Journal of Experimental Psychology:
Human Perception and Performance
2010, Vol. 36, No. 1, 175–194

0096-1523/10/$12.00 DOI: 10.1037/a0015795

Is the Orthographic/Phonological Onset a Single Unit in Reading Aloud?

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Two main theories of visual word recognition have been developed regarding the way orthographic units in printed words map onto phonological units in spoken words. One theory suggests that a string of single letters or letter clusters corresponds to a string of phonemes (Coltheart, 1978; Venezky, 1970), while the other suggests that a string of single letters or letter clusters corresponds to coarser phonological units, for example, *onsets* and *rimes* (Treiman & Chafetz, 1987). These theoretical assumptions were critical for the development of coding schemes in prominent computational models of word recognition and reading aloud. In a reading-aloud study, we tested whether the human reading system represents the orthographic/phonological onset of printed words and nonwords as single units or as separate letters/phonemes. Our results, which favored a letter and not an onset-coding scheme, were successfully simulated by the dual-route cascaded (DRC) model (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). A separate experiment was carried out to further adjudicate between 2 versions of the DRC model.

Keywords: orthographic coding scheme, visual word recognition, reading aloud, masked onset priming effect (MOPE), computational models of reading

A common hypothesis of theories of visual word recognition is that skilled readers parse the individual letters or letter clusters of printed words into units that correspond to particular phonemes (Coltheart, 1978). According to this view, the word *SLIP* is parsed into four units, that is, *S*, *L*, *I*, and *P*, because each of the letters corresponds to a different phoneme; however, the word *SHIP* is parsed into three units, that is, *SH*, *I*, and *P*, because the combination of the first two letters, *S* and *H*, or in other words the grapheme *SH*, corresponds to the single phoneme /ʃ/, while the remaining two letters, *I* and *P*, correspond to two different phonemes. An alternative hypothesis is that spoken syllables have a hierarchical internal structure rather than a linear internal structure, and so if the syllable consists of an onset (initial consonant or cluster) plus a rime (vowel and any following consonants)[1] and these units are in turn composed of phonemes, printed words must also include similar units (Treiman & Chafetz, 1987). According to the latter view then, both *SLIP* and *SHIP* are parsed into two units, that is, *SL* and *IP* and *SH* and *IP*, respectively. The former unit in each of these words corresponds to the orthographic onset, while the latter unit corresponds to the orthographic rime or body (Kay & Bishop, 1987; Patterson & Morton, 1985).

Several studies have provided evidence in favor of the latter hypothesis, namely that printed words include similar units to those included in spoken syllables (Bowey, 1990; Brand, Giroux, Puijalon, & Rey, 2007; Kinoshita, 2000; Nuerk, Rey, Graf, & Jacobs, 2000; Treiman & Chafetz, 1987).

For example, Treiman and Chafetz (1987) used an anagrams task and a lexical decision task to investigate whether printed words include units that correspond to onsets and units that correspond to rimes. In the anagrams task (Experiments 1 and 2)[2] the participants were asked to judge whether two of four word fragments could be combined to form an English word. They were told to press "no" if no real word could be formed (e.g., IPS BR ORD SP), and to press "yes" and say the word aloud if a real word could be formed (e.g., EFT IST TW PL). The results from Experiments 1 and 2 showed that participants found a word such as *TWIST* more easily when it was divided into TW and IST (e.g., in the four-fragment list EFT IST TW PL) rather than when it was divided into TWI and ST (e.g., in the four-fragment list FT ST TWI PLE). For words with three-consonant initial clusters, such as SPREE, a SPR EE division was easier than was a SP REE division (Experiment 2). In the lexical decision task (Experiment 3), reaction times to stimuli with slashes after the initial consonant letters, whether these letters corresponded to a single phoneme (e.g., TH//ING) or to two phonemes (e.g., CR//ISP), were faster than were reaction times to stimuli with slashes after the vowel (e.g., THI//NG or CRI//SP). Treiman and Chafetz (1987) concluded that there must be orthographic units that correspond to the onset and rime units of spoken syllables.

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We would like to thank the editor, Ken Forster, Jeff Bowers, and an anonymous reviewer for valuable comments on a previous version of this article.

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[1] The vowel and the final consonant or consonants contained in the rime have been referred to in the literature as nucleus and coda, respectively.

[2] In Experiment 1, all the words had two consonant letters followed by a vowel followed by two consonants (e.g., FLANK and TWIST), while in Experiment 2, performance on stimuli with two-consonant and three-consonant initial clusters was compared (e.g., SPILL vs. SPREE).

Further evidence in favor of the idea that orthographic onset and rime serve as functional units of reading was provided by a study carried out by Bowey (1990). In a reading-aloud task that used a partial identity priming procedure, primes were presented for 120 ms, and they were then followed by a 120-ms interstimulus mask (four asterisks; ****), which was in turn followed by the target word. The results showed that priming the target word *swig* with *ig* (rime unit) yielded faster target-naming latencies in comparison with a control condition in which target words were not primed. However, prior presentation of *ft* did not facilitate naming of the target word *deft* in relation to the control condition. Additionally, priming the target word *brand* with *br* (onset unit) yielded faster target-naming latencies in comparison with a control condition in which target words were not primed. Nevertheless, prior presentation of *bi* did not facilitate naming of the target *birch* in relation to the control condition.

A different study that tested precisely whether the frequency of onsets, nuclei, and codas plays a role in visual word recognition (Nuerk et al., 2000) also supported the hypothesis that printed words and spoken syllables include similar sublexical units. In particular, a sublexical measure called *subcomponent frequency* (SCF)—which was defined as the mean of the logarithms of orthographic onset, nucleus, and coda frequency—was used in that study. Orthographic onset frequency of a target word was calculated as the summed frequency of all monosyllabic words that shared the same onset. Orthographic nucleus and coda frequency of a target word were calculated as the summed frequencies of all monosyllabic words that shared the same orthographic nucleus or coda, respectively. The human results from a lexical decision task showed that SCF facilitated visual word recognition for low-frequency words but not for high-frequency words. Also, nonwords with high SCF were harder to distinguish from words in comparison with nonwords with low SCF. This finding indicated that the human reading system represents words in terms of onsets, nuclei, and codas.

A more recent study carried out in French by Brand et al. (2007) focused, in particular, on the role of the syllable onset in reading. In a letter-detection task (Experiment 1) no difference was observed between the detection latencies of letters embedded in a multiletter syllable onset (e.g., C in eclater) in relation to a single-letter syllable onset (e.g., C in ecarter). In Experiment 2, detection latencies were slower for target letters that were in the second position of a multiletter onset (e.g., L in tablier) in comparison with when they were single-letter onsets (e.g., L in ecolier). In Experiment 3, the position effect was replicated for graphemes so that no difference was observed between the detection latencies of letters that were the initial letter of multiletter graphemes (e.g., A in trait) in relation to those that were single-letter graphemes (e.g., A in trace). Nevertheless, detection latencies were slower for target letters that were in the second position of multiletter graphemes (e.g., U in boule) in comparison with those that were single-letter graphemes (e.g., U in brune). Experiment 4, which was carried out in order to reject an alternative explanation of the effect in terms of letter saliency, showed that detection latencies were slower for target letters that were in the second position of a multiletter onset (e.g., L in tablier) in comparison with when they were single-letter onsets, either positioned between two vowels (e.g., L in ecolier) or preceded by a consonant (e.g., L in horloge). Overall, the findings from this study indicated that onsets are functional units of the reading system but that the unitization effect is position dependent.

Another study that addressed specifically the role of the orthographic/phonological onset in reading aloud was carried out by Kinoshita (2000, Experiment 2). This study used as a tool the masked onset priming effect (hereinafter MOPE), which refers to the finding that human naming latencies are faster when the target to be named (e.g., BREAK) is preceded by a briefly presented masked prime that shares its initial sound with the target (e.g., *belly*) in comparison with when it does not (e.g., *merry*; Forster & Davis, 1991, p. 7).[3] In particular, Kinoshita sought to determine whether it is the shared letter/phoneme between the prime and the target or the shared orthographic/phonological onset that causes the MOPE to occur. Her study thus included single-letter/single-phoneme ("simple") onset targets (e.g., PASTE) and multiletter/multiphoneme ("complex") onset targets (e.g., BLISS). The simple onset targets were preceded by primes that either shared their initial letter/phoneme with the target (e.g., *penny*–PASTE) or did not (e.g., *mummy*–PASTE). Similarly, the complex onset targets were preceded by primes that either shared their initial letter/phoneme with the target (e.g., *bingo*–BLISS) or did not (e.g., *solid*–BLISS). Kinoshita formed the following hypothesis: If it is just the initial shared letter or phoneme between the prime and the target that causes the MOPE to occur, target naming should be faster for the condition in which the prime and the target share their first letter/phoneme in comparison with the condition in which the prime and the target do not share their first letter/phoneme, and this should be so for either simple or complex onset targets, that is, *penny*–PASTE < *mummy*–PASTE and *bingo*–BLISS < *solid*–BLISS. However, if it is the orthographic or phonological onset of the word that causes the MOPE to occur, target naming should be faster for the condition in which the prime and the target share their first letter/phoneme in comparison with the condition in which the prime and the target do not share their first letter/phoneme, but now this should be so for the simple onset targets only, that is, *penny*–PASTE < *mummy*–PASTE, but *bingo*–BLISS = *solid*–BLISS. Kinoshita (2000, p. 137) summarized her results thus:

> The main finding from Experiment 2 was that reliable facilitation due to the overlap of just the initial grapheme/phoneme was observed with simple onset targets (e.g., *penny*–PASTE) but not with complex onset targets (e.g., *bingo*–BLISS). Such a finding is at odds with the notion that the unit underlying the masked onset priming effect is a letter (or a grapheme/phoneme), as has been suggested by the DRC model (Coltheart & Rastle, 1994), but is consistent with the speech production view that the unit corresponds to the onset of a word.

