincingly shown that the DRC 1.2 model, which is a computational realisation of this theory, has been able to simulate most facts about the MOPE that have been reported in the literature to date. Another computational dual-route model which additionally has connectionist features, namely the CDP+ (Perry et al., 2007) model, has recently been developed. It would be interesting to see thus whether this model can also simulate all the facts about the MOPE that the DRC 1.2 model has simulated.

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APPENDIX

Empirical findings on the MOPE and their simulations by the DRC 1.2 computational model of reading

Studies on the MOPE	*Human data*	*DRC 1.2*
Forster & Davis, 1991, Exp. 1 (Section 1)	*belly*-BREAK <*merry*-BREAK = *take*-BREAK	–
Kinoshita, 2000, Exp. 1 (Section 2)	*suf*-SIB = *sif*-SIB <*mof*-SIB *mub*-SIB = *mib*-SIB = *mof*-SIB	√
Masson & Isaak, 1999, Exp. 1 (Section 3)	*nump*-NUMP = *nurp*-NUMP <*nalk*-NUMP[a]	√
Malouf & Kinoshita, 2007, Exp. 1 (Section 4)	(1) MOPE for HF and LF target words	√
	(2) No interaction Frequency × Size of MOPE	√
	(3) Frequency effect	√
Experiment on the MOPE with regular and irregular words (Section 5)	(1) MOPE for regulars (blocked design)	√
	(2) No MOPE for irregulars (blocked design)	√
	(3) Regularity effect (blocked design)	√
	(4) MOPE for regulars (mixed design)	√
	(5) No MOPE for irregulars (mixed design)	√
	(6) Regularity effect (mixed design)	√
	(7) Regularity effect in mixed design <Regularity effect in blocked design[b]	√
Experiments 1a, 1b, 2a, and 2b from Mousikou et al., 2010 (Section 6)	*biln*-BREV <*kalt*-BREV	√
	brev-BILN <*kalt*-BILN	√
	disc-DRUM <*melt*-DRUM	√
	drum-DISC <*melt*-DISC	√
Study on the orthographic vs. phonological nature of the MOPE (Section 7)	(1) *kalt*-KEMP = *calc*-KEMP <*diff*-KEMP	√
	(2) *fich*-FERF <*phal*-FERF=sisp-FERF	√
	(3) *tinc*-TALM = *thef*-TALM <*besk*-TALM	√

A "√" indicates successful simulation of the human results by the model; a " –" indicates a failure in simulating the human results.

[a]We would like to remind the reader that although DRC 1.2 succeeded in simulating an orthographic priming effect after the parameter modifications, it was still unable to simulate equal target naming latencies in the repetition priming and orthographic priming conditions as the human data showed.

[b]We remind the reader that this difference was significant in the subject analysis, but not in the item analysis.