Although all of the above-mentioned studies provide empirical evidence in favor of the claim that the visual word-recognition system represents the orthographic/phonological onset as a unit and not as separate letters/phonemes, there have also been some

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[3] It is worth noting here that the original experiment of Forster and Davis (1991) that defined the MOPE did not include a crucial orthographic control condition, for example, *dip*–DOG versus *peg*–DOG versus *pen*–DOG; therefore, it could be that any orthographic overlap between the prime and the target, independent of whether this is in the initial or any other position, yields faster target-naming latencies than in an unrelated condition.

studies that provided empirical evidence in the opposite direction (Booth & Perfetti, 2002; Gross, Treiman, & Inman, 2000; Schiller, 2004).

For example, in a letter-detection task, Gross et al. (2000) investigated the role of onsets and rimes in visual word recognition. Although their results were consistent with the claim that the rime is a functional unit in reading, they were inconsistent with the same claim made about the onset because participants were as fast at detecting the letter *b* in *bink* as they were at detecting it in *brid*. In other words, if the orthographic/phonological onset is represented as a unit in the visual word-recognition system, participants should respond "yes" to *b* faster and more accurately in the condition in which *b* corresponds to the onset of the nonword in question, that is, *bink*, in comparison with the condition in which it does not, that is, *brid*, because in the latter nonword the onset is *br*. The results from this study indicated then that the orthographic/phonological onset is processed as separate letters/phonemes.

Further evidence for this idea was provided by Booth and Perfetti (2002). In their study, the first three experiments used a brief identification paradigm, in children at short (Experiment 1) and long (Experiment 2) stimulus duration, and in adults at short stimulus duration (Experiment 3). The aim of Experiment 4 was to replicate the onset–rime effect on naming latency in a reading-aloud task with adult participants so as to ensure that the stimuli used in their study were not qualitatively different from those used in previous studies (Bowey, 1990).

In particular, in Experiment 1 the target (e.g., *plan* or *barn*) was presented first briefly (28 ms), followed immediately by a brief presentation (28 ms) of a begin nonword mask that overlapped with the first two letters of the target (e.g., *PLEM* or *BALT*, respectively) or an end nonword mask that overlapped with the last two letters of the target (e.g., *GRAN* or *FORN*, respectively). The control nonword mask did not overlap with any letters of the target (e.g., *GREM* or *FOLT*, respectively). The mask was immediately followed by a pattern mask of the form *XXXXX* (500 ms). The participants' task was to write down the target word after each trial. The masks used for CCVC (in which C is consonant and V is vowel) words (e.g., *plan*) always corresponded either to the onset or to the rime; however, the masks used for CVCC words (e.g., *barn*) never corresponded to the onset or to the rime. Booth and Perfetti (2002) formed the hypothesis that if the onset–rime distinction is important in early word-recognition processes, begin masks (first two letters) should increase accuracy more for CCVC targets than for CVCC targets, and end masks (last two letters) should increase accuracy more for CCVC targets than for CVCC targets. Experiment 2 was similar; however, the target and the mask were presented for 56 ms instead of for 28 ms. Experiment 3 differed from the first two in that the target and the mask were presented for 14 ms and also a partial identity masking procedure was used, so that each target was followed by a begin mask of the first two letters (*PL##*, *BA##*), an end mask of the last two letters (*##AN, ##RN*), and a control mask of no letters (####). Finally, Experiment 4 used a partial identity priming paradigm, and so each trial consisted of a prime (*PL* or *AN*, and *BA* or *RN*) presented for 150 ms, followed by a mask (####) also presented for 150ms, followed by a target (*PLAN* and *BARN*, respectively). In this experiment, participants were asked to name the target as quickly as possible.

The results from the Booth and Perfetti study showed no evidence for the importance of onset–rime in children (2nd through 6th graders) or in adults when a brief identification paradigm was used. However, Experiment 4 replicated the effects of Bowey (1990) by showing that onset–rime structure is important in the reading-aloud task. The authors concluded that "onset and rime structure effects emerge in a phonologic production task for adults but not in a brief identification task for children or adults. This suggests that onset–rime structure does not affect the early stages of assembly in word identification but does influence the later stages of phonologic output" (Booth & Perfetti, 2002, p. 18).

The idea put forward by Booth and Perfetti contrasted with the results from a reading-aloud study carried out in Dutch (Schiller, 2004), which similarly to Kinoshita's study sought to determine whether it is the orthographic/phonological onset or the shared letter/phoneme between the prime and the target that causes the MOPE to occur. The results from Schiller's (2004, Experiment 3) study showed that simple onset target words such as BALLET ("ballet") and complex onset target words such as BROEDER ("brother") were named faster when preceded by masked primes that shared either their initial letter/phoneme with the targets (e.g., *b%%%%%%*–BALLET and *b%%%%%%*–BROEDER, respectively) or the first two letters/phonemes (e.g., *ba%%%%%*–BALLET and *br%%%%%*–BROEDER, respectively) in comparison with when the same targets were preceded by control primes that consisted of percentage signs only (e.g., %%%%%%%–BALLET and %%%%%%%–BROEDER). Schiller stated:

> Naming latencies were fastest in the first-two-segments condition (481 ms), followed by the first-segment condition (490 ms), and the control condition (495 ms). Most importantly, however, the interaction between Target Type and Prime Type was not significant (F_1 (1, 23) < 1; F_2 (1, 70) < 1). This shows that the form-priming effect was no different in the CC-onset condition than in the C-onset condition, i.e., there is no evidence from this experiment that the word onset as a unit played a role (Schiller, 2004, p. 485).

Therefore, Schiller's (2004, Experiment 3) results also contrasted with Kinoshita's (2000, Experiment 2) results.

The literature review clearly demonstrates then that there has been a lot of empirical discrepancy with regard to how the orthographic/phonological onset is represented in the human reading system. The aim of our study was to address this issue by using the MOPE, an effect that has been observed in different laboratories and in different languages both with word and nonword stimuli (Forster & Davis, 1991; Grainger & Ferrand, 1996; Kinoshita, 2000; Kinoshita & Woollams, 2002; Malouf & Kinoshita, 2007; Schiller, 2004, 2007, 2008). Because this effect taps into the very early stages involved in the reading-aloud process, it can be a useful tool for studying in particular how the human reading system represents orthographic/phonological onsets.

As was mentioned earlier though, the findings from two studies that used the MOPE in order to investigate the same issue (Kinoshita, 2000; Schiller, 2004) were inconsistent with each other: While the results from the former study provided evidence in favor of an onset coding scheme, the results from the latter study supported a letter coding scheme. The discrepancy between the two studies could be due to several reasons. First of all, Kinoshita's (2000) study was carried out in English, while Schiller's

(2004) study was carried out in Dutch. Second, the experimental items in Schiller's study were all disyllabic, while in Kinoshita's study all target items were monosyllabic, but the primes consisted of both monosyllabic and disyllabic items. Third, in Kinoshita's study the primes were whole words, while in Schiller's study the primes were either a single letter followed by percentage signs in the related condition (e.g., *b%%%%%*–BALLET) or just percentage signs in the control condition (e.g., *%%%%%%*–BALLET). Because there is no empirical evidence regarding how the human reading system processes percentage signs (see Finkbeiner, Almeida, & Caramazza, 2006), it could be the case that Schiller's results were influenced by factors beyond the main scope of his study.

Thus, we tried to solve the discrepancy between the two studies by carrying out two experiments on the MOPE: one that used nonword stimuli and another that used word stimuli. In each experiment, we tested whether complex onset targets are named faster when preceded by primes that share their first letter/phoneme with the target (e.g., *disc*–DRUM; related condition) in comparison with when they are preceded by primes that do not share their first letter/phoneme with the target (e.g., *melt*–DRUM; unrelated condition). Similarly, we tested whether simple onset targets are named faster when preceded by complex onset primes that share their first letter/phoneme with the target (e.g., *drum*–DISC; related condition) in comparison with when they are preceded by primes that do not share their first letter/phoneme with the target (e.g., *melt*–DISC; unrelated condition). Because in the related conditions (*disc*–DRUM and *drum*–DISC) the primes and the targets never shared their orthographic/phonological onset, but just their first letter/phoneme, if the human data showed that the related condition was faster than the unrelated condition, this could only be due to the shared letter/phoneme between the prime and the target. This would then mean that the human reading system processes the orthographic/phonological onset as separate letters/phonemes. However, if the human data showed no difference in target naming latencies between the related and the unrelated condition, this would mean that the human reading system processes the orthographic/phonological onset as a single unit.

From a theoretical point of view, defining whether humans process onsets as separate letters/phonemes or as units is crucial for adjudicating between computational models of reading that have adopted different coding schemes and offer therefore different accounts of how the human visual word-recognition system operates. The most representative examples of computational models that have implemented the two opposing coding schemes, that is, letter based vs. onset based, are the dual-route cascaded (DRC) model (Coltheart et al., 2001) and the parallel distributed processing (PDP) model of Plaut, McClelland, Seidenberg, and Patterson (1996).[4]

In particular, the DRC model (Figure 1), which is a computational implementation of the dual-route theory of reading (Forster & Chambers, 1973; Marshall & Newcombe, 1973), proposes that there are two routes involved in the reading process: a lexical route that is considered to be capable of reading all letter strings that are real words (either with a regular or an irregular pronunciation, e.g., *cat* and *yacht*, respectively), and a nonlexical route that is assumed to be capable of reading correctly all nonwords (e.g., *slev*) and also all letter strings that are real words with a regular pronunciation (e.g., *cat*). The DRC model assumes a letter-coding scheme, so that the input units at the letter level are represented by single letters. For example, the word *SLIP* is coded at the letter level as *S*, *L*, *I*, and *P*.

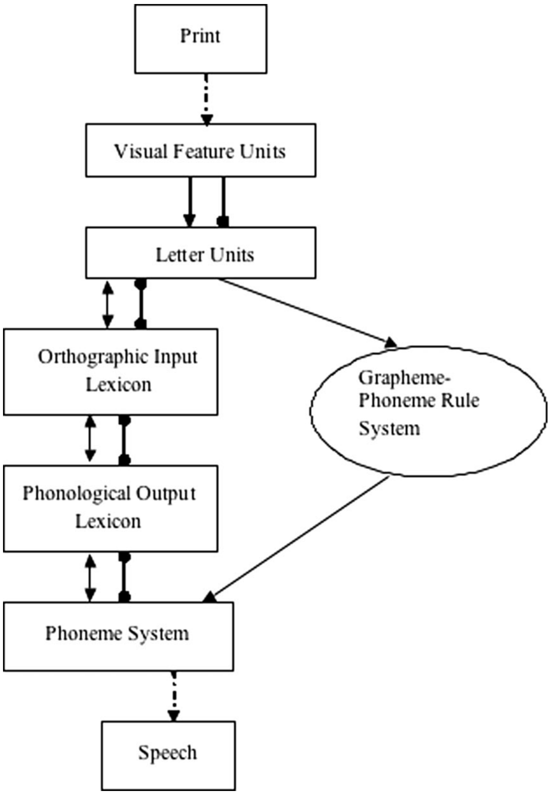

Figure 1. Dual-route cascaded (DRC) model (Coltheart et al., 2001).

The PDP model of Plaut et al. (Figure 2) consists of an input layer in which orthographic units are represented and an output layer in which phonological units are represented. The two layers are mediated by a layer of hidden units. The units between each layer are interconnected with weights, which are adjusted by comparing the pronunciation output produced by the model to the correct pronunciation output of the set of printed words given to the model during training. That is how the model learns to map the orthographic representations of regular words, exception words, and nonwords onto their corresponding phonological representations. In the implemented version of the PDP model, the input units are represented by onsets, nuclei, and codas; so for example, the word *SLIP* is coded as *SL*, *I*, and *P*, respectively. Also, the process of parsing a letter string into onset, nucleus, and coda precedes the orthography-to-phonology mapping process.

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[4] It is worth mentioning here that the PDP model we refer to as having an opposing coding scheme to that of the DRC model is the one of Plaut et al. (1996). In particular, both the older version of the PDP model (Seidenberg & McClelland, 1989) and the newer version (Harm & Seidenberg, 1999) do not have the same coding scheme as that of Plaut et al. (1996). Interestingly, Plaut et al. (1996) attributed the previous model's poor performance on nonword reading to the particular coding scheme used in that version, which did not facilitate the learning process of spelling-to-sound correspondences and therefore hindered generalization.

Figure 2. Representation of the implemented Plaut et al. (1996) parallel distributed processing (PDP) model shown in bold.

Hence, if the human data from our study showed that the orthographic/phonological onset is processed as separate letters/phonemes, then a letter-coding scheme as implemented in the DRC model would be favored. However, if the human data showed that the orthographic/phonological onset is processed as a single unit, then an onset-coding scheme as implemented in the PDP model of Plaut et al. (1996) would be favored.

Experiments 1a and 1b

Method

Materials. In Experiment 1a, 210 four-letter-long pronounceable monosyllabic nonwords were selected from the ARC nonword database (Rastle, Harrington, & Coltheart, 2002). Seventy nonwords with graphemic and phonological CCVC (consonant-consonant-vowel-consonant) structure served as target items.[5] The remaining 140 nonwords with graphemic CVCC, CVCV, and CVVC structures served as related and unrelated primes. In particular, two groups of 70 prime–target pairs were formed with the targets remaining the same in both groups. There were two types of primes: primes that shared the first letter/phoneme with their targets (related)—for example, *biln*–BREV—and primes that did not share the first letter/phoneme with their targets (unrelated)—for example, *kalt*–BREV. Primes and targets were matched on N[6] (not all of the primes had exactly the same N as their corresponding targets, but the difference between the two was kept minimal across all pairs). The complete list of the prime–target pairs used in Experiment 1a can be seen in Appendix A. In addition to the 140 prime–target pairs that formed the experimental stimuli, 6 more pairs of primes and targets that matched the experimental stimuli on the same criteria were selected as practice items.

In Experiment 1b, the same stimuli as in Experiment 1a were used; however, the items that served as related primes in Experiment 1a formed the target items in Experiment 1b. Similarly, the items that served as targets in Experiment 1a were used as related primes in Experiment 1b. The items that served as unrelated primes in Experiment 1a remained as unrelated primes in Experiment 1b. As a result, 70 nonwords with graphemic CVCC, CVCV, and CVVC structure served as target items, and 70 nonwords with graphemic CCVC structure (except for the item *prew*, which had a CCV structure) served as related primes. The remaining 70 nonwords with graphemic CVCC, CVCV, and CVVC structure served as unrelated primes. To state this explicitly, if for example in Experiment 1a the related and unrelated conditions were represented respectively by pairs such as *biln*–BREV and *kalt*–BREV, then in Experiment 1b the pairs that represented the related and unrelated conditions, respectively, were *brev*–BILN and *kalt*–BILN. Prime–target matching and group formation was similar to that of Experiment 1a. The complete list of the prime–target pairs used in Experiment 1b can be seen in Appendix B. Also, six pairs of primes and targets that matched the experimental stimuli on the same criteria were selected as practice items.

Design. Each experimental condition (related and unrelated) consisted of 70 prime–target pairs for a total of 140 pairs per participant in a fully counterbalanced design. This meant that every participant saw the 70 targets twice, each time preceded by a different type of prime. A mixed design was used so that the two prime-type conditions were presented in a random order across the experiment. Furthermore, the 140 trials were divided into two blocks so that the same target would not appear more than once within the same block; a brief break was administered between the blocks. Last, two lists (List A and List B) were constructed to counterbalance the order of block presentation. An equal number of participants ($N = 6$) were tested on each list.

Participants. Twenty-four undergraduate Macquarie University students participated in this experiment for course credit. Half of them were tested on Experiment 1a and the remaining half on Experiment 1b. All participants were native speakers of Australian English.

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

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

Each trial started with the presentation of a forward mask (####) that remained on the screen for 501 ms. The prime was then

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[5] Only one nonword target item, PREW, had a phonological CCV structure.

[6] Neighborhood size (N) is the number of words differing by a single letter from the stimulus, preserving letter positions; for example, *worse* and *house* are orthographic neighbors of *horse* (Coltheart, Davelaar, Jonasson, & Besner, 1977).

presented in lowercase letters for 50.1 ms (five ticks based on the machine's refresh rate of 10.02 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 (14-point Courier New font) and remained on the screen for 2,000 ms or until participants responded. The intertrial interval was 1,002 ms. The order of trial presentation within blocks and lists was randomized across participants.

Results

Participant responses were hand marked using CheckVocal (Protopapas, 2007).[7] To reduce the effects of outliers, any reaction times (RTs) slower than 1,500 ms or faster than 200 ms were discarded from the analyses. Also, any RTs more than 2 *SD* units away from the overall mean RT for each participant were trimmed by setting them equal to the default cutoff value. The target items FLIL and PLIL (from Experiment 1a) and the target items BESE, BEWN, DESE, FUGE, FULE, FEPE, FEUM, PUCH, and SAFF (from Experiment 1b) were removed from the analyses because they caused an average of more than 20% of errors in the two prime-type conditions. The results from Experiments 1a and 1b are shown on Table 1.

In the RT analysis of Experiment 1a, a repeated-measures analysis of variance (ANOVA) with prime type (related vs. unrelated) as a within-subjects factor and block of presentation (List A vs. List B) as a between-subjects factor showed that there was a significant main effect of prime type, $F_1(1, 10) = 162.39$, $p < .001$, partial $\eta^2 = .942$, $F_2(1, 268) = 21.88$, $p < .001$, partial $\eta^2 = .075$, with target-naming latencies in the related condition being significantly faster than those in the unrelated condition.[8] The results showed no interaction between prime type and block of presentation, $F_1(1, 10) < 1$, partial $\eta^2 = .001$, $F_2(1, 268) < 1$, partial $\eta^2 = .000$.[9] The error analysis yielded no significant differences between the two conditions.

In the RT analysis of Experiment 1b, the results showed a significant main effect of prime type, $F_1(1, 10) = 13.25$, $p = .005$, partial $\eta^2 = .570$, $F_2(1, 240) = 8.19$, $p = 0.05$, partial $\eta^2 = 0.33$, with target-naming latencies in the related condition being significantly faster than those in the unrelated condition, a significant main effect of block of presentation (in the by-items analysis), $F_2(1, 240) = 4.23$, $p = 0.41$, partial $\eta^2 = .017$, with naming latencies in List B being faster than those in List A, but no interaction between prime type and block of presentation, $F_1(1, 10) < 1$, partial $\eta^2 = .082$, $F_2(1, 240) = 1.38$, $p > .05$, partial $\eta^2 = .006$. The error analysis showed that more errors were made in the unrelated condition than in the related condition. However, the difference was significant in the items analysis only, $F_2(1, 240) = 5.22$, $p = .023$, partial $\eta^2 = .021$, while in the participants analysis it only approached significance, $F_1(1, 10) = 4.06$, $p = .071$, partial $\eta^2 = .289$. Last, the main effect of block of presentation was significant (in the by-items analysis), $F_2(1, 240) = 4.33$, $p = .039$, partial $\eta^2 = .018$, with more errors occurring in List A than in List B.

Table 1
Mean Reaction Times (in Milliseconds) and Mean Errors From Experiments 1a and 1b

Prime type	Mean RTs[a] (*SD*)	Mean errors (*SD*)
Experiment 1a		
Related	445.6 (35.6)	4.7 (2.7)
Unrelated	468.9 (34.3)	4.3 (2.6)
MOPE	23.3	−0.4
Experiment 1b		
Related	469.8 (55.3)	4.2 (2.9)
Unrelated	486.2 (52.8)	7.3 (6.0)
MOPE	16.4	3.1

Note. RT = reaction time; *SD* = standard deviation; MOPE = masked onset priming effect.
[a] The means and effect sizes were rounded to the nearest whole number in all experiments.

Discussion

In Experiment 1a we tested whether nonword targets with complex onsets (e.g., BREV) are named faster when preceded by related nonword primes (e.g., *biln*) in comparison with when they are preceded by unrelated nonword primes (e.g., *kalt*). In Experiment 1b we tested whether nonword targets with simple onsets (e.g., BILN) are named faster when preceded by related nonword primes (e.g., *brev*) in comparison with when they are preceded by unrelated nonword primes (e.g., *kalt*). The results from both experiments showed a significant MOPE, indicating that the human reading system processes the orthographic/phonological onset of nonwords as separate letters/phonemes and not as a single unit. Although these results provide clear evidence in favor of a letter-coding scheme, they could be limited to nonword reading. Because the other two studies on the MOPE that investigated the same issue (Kinoshita, 2000; Schiller, 2004) used word stimuli, it was necessary to carry out an experiment with word stimuli so as to test whether the observed effects are independent of the lexical status of the items.

Experiments 2a and 2b

Method

Materials. In Experiment 2a, 180 four-letter-long monosyllabic words were selected from the CELEX word database

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[7] CheckVocal is a Windows program written for the experimenter who uses naming tasks, aiming to facilitate the manual processing of spoken responses. It determines response accuracy, and it also ensures that the voice-trigger mechanism has correctly registered the participant's naming response, because it is very likely that voice keys are triggered by nonspeech sounds made by the participant prior to the response (e.g., lip smacking, coughing, and hesitation fillers), or late responses to the preceding items. Although it is possible to exclude some sources of timing errors by setting absolute thresholds (e.g., discarding response times below 100 ms or above a certain delay), it is not possible to ensure reliable response times entirely automatically (Protopapas, 2007, p. 859).

[8] In the item analysis, prime type was a between-groups factor. For the items, then, a univariate analysis of variance was carried out with prime type (related vs. unrelated) and block of presentation (List A vs. List B) as fixed factors. This analysis also applied to Experiments 1b, 2a, and 2b.

[9] In Experiments 1a, 1b, 2a, and 2b, each participant saw the targets twice, each time in a different prime-type condition. RTs on the second presentation were always faster than on the first. However, the size of the MOPE never interacted with order of presentation.

(Baayen, Piepenbrock, & Van Rijn, 1993). Sixty words with graphemic CCVC and CCVV structures served as target items. The remaining 120 words with graphemic CVCC, CVCV, and CVVC structures served as related and unrelated primes. In particular, two groups of 60 prime–target pairs were formed, with the targets remaining the same in both groups. There were two types of primes: primes that shared their first letter/phoneme with the targets (related), for example, *disc*–DRUM, and primes that did not share their first letter/phoneme with the targets (unrelated), for example, *melt*–DRUM. The CELEX mean written frequency value for the targets was 706, for the related primes was 556.75, and for the unrelated primes was 517.28. The CELEX mean N values for the targets, related primes, and unrelated primes were 6.5, 10.43, and 10.57, respectively. The complete list of the prime–target pairs used in Experiment 2a can be seen in Appendix C. In addition to the 120 prime–target pairs that formed the experimental stimuli, 6 more pairs of primes and targets that matched the experimental stimuli on the same criteria were selected as practice items.

In Experiment 2b, the same stimuli as in Experiment 2a were used; however, the items that served as related primes in Experiment 2a were used as target items in Experiment 2b. Similarly, the items that served as targets in Experiment 2a were used as related primes in Experiment 2b. The items that served as unrelated primes in Experiment 2a remained as unrelated primes in Experiment 2b. As a result, 60 words with graphemic CVCC, CVCV, and CVVC structures served as target items, and 60 words with graphemic CCVC and CCVV structures served as related primes. The remaining 60 words with graphemic CVCC, CVCV, and CVVC structures served as unrelated primes. To state this explicitly, if for example in Experiment 2a the related and unrelated conditions were represented respectively by pairs such as *disc*–DRUM and *melt*–DRUM, then in Experiment 2b the pairs that represented the related and unrelated conditions respectively were *drum*–DISC and *melt*–DISC. Similarly to that in Experiment 2a, two groups of 60 prime–target pairs were formed, with the targets remaining the same in both groups. The CELEX mean written frequency value for the targets was 556.75, for the related primes was 706, and for the unrelated primes was 517.28. The CELEX mean N values for the targets, related primes, and unrelated primes were 10.43, 6.5, and 10.57, respectively. The complete list of the prime–target pairs used in Experiment 2b can be seen in Appendix D. Also, six pairs of primes and targets that matched the experimental stimuli on the same criteria were selected as practice items.

Design. Experiments 2a and 2b had the same design as Experiments 1a and 1b.

Participants. Twenty-four[10] undergraduate Macquarie University students participated in this experiment for course credit. Half of them were tested on Experiment 2a and the remaining half on Experiment 2b. All participants were native speakers of Australian English.

Procedure. The procedure followed in Experiments 2a and 2b was similar to that of Experiments 1a and 1b. However, participants were now instructed (verbally first and then by written instructions on the monitor) that a list of words, preceded by a series of pound signs (####), would be presented on the screen one at a time and that their task was to read aloud the word in uppercase letters as quickly and as accurately as possible.

Results

The analysis of the participants' responses and the data-trimming criteria were the same as those in Experiments 1a and 1b. The target items BROW, CRAB, PROP, and PLAY (from Experiment 2a) and the target items GOWN, FIST, POPE, DOLL, COCK, BEET, DATE, and SELL (from Experiment 2b) were removed from the analyses because they caused an average of more than 20% of errors in the two prime-type conditions. The results from Experiments 2a and 2b are shown on Table 2.

Experiments 2a and 2b were analyzed in a manner similar to that in Experiments 1a and 1b. The RT data from Experiment 2a showed that there was a significant main effect of prime type, $F_1(1, 10) = 56.93$, $p < .001$, partial $\eta^2 = .851$, $F_2(1, 220) = 19.63$, $p < .001$, partial $\eta^2 = .082$, with target-naming latencies in the related condition being significantly faster than those in the unrelated condition and a significant main effect of block of presentation (in the by-items analysis), $F_2(1, 220) = 41.39$, $p < .001$, partial $\eta^2 = .158$, with naming latencies in List A being faster than those in List B. However, there was no significant interaction between prime type and block of presentation, $F_1(1, 10) < 1$, partial $\eta^2 = .001$, $F_2(1, 220) < 1$, partial $\eta^2 = .000$. In the error analysis, only the main effect of block of presentation (in the by-items analysis) was significant, $F_2(1, 220) = 4.44$, $p = .036$, partial $\eta^2 = .020$, with a mean of 2.2 more errors in List A in comparison with those in List B.

In the RT analysis of Experiment 2b, the results showed a significant main effect of prime type, $F_1(1, 10) = 69.59$, $p < .001$, partial $\eta^2 = .874$, $F_2(1, 204) = 6.93$, $p = .009$, partial $\eta^2 = .033$, with target-naming latencies in the related condition being significantly faster than those in the unrelated condition and no interaction between prime type and block of presentation, $F_1(1, 10) < 1$, partial $\eta^2 = .002$, $F_2(1, 204) < 1$, partial $\eta^2 = .000$. The error analysis yielded no significant differences between the two conditions.

Discussion

In Experiment 2a, we tested whether word targets with complex onsets (e.g., DRUM) are named faster when preceded by related word primes (e.g., *disc*) than when preceded by unrelated word primes (e.g., *melt*). In Experiment 2b, we tested whether word targets with simple onsets (e.g., DISC) are named faster when preceded by related word primes (e.g., *drum*) than when preceded by unrelated word primes (e.g., *melt*). The results from both experiments showed a significant MOPE, indicating that the human reading system processes the orthographic/phonological onset of words as separate letters/phonemes and not as a single unit.

Experiments 1a and 1b and 2a and 2b Combined

Because the results from our experiments showed a significant MOPE in terms of naming latencies both for words and nonwords, the RT data from both experiments were combined in a single analysis in order to test whether the size of the effect is modulated by lexicality. The results showed a significant main effect of prime

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[10] Two participants had to be replaced from Experiment 2a because they made more than 20% of errors overall.

Table 2
Mean Reaction Times (in Milliseconds) and Mean Errors From Experiments 2a and 2b

Prime type	Mean RTs (*SD*)	Mean errors (*SD*)
Experiment 2a		
Related	443.4 (49.4)	3.3 (3.1)
Unrelated	465.7 (45.9)	4.3 (2.9)
MOPE	22.3	1.0
Experiment 2b		
Related	416.1 (39.5)	5.9 (4.7)
Unrelated	429.7 (37.3)	7.8 (4.1)
MOPE	13.6	1.9

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

type, $F_1(1, 46) = 152.77$, $p < .001$, partial $\eta^2 = .769$, $F_2(1, 939) = 47.01$, $p < .001$, partial $\eta^2 = .048$, with target-naming latencies in the related condition being significantly faster than those in the unrelated condition and no significant interaction between prime type and lexicality, $F_1(1, 46) < 1$, partial $\eta^2 = .009$, $F_2(1, 939) < 1$, partial $\eta^2 = .000$, indicating that the size of the MOPE does not depend on the lexical status of the items. Additionally, the results showed a lexicality effect so that words were named 28.9 ms faster than were nonwords, $F_1(1, 46) = 4.89$, $p = .032$, partial $\eta^2 = .096$, $F_2(1, 939) = 90.18$, $p < .001$, partial $\eta^2 = .088$. The combined analysis of Experiments 1 and 2 is shown in Figure 3.

Simulations

DRC model. The results from the human experiments were simulated by the DRC 1.1.4 version (Figure 1), (Biedermann, Coltheart, Nickels, & Saunders, 2009; Nickels, Biedermann, Coltheart, Saunders, & Tree, 2008). The differences between the original DRC as was reported in the 2001 *Psychological Review* article (Coltheart et al., 2001) and DRC 1.1.4 are fully documented at the following Web site: http://www.maccs.mq.edu.au/~ssaunder/PDsims/Differences.html. All but two of these differences are trivial (mainly minor corrections and bug fixes). The two that are not trivial are the following:

1. In the original DRC the representations of word frequencies in the orthographic and phonological lexicons are the same: Both are the CELEX written word frequencies. In DRC 1.1.4, the orthographic lexicon has written word frequencies from CELEX, while the phonological lexicon has CELEX spoken word frequencies.

2. In the original DRC the input to the nonlexical route would, given enough cycles, eventually include the most active letters in all the letter units. For example, if the input to the model was TREE, given enough cycles, the input to the nonlexical route could end up being TREE++++ (for which the plus sign indicates the null letter unit in that position). This would lead to the nonlexical route's output being /tri+++++/ (here the plus sign represents the null phoneme unit in any set of phoneme units). This has been changed in DRC 1.1.4 so that letters stop being added to the nonlexical route's input after the first blank. As a result, the output of the nonlexical route will only contain at most one blank, that is, /tri+/. A change has also been made to the way the units in the orthographic lexicon are connected to the letter layer and the way the units in the phonological lexicon are connected to the phoneme layer. Previously, each lexical unit was connected to all the units in the associated layer. This has been changed in DRC 1.1.4 so that each lexical unit is only connected to one letter or phoneme unit for each letter or phoneme that it contains, plus one for a blank. The orthographic and phonological lexicon unit for the word TREE, for example, is connected respectively to only the first five letter units, that is, TREE+, and to only the first four phoneme units, that is, /tri+/.

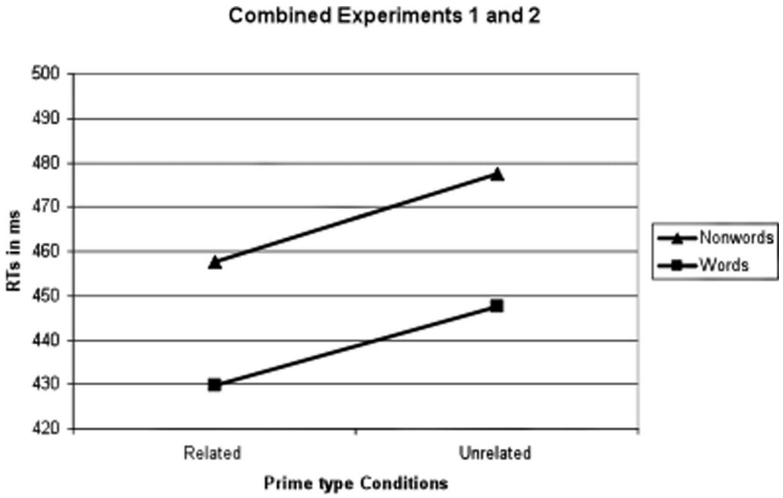

Figure 3. Interaction between prime type and lexicality. RT is reaction time.

Although DRC 1.1.4 has not yet been completely evaluated, work to date has not revealed any cases of reading phenomena, which the original DRC could simulate but which DRC 1.1.4 cannot. One reading phenomenon that both versions could simulate is the MOPE; however, more extensive work on this effect has been carried out with DRC 1.1.4. In particular, the way DRC 1.1.4 simulates the MOPE with four-letter-long nonwords, for example, is the following:

1. When a nonword target preceded by a nonword prime is presented to the model, the letters of the prime are activated in parallel at the letter level.
2. The nonlexical route processes the first letter of the prime and activates its corresponding phoneme at the phoneme level.
3. With a prime duration of 44 cycles[11] the nonlexical route has already processed the first two letters of the prime and has activated their corresponding phonemes at the phoneme level.
4. At prime offset the target replaces the prime and decay at the letter level switches off the activation of the prime's letters to simulate backward masking.
5. The target's letters are activated in parallel at the letter level.
6. The nonlexical route processes the first letter of the target.
7. A fixed number of cycles has to elapse before the nonlexical route moves on to the second letter of the target and then to the third, until it reaches the blank letter that indicates the end of the input string.
8. The model will then name the target when the slowest phoneme reaches the value that corresponds to the MinReadingPhonology parameter.[12]
9. What causes the MOPE to occur—that is, the target BREV is named faster when preceded by the prime *biln* than when it is preceded by the prime *kalt*—is the fact that the initial phoneme of the onset-unrelated prime, which has been highly activated at a prime duration of 44 cycles, competes with the initial phoneme of the target. This competition makes the target's first phoneme reach the MinReadingPhonology parameter last, and so there is some delay in target naming in comparison with the onset-related condition in which there is no such competition in the first phoneme position.

DRC 1.1.4 simulations for Experiments 1a and 1b. Experiments 1a and 1b were simulated with the default parameters of DRC 1.1.4 and with the MinReadingPhonology parameter set to 0.3 to simulate speeded naming. The prime duration used was 44 cycles, because at a lower prime duration DRC 1.1.4 could not show a significant MOPE with four-letter-long nonword stimuli. A paired-samples t test showed that target-naming latencies in the related condition were faster than they were in the unrelated condition, and this was so both for Experiment 1a and Experiment 1b, $t(69) = 27.13$, $p < .001$, and $t(69) = 3.42$, $p = .001$, respectively (see Table 3).[13]

DRC 1.1.4 simulations for Experiments 2a and 2b. The same parameters as in Experiments 1a and 1b were used in Experiments 2a and 2b; however, the stimuli in Experiments 2a and 2b were words, and we found that when a 44-cycle prime duration was used with DRC, the prime words would activate their lexical entries very quickly in the orthographic lexicon and the primes' entries would then strongly compete with the targets' lexical entries, causing the DRC model to name the primes instead of the targets. As a result, we used a shorter prime duration so that the model would correctly name the target and not the prime. With a prime duration of 28 cycles, DRC 1.1.4 successfully simulated the MOPE in both experiments. A paired-samples t test showed that target-naming latencies in the related condition were significantly faster than those in the unrelated condition, $t(59) = 8.34$, $p < .001$, and $t(59) = 2.58$, $p = .012$, respectively, for Experiments 2a and 2b (see Table 3).

Discussion of Simulations

DRC 1.1.4 could not simulate both the word and the nonword data with the same prime duration. This is a serious problem for DRC 1.1.4, because since the word and nonword human experiments showed a MOPE at the same prime duration (50 ms), the model should also be able to simulate the human results from the two experiments using a single prime duration; nevertheless, it could not. Why not?

For the masked onset priming effect to occur with nonwords in DRC 1.1.4 the initial phoneme of the unrelated prime (e.g., /k/ from *kalt*), which has already been activated at the phoneme system during the prime's exposure, has to compete so strongly with the initial phoneme of the target (e.g., /b/ from BREV) so as to cause this phoneme to be the last phoneme of the target to reach the critical MinReadingPhonology parameter value and therefore delay target naming in comparison with the related condition (*biln*–BREV). The nature of the masked onset priming effect with nonwords as explained by DRC 1.1.4 is inhibitory then.

The reason why DRC 1.1.4 does not show a MOPE with nonwords at a relatively short prime duration (28 cycles), but only at a longer prime duration (44 cycles), is because the nonlexical route's left-to-right movement is controlled by a rule of the fol-

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[11] This is the shortest prime duration that can be used in order for a MOPE to arise with four-letter-long nonwords.

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

[13] Model RTs are measured in cycles, and so they could not be directly comparable to human RTs. Also, the effect sizes are very small, because they are also measured in cycles. However, we statistically analyze the difference between the different conditions, and if these are significant, then the effect is real, independent of whether its absolute value does not match that of humans. Last, human performance consists of other sorts of processes that require additional time to be carried out and that the models do not try to simulate, for example, visual processing or articulation.

Table 3
Mean Naming Latencies (Reaction Times in Cycles) and Size of MOPE (in Cycles) From Simulations of Experiments 1a, 1b, 2a, and 2b With DRC 1.1.4 and DRC beta6

		Mean reaction time (*SD*)	
Experiment	Prime type	DRC 1.1.4	DRC beta6
1a	Related	135.11 (0.96)	142.04 (0.36)
1a	Unrelated	136.03 (0.88)	143.04 (0.36)
1a	MOPE	0.92	1
1b	Related	143.63 (12.05)	139.44 (4.57)
1b	Unrelated	145.61 (14.79)	142.44 (4.41)
1b	MOPE	1.98	3
2a	Related	77.77 (1.99)	71.55 (2.34)
2a	Unrelated	79.43 (1.67)	73.75 (1.65)
2a	MOPE	1.66	2.2
2b	Related	78.8 (3.12)	72.28 (2.40)
2b	Unrelated	79.7 (2.68)	74.50 (2.19)
2b	MOPE	0.9	2.22

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

lowing form: Move on to the next letter after 17 processing cycles have elapsed. A consequence of this way of controlling the left-to-right movement of the nonlexical route is that at the shorter prime duration the activation of the first phoneme of the prime is weak. This allows competition with the first phoneme of the target (when these are different) to have been resolved (via lateral inhibition between the competing phonemes) by the time the nonlexical route reaches the last letter of the target.

Thus, it seems that if the nonlexical route operated in a way that would prevent it from moving 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 onset-unrelated prime should be able to delay target naming in comparison with an onset-related prime, because processing of all of the target's letters would be delayed in the unrelated condition in comparison with the related condition. Hence, a newer version than DRC 1.1.4, named DRC beta6, was developed. The only difference between DRC 1.1.4 and DRC beta6 is in the way the nonlexical route decides when to move to a new letter. In DRC 1.1.4 a fixed number of cycles have to elapse before the nonlexical route moves from one letter to another in a serial left-to-right manner. In DRC beta6 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 that is 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. According to this new rule implemented in the model, the masked onset priming effect is both a facilitatory and an inhibitory effect. Facilitation in the related condition occurs because the preactivation of the first phoneme of the prime contributes to the activation of the first phoneme of the target, and so the latter reaches the GPCCriticalPhonology parameter earlier than it would in the unrelated condition. As a result, the nonlexical route moves on to the next letter of the target earlier. Inhibition in the unrelated condition occurs because at prime offset, the first phoneme of the prime has already been activated at the phoneme level, so that when the target comes in, there is competition between the (incorrect) first phoneme of the prime and the (correct) first phoneme of the target. Until this competition is resolved, the nonlexical route does not move on to the second letter of the target, and as a result there is delay in processing the target. Therefore, the nature of the MOPE with nonwords as simulated by DRC beta6 is both facilitatory and inhibitory.[14]

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*. The purpose of applying decay to unsupported phoneme units is to allow DRC to resolve competition between phonemes, such as the competition between the first phoneme of an unrelated prime and its target (e.g., *kalt*-BREV) in masked priming simulations, correctly, and in a reasonable amount of time. Simulations of Experiments 1a, 1b, 2a, and 2b with DRC beta6 were then carried out in order to investigate whether the revised DRC version could simulate the word and the nonword stimuli with a single prime duration.

DRC beta6 simulations: Experiments 1a, 1b, 2a, and 2b. The MinReadingPhonology parameter was set to 0.3 to simulate speeded naming, and the value of the parameter GPCCriticalPhonology, which controls the rate at which the nonlexical route moves from left to right across the letter string, was set to .055. The results are shown on Table 3. At a prime duration of 28 cycles the simulations of Experiment 1a showed that target-naming latencies in the related condition were faster than they were in the unrelated condition by one cycle across all pairs of items. A Wilcoxon test showed that this difference was highly significant ($z = -8.367$, $p < .001$). Similarly, the results from Experiments 1b, 2a, and 2b showed a significant MOPE, $t(69) = 5.52$, $p < .001$, $t(59) = 8.53$, $p < .001$, and $t(59) = 9.37$, $p < .001$, respectively.

DRC 1.1.4 Versus DRC beta6. Because the nonlexical routes of the DRC 1.1.4 and DRC beta6 models operate quite differently with respect to how serial processing is implemented, the two models make different predictions about how prime and target letter length will influence the MOPE. For DRC 1.1.4, the longer the primes and targets are, the more likely it will be that the conflict between the first phoneme of the prime and the first phoneme of the target will have been resolved by the time the serially operating nonlexical route reaches the end of the target. So for DRC 1.1.4 the longer the items are, the smaller the MOPE will be, and indeed there may even be no MOPE when primes and targets are long enough. In contrast, with DRC beta6 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 beta6 the size of the MOPE will be independent of length. The novel prediction made by the two different versions of the DRC model led us to a third experiment in which we investigated whether or not the size of the MOPE is affected by prime and target length.

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[14] It is worth noting that there is no empirical evidence to date regarding whether the MOPE is facilitatory or inhibitory in nature. However, in a different series of experiments in which we manipulated prime duration, the human results showed that priming effects are both facilitatory and inhibitory in nature.

Experiment 3

Method

Materials. The target nonwords to be read aloud were 44 three-letter three-phoneme nonwords and 44 five-letter five-phoneme nonwords. The two sets of nonwords were matched on orthographic *N* (means 3.64 and 3.68, respectively). To avoid "whammy effects" (Rastle & Coltheart, 1998), the three-letter nonwords all had three phonemes and the five-letter nonwords all had five phonemes. This requirement, plus the need to match on *N*, made it impossible to also match the two conditions on initial phoneme (this is discussed further below).

For each target nonword, an onset-prime nonword and a control-prime nonword were chosen. Each prime–target pair had the same number of letters and phonemes. Onset primes had the same initial letter and phoneme as the target but no other letters in common. Control primes had no letters in common with their associated targets. Targets and primes are listed in Appendix E.

The target word set was divided into two matched subsets of 22 items. The assignment of target nonwords to the two prime-type conditions (onset prime vs. control) was fully counterbalanced across participants, so that each participant saw every target nonword once, and each target nonword occurred in each prime-type condition once in every pair of participants.

Computational modeling results. The DRC 1.1.4 model read all targets correctly. Every three-letter target was read 10 cycles faster in the related than unrelated condition. Every five-letter target yielded the same RT in the related and unrelated condition. Thus, target length not only had a large effect on the model's RTs but also on the size of the MOPE, which was large for all three-letter targets and absent for all five-letter targets.

The DRC beta6 model read all targets correctly. Every three-letter target was read one cycle faster in the related than unrelated condition; that was also the case with every five-letter target. Thus target length, though it had a large effect on the model's RTs, had no effect at all on the size of the MOPE. The results are shown on Table 4.

Thus, for DRC beta6, the size of the MOPE was independent of target length. For DRC 1.1.4, the MOPE was large with short targets and abolished with long targets. Hence, it was of interest to know what effect target length has on the MOPE with human readers.

Human-reader data. Twenty-two first-year Macquarie University students participated in this experiment as part of a course requirement. All participants were native Australian English speakers.

Table 4

Mean Naming Latencies (Reaction Times, in Cycles) and Size of MOPE (in Cycles) From Simulations of Experiment 3 With DRC 1.1.4 and DRC beta6

	DRC 1.1.4		DRC beta6	
Prime type	3 letters	5 letters	3 letters	5 letters
Related	126.0 (0.0)	145.5 (3.2)	133.0 (0.0)	151.1 (0.8)
Unrelated	136.0 (0.0)	145.48 (3.2)	134.0 (0.0)	152.1 (0.8)
MOPE	10.0	0.0	1.0	1.0

Note. MOPE = masked onset priming effect; DRC = dual-route cascaded.

Procedure. Each trial started with the presentation of a forward mask (pound signs; ######) for 500 ms, followed by a prime presented in lowercase letters for four cycles of the screen refresh rate (53 ms); then a target was presented in uppercase letters. The target remained on the screen for a maximum of 2,000 ms, or until the voice key was triggered by the participant's response. After a 1,000-ms blank screen, the next trial started. The participants received no feedback during the experiment. The three- and five-letter nonword targets were randomly presented in one block.

Results

The preliminary treatment of trials was as follows: Any trial on which a participant or voice key error occurred was excluded from the latency analysis. To reduce the effects of outliers, very long or very short RTs were removed from the analysis using a cutoff value of 2 *SD* above or below the mean for each participant. This resulted in the exclusion of 8.01% of the total data set. The mean naming latencies and percent error rates are presented in Table 5.

In the analyses of naming latencies, the MOPE was significant, $F_1(1, 21) = 31.90$, $p < .001$, partial $\eta^2 = .603$; $F_2(1, 86) = 10.46$, $p = .002$, partial $\eta^2 = .108$, the letter length effect was not significant,[15] $F_1(1, 21) = 1.68$, $p > .05$, partial $\eta^2 = .074$; $F_2(1, 86) = 2.90$, $p > .05$, partial $\eta^2 = .033$, and the interaction effect was not significant by participants or items, $F_1(1, 21) = 2.19$, $p > .05$, partial $\eta^2 = .094$; $F_2(1, 86) < 1$, partial $\eta^2 = .011$.

In the analyses of error rates, the masked onset priming effect was not significant, $F_1(1, 21) < 1$, partial $\eta^2 = .022$; $F_2(1, 86) < 1$, partial $\eta^2 = .008$, the letter length effect was significant, $F_1(1, 21) = 5.12$, $p = .034$, partial $\eta^2 = .196$; $F_2(1, 86) = 4.46$, $p = .038$, partial $\eta^2 = .049$, and the interaction effect was not significant, $F_1(1, 21) = 1.67$, $p > .05$, partial $\eta^2 = .074$; $F_2(1, 86) = 3.21$, $p > .05$, partial $\eta^2 = .036$.

In human readers, then, the size of the MOPE is independent of target length. This is consistent with DRC beta6 but inconsistent with DRC 1.1.4.

General Discussion

Several empirical studies to date have investigated the role of the orthographic/phonological onset in visual word recognition using different tasks, for example, reading aloud, lexical decision, letter detection, perceptual identification, and an anagrams task. Although some of these studies provided evidence in favor of the theoretical assumption that supports that the onset is processed as a unit by the visual word-recognition system, other studies provided evidence against this claim. It is likely that task differences could account for the inconsistent results among different studies; however, as was mentioned in the introduction, some of the studies used the same task and still found opposite results (e.g., Treiman & Chafetz, 1987, vs. Nuerk et al., 2000, in lexical decision;

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[15] As was mentioned earlier, the requirement to match number of letters, number of phonemes, and *N* made it impossible to match initial phoneme across the two length conditions, and this confounding makes the absence of a length effect uninterpretable. That is not relevant to the aim of the experiment, however (which was to measure the MOPE as a function of target and prime lengths), because each target served as its own control, that is, it occurred in both primed and unprimed conditions.

Table 5
Mean Reaction Times, (in Milliseconds) and Percent Errors for Human Subjects in Experiment 3

	Prime type			
	Related		Control	
Letter length	RT	% error	RT	% error
3 letters	629	9.6	654	9.8
5 letters	648	14.1	665	13.0

Bowey, 1990, Kinoshita, 2000, and Booth & Perfetti, 2002, vs. Schiller, 2004, in reading aloud; Gross et al., 2000, vs. Brand et al., 2007, in letter detection).

The data from the above-mentioned studies equally supported the two theoretical assumptions regarding the type of coding scheme that may represent the human visual word-recognition system. As a result, different computational models of reading, which claim to account for how word-recognition and reading-aloud processes occur in humans, adopted different coding schemes.

Both from empirical and theoretical points of view, then, it was important to determine how the visual word-recognition system codes printed words. The aim of our study was to first establish empirically whether onsets are perceived as units or as separate letters/phonemes and, second, adjudicate between computational models of reading that use different coding schemes. Because current computational models of reading are able to efficiently simulate human reading effects found in the reading-aloud task and also because reaction times in this task are unaffected by decision processes that may influence the obtained response times and therefore not reflect solely the very early stages of the word-recognition process (as has been claimed in the lexical decision task, for example), our study involved reading aloud.

In particular, two experiments tested whether there is MOPE for nonword and word items that share their initial letter/phoneme but not their whole orthographic/phonological onset. The human results from both experiments showed a MOPE and thus falsified the assumption that the onset of printed words/nonwords is processed as a unit. The question that arises, though, is why our results were different from those obtained in other studies that used the reading-aloud task to investigate the same issue in the English language (e.g., Booth & Perfetti, 2002; Bowey, 1990) and most important, in a study that used the MOPE (e.g., Kinoshita, 2000).

One possible reason for the discrepancy between our study and the other studies could be the different method used for measuring naming responses to the targets. This idea is supported by a series of studies that investigated this issue in detail. In particular, the results from a study that investigated the effect of onset complexity on naming latency (Frederiksen & Kroll, 1976) showed that words with complex onsets (e.g., *spin*) are read aloud more slowly than are words with simple onsets (e.g., *sin*). Kawamoto and Kello (1999) carried out a similar study and found the opposite result. Given that in both studies stimuli were matched for initial phoneme, the authors of the latter study attributed the discrepancy of the data to the different measurement of onset latency used in each of the studies: a voice key in the Frederiksen and Kroll (1976) study and a software algorithm in the Kawamoto and Kello (1999) study. The idea was that because the second phoneme of some complex onsets is silent (e.g., *spin*), voice keys might be triggered by the following vowel, which is when onset of voicing occurs when words start with such complex onsets. As a result, voice key measurements will show that naming responses to complex-onset words occur later than do responses to simple-onset words, independently of whether the two types of words are matched on the initial phoneme or not.

Further evidence for this idea was provided by a different study that used three types of naming latency measurements (hand coding, a simple threshold voice key, and an integrator voice key) to investigate effects of onset complexity on reading aloud (Rastle & Davis, 2002). The three measurement techniques produced three different results, respectively: a significant complexity advantage, a significant complexity disadvantage, and a null effect.

The findings from the above-mentioned studies could explain why Kinoshita (2000) failed to find a MOPE with complex-onset targets when a voice key was used to measure participants' naming latencies. In particular, if the voice key was triggered by the vowel following the complex onset, any influence of the first letter/phoneme of the prime on the first letter/phoneme of the target (either facilitation in the related condition or interference in the unrelated condition) could not have been detected. The same findings could not explain why Schiller (2004) found a significant MOPE for complex-onset words because in his study, similar to Kinoshita's study, a voice key was used to measure participants' naming latencies. A possible reason for that could be that each voice key treated differently the different types of complex onsets used in each study. Additionally, as was demonstrated by the Rastle and Davis (2002) study, different types of voice keys could produce different outcomes. This was not the case in our study, in which participants' responses were hand marked using CheckVocal (Protopapas, 2007).

With regard to the other two studies of reading aloud (Booth and Perfetti, 2002; Bowey, 1990)—which showed that priming *brand* with *br* increased word-naming speed, but priming *birch* with *bi* did not facilitate naming in relation to a control condition in which target words were not primed—it could be the case that although partial identity primes such as *br* are informative regarding the pronunciation of the first two phonemes contained in the to-be-named target, partial identity primes such as *bi* or *ba* or *be* are not, because the pronunciation of the second phoneme of the to-be-named target depends on the subsequent letter. Additionally, both of these studies used a relatively long prime duration (120 and 150 ms, respectively) that could allow participants to fully perceive the prime and prepare their response accordingly, in which case responses to complex-onset targets would be expected to be faster than would responses to simple-onset targets.

Thus, we tried to simulate with DRC 1.1.4 the findings from our study. The model failed to simulate a MOPE with word and nonword items using the same prime duration due to the rule implemented in the model regarding the left-to-right operation of the nonlexical route. Therefore, a new rule was implemented in the model that modified the way the nonlexical route moves from one letter to another in a left-to-right manner. This new version of the DRC model, called DRC beta6, was able to simulate a MOPE both with words and with nonwords at the same prime duration. However, the two different versions of the model made different predictions about how prime/target letter length would influence the MOPE: DRC 1.1.4 showed that the size of the MOPE in human readers depends on target and prime length, while DRC beta6 did not show such dependency.

Therefore, we carried out a third experiment in order to adjudicate between the two versions; the human data showed that the size of the MOPE is independent of target and prime length, confirming the prediction made by the DRC beta6 version.

However, the principle of nested (incremental) modeling requires that now investigations be carried out concerning whether the DRC beta6 version of the DRC model can correctly simulate all the other effects from studies of human reading that the DRC 1.1.4 model and the original DRC model (Coltheart et al., 2001) can simulate, because only if this is the case can one argue that the DRC beta6 model should be preferred to the earlier versions of the DRC model. Such investigations are currently under way.

Conclusion

The human data from two experiments on the MOPE show that the human reading system does not represent complex onsets as whole units but as separate letters/phonemes and that this type of representation applies both to word and to nonword reading. These data can easily be explained by a letter-coding scheme as implemented in the DRC computational model of reading, but it remains to be seen whether a whole-onset coding scheme as implemented in the Plaut et al. (1996) model, for example, would succeed in simulating these results. It is also worth noting that other computational models of reading, such as the Harm and Seidenberg (1999) model or the CDP+ model (Perry, Ziegler, & Zorzi, 2007), could possibly capture the letter-based effects observed in our data, because the former model does not contain complex onsets as input units, while the latter represents first the input units as single letters at the letter level and then classifies their graphemic representations (within a Graphemic Buffer) in terms of onsets, nuclei, and codas. However, one cannot tell whether each of these models would show an effect of the whole orthographic/phonological onset or instead an effect at the level of letters unless simulations of our data with both models determine that.

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Appendix A

Items Used in Experiment 1a

Related primes	Unrelated primes	Targets
biln	kalt	BREV
bese	samn	BRUT
berb	pusp	BLAG
boff	koch	BRUS
birt	suke	BLAV
bume	taph	BLUV
bish	felp	BROG
byme	gegg	BRUP
bewn	tief	BLUB
bamb	surn	BLEC
belk	galm	BRIS
debe	feke	DROF
dype	giff	DRUP
dese	tebb	DROZ
doop	fulk	DRAS
dodd	geaf	DRYS
disp	geme	DRUT
dibe	sume	DRAK
doob	gesh	DRUN
deve	kulb	DROC
fett	kisk	FLOB
fuge	goap	FLIL
feff	kybe	FRID
fule	gamb	FROT
falp	kyme	FRIV
fupe	dach	FLIM
fask	domp	FLEV
faff	kebe	FRUP
fich	guth	FROZ
fepe	guzz	FRYM
fisk	kewn	FRIP
famp	toop	FLEN
fomp	gorb	FLYS
fumb	gimp	FREC
feum	kume	FRIC
puzz	durg	PLAL
panc	dirl	PRUG
pizz	tirt	PLAP
purb	derg	PLIL
pume	gume	PRIS
puch	dalt	PRIP
pawp	durb	PLYS
poin	gulk	PRAB
pibe	goob	PRAC
paif	gype	PREL
pilk	giln	PRET
pask	gusk	PREW
piln	kibe	PREZ

Appendix A (*continued*)

Related primes	Unrelated primes	Targets
saff	keat	SPOM
salf	dilk	STEB
segg	karc	SPOZ
sote	fute	SPAD
surp	puth	SMED
soch	kurf	SMEG
sern	guse	STIM
sube	kung	SLET
samb	furb	SLEV
sont	parb	SLUP
sisp	korb	SKUV
soof	darp	SLEM
semp	torb	STID
seff	perv	SNUD
salc	birl	SLEZ
tilm	serm	TREP
tolk	pulk	TRID
toof	sose	TRAG
taff	gelm	TRON
tisc	sauk	TREF
tiln	kise	TRUD
telk	guke	TRUN

Appendix B

Items Used in Experiment 1b

Related primes	Unrelated primes	Targets
brev	kalt	BILN
brut	samn	BESE
blag	pusp	BERB
brus	koch	BOFF
blav	suke	BIRT
bluv	taph	BUME
brog	felp	BISH
brup	gegg	BYME
blub	tief	BEWN
blec	surn	BAMB
bris	galm	BELK
drof	feke	DEBE
drup	giff	DYPE
droz	tebb	DESE
dras	fulk	DOOP
drys	geaf	DODD
drut	geme	DISP
drak	sume	DIBE
drun	gesh	DOOB
droc	kulb	DEVE
flob	kisk	FETT
flil	goap	FUGE
frid	kybe	FEFF
frot	gamb	FULE
friv	kyme	FALP
flim	dach	FUPE
flev	domp	FASK
frup	kebe	FAFF
froz	guth	FICH
frym	guzz	FEPE

(*Appendices continue*)

Appendix B (*continued*)

Related primes	Unrelated primes	Targets
frip	kewn	FISK
flen	toop	FAMP
flys	gorb	FOMP
frec	gimp	FUMB
fric	kume	FEUM
plal	durg	PUZZ
prug	dirl	PANC
plap	tirt	PIZZ
plil	derg	PURB
pris	gume	PUME
prip	dalt	PUCH
plys	durb	PAWP
prab	gulk	POIN
prac	goob	PIBE
prel	gype	PAIF
pret	giln	PILK
prew	gusk	PASK
prez	kibe	PILN
spom	keat	SAFF
steb	dilk	SALF
spoz	karc	SEGG
spad	fute	SOTE
smed	puth	SURP
smeg	kurf	SOCH
stim	guse	SERN
slet	kung	SUBE
slev	furb	SAMB
slup	parb	SONT
skuv	korb	SISP
slem	darp	SOOF
stid	torb	SEMP
snud	perv	SEFF
slez	birl	SALC
trep	serm	TILM
trid	pulk	TOLK
trag	sose	TOOF
tron	gelm	TAFF
tref	sauk	TISC
trud	kise	TILN
trun	guke	TELK

Appendix C

Items Used in Experiment 2a

Related primes	Unrelated primes	Targets
beam	cult	BROW
disc	melt	DRUM
pest	foil	PRAM
toss	deed	TRIM
gown	vice	GRAB
surf	jazz	SPIN
cuff	wink	CRAB
cork	mink	CLAD
fist	noon	FLAG
pope	vein	PLUG
sill	peck	SNUG
sung	loop	SLAP
sage	toil	SKIP
doll	bite	DRAG
bake	reed	BLOC
fore	gust	FLAK

Appendix C (*continued*)

Related primes	Unrelated primes	Targets
gulf	pond	GRIM
pill	nest	PRAY
tick	gulp	TRAM
silt	heed	STAG
cock	peer	CLAN
fuzz	hack	FROG
pike	bust	PROP
fern	sash	FLOP
beet	posh	BRAN
gait	hoof	GLUE
seam	pawn	SLUG
sock	vine	SLAM
bass	poke	BLUR
curb	moth	CLAW
gale	coke	GRIP
doom	lush	DRAB
daze	lull	DRIP
pang	rift	PLUM
pulp	jack	PRIM
buzz	hose	BRAD
goat	dumb	GRIN
sect	ling	STAB
bank	wish	BLUE
camp	wine	CLUB
cave	silk	CROP
dust	pink	DRAW
date	bill	DROP
firm	neck	FLAT
fish	lack	FREE
gift	moon	GLAD
gain	loss	GREY
pick	hurt	PLAN
poor	seem	PLAY
pack	bone	PLUS
soft	race	SKIN
seed	burn	SLIP
seek	card	SPOT
sell	mood	STAR
send	film	STAY
sick	farm	STEP
safe	kill	STOP
till	sand	TREE
tend	cool	TRIP
town	boys	TRUE

Appendix D

Items Used in Experiment 2b

Related primes	Unrelated primes	Targets
brow	cult	BEAM
drum	melt	DISC
pram	foil	PEST
trim	deed	TOSS
grab	vice	GOWN
spin	jazz	SURF
crab	wink	CUFF

(*Appendices continue*)

Appendix D (*continued*)

Related primes	Unrelated primes	Targets
clad	mink	CORK
flag	noon	FIST
plug	vein	POPE
snug	peck	SILL
slap	loop	SUNG
skip	toil	SAGE
drag	bite	DOLL
bloc	reed	BAKE
flak	gust	FORE
grim	pond	GULF
pray	nest	PILL
tram	gulp	TICK
stag	heed	SILT
clan	peer	COCK
frog	hack	FUZZ
prop	bust	PIKE
flop	sash	FERN
bran	posh	BEET
glue	hoof	GAIT
slug	pawn	SEAM
slam	vine	SOCK
blur	poke	BASS
claw	moth	CURB
grip	coke	GALE
drab	lush	DOOM
drip	lull	DAZE
plum	rift	PANG
prim	jack	PULP
brad	hose	BUZZ
grin	dumb	GOAT
stab	ling	SECT
blue	wish	BANK
club	wine	CAMP
crop	silk	CAVE
draw	pink	DUST
drop	bill	DATE
flat	neck	FIRM
free	lack	FISH
glad	moon	GIFT
grey	loss	GAIN
plan	hurt	PICK
play	seem	POOR
plus	bone	PACK
skin	race	SOFT
slip	burn	SEED
spot	card	SEEK
star	mood	SELL
stay	film	SEND
step	farm	SICK
stop	kill	SAFE
tree	sand	TILL
trip	cool	TEND
true	boys	TOWN

Appendix E

Items Used in Experiment 3

Experimental primes	Control primes	Targets
kuk	juc	KAV
zuk	juf	ZAZ
zov	vul	ZIK

Appendix E (*continued*)

Experimental primes	Control primes	Targets
zok	wuc	ZIV
kuv	luz	KAK
vuv	miv	VEK
yov	zuv	YIF
yoz	wuv	YIV
zoc	luz	ZAF
zif	vif	ZAV
jik	fuf	JEV
jiv	lif	JEZ
kek	juv	KAS
vef	kom	VAZ
vov	nuc	VEZ
yof	nuz	YIK
yoc	zek	YIZ
zek	vup	ZAL
dev	gok	DAZ
jup	goz	JEC
kac	jiz	KEF
kif	zas	KEZ
muz	kiv	MEF
nuk	zas	NEF
veb	dez	VAF
ves	wup	VAV
vus	mev	VOF
yup	vof	YIC
zus	muz	ZEF
zol	nuk	ZEV
zos	jup	ZEZ
zom	mez	ZIL
jic	daf	JEP
jus	kec	JOV
kiz	dav	KEB
niv	fuv	NAZ
nuv	goc	NEM
vud	gof	VEC
voc	riz	VEL
wus	gov	WEK
yil	vem	YAZ
yus	vep	YOL
zis	jok	ZEB
zup	lif	ZEC
brilc	frukt	BLEFS
grolm	dalcs	GLINZ
solbs	yects	SNULK
twect	gloct	TRILP
crild	drufs	CLONT
sosks	galvs	SCRIT
solps	krunt	SKILF
swemp	lesps	SPILC
spefs	krist	STRUV
tolbs	blanz	TRISP
bulds	crefs	BLOST
blebs	glols	BRASK
crefs	drets	CLOMP
filbs	crils	FLOND
felms	trebs	FLOSK
gulns	palfs	GREPT
prand	jacts	PLUSK
smeps	trevs	SPLUT
calds	bocts	CRESK
snims	brops	SPELK
fregs	crebs	FLAND

(*Appendices continue*)

Appendix E (*continued*)

Experimental primes	Control primes	Targets
flost	cromp	FRAGS
stolp	flast	SCRUP
slivs	fligs	SCRAT
culfs	flofs	CRAND
folfs	helks	FRIST
bepts	jants	BRILK
plovs	scacs	PRIND
telps	folfs	TRISK
spums	crols	STRAN
slelt	trusk	SCRAD
selds	vasks	SPRUT
balbs	gasks	BLINT
bolbs	josts	BREND
colps	lulks	CREFT
folms	kilds	FLUNT
fasps	lusks	FRINT
pucts	samps	PRISK
spacs	trads	SCONT
slons	plols	SKIFT
sneps	trets	SLAND
spunt	brint	STALP
swent	trunt	STILK
twims	slibs	TRAFT

Received May 16, 2008
Revision received January 7, 2009
Accepted January 12, 2009 ■