The Locus of Serial Processing in Reading Aloud:

Orthography–to–Phonology Computation or Speech Planning?

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Abstract

Dual-route theories of reading posit that a sublexical reading mechanism that operates serially and from left to right is involved in the orthography–to–phonology computation. These theories attribute the Masked Onset Priming Effect (MOPE) and the Phonological Stroop Effect (PSE) to the serial left–to–right operation of this mechanism. However, both effects may arise during speech planning, in the phonological encoding process, which also occurs serially and from left to right. In the present paper, we sought to determine the locus of serial processing in reading aloud by testing the contrasting predictions that the dual-route and speech planning accounts make in relation to the MOPE and the PSE. The results from three experiments that used the MOPE and the PSE paradigms in English are inconsistent with the idea that these effects arise during speech planning, and consistent with the claim that a sublexical serially-operating reading mechanism is involved in the print–to–sound translation. Simulations of the empirical data on the MOPE with the DRC and CDP++ models, which are computational implementations of the dual-route theory of reading, provide further support for the dual-route account.

Keywords: Theories of reading, Speech planning, Masked Onset Priming Effect (MOPE), Phonological Stroop Effect (PSE), Computational models of reading

How do people read aloud familiar words such as *flirt*, *term*, and *tweets*, and newly encountered words such as *smirt*, *derp*, and *tweeps*? According to the so-called dual-route theories of reading (e.g., Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Perry, Ziegler, & Zorzi, 2007; 2010), our reading system consists of a lexical procedure, which operates in parallel upon letters translating familiar words into their corresponding phonological representations, and a sublexical procedure, which operates serially and from left to right upon letters converting novel words into their corresponding sounds. Several empirical phenomena observed in the reading aloud domain are thought to be due to the serial left–to–right nature of the sublexical reading procedure (for a list of these phenomena see Rastle & Coltheart, 2006). One such phenomenon is the Masked Onset Priming Effect (MOPE).

The MOPE (e.g., Forster & Davis, 1991; Kinoshita, 2000) refers to the finding that target reading aloud occurs faster when targets are preceded by briefly-presented masked primes that share their initial letter/phoneme with the target (e.g., *suf*-SIB), compared to when primes and targets are unrelated to each other (e.g., *mof*-SIB). The DRC model, a computational instantiation of the dual-route theory of reading (Coltheart et al., 2001), successfully simulates this effect thanks to the serial left–to–right nature of processing of the implemented sublexical reading procedure. According to this model, the MOPE is due to the activation of the first phoneme of the prime by the sublexical reading procedure (during the prime's brief exposure), which has an influence (facilitatory in the onset-related condition and/or inhibitory in the unrelated condition) on the speed of processing of the first phoneme of the target (see Mousikou, Coltheart, Finkbeiner, & Saunders, 2010a). Several studies have further investigated whether the observed priming effect is due to first-phoneme overlap between the prime and the target, or to *any* phoneme overlap (e.g., Kinoshita, 2000; Mousikou et al., 2010a; Mousikou & Coltheart, 2014). The results from these studies indicated robust priming when the phoneme overlap between the prime and the target was in the first position, and no priming (or significantly less priming) when the overlap was in a later position. According to proponents of the dual-route account of the

MOPE, the finding that the effect is significantly larger when the position of phoneme overlap between the prime and the target is the first reflects the serial left–to–right nature of the orthography–to–phonology computation.

However, an alternative account of the MOPE, known as the *speech-planning account*, postulates that the effect arises further downstream, in the preparation of a speech response, in particular, in the *phonological encoding* process (Kinoshita, 2000; Kinoshita & Woollams, 2002). During phonological encoding, an ordered string of phonological segments is retrieved and a syllable frame is created with three ordered slots that represent the onset, nucleus, and coda. The phonological segments are then associated to the corresponding slots of the syllable frame (segment–to–frame association process) in a sequential left–to–right manner (Levelt, Roelofs, & Meyer, 1999; Meyer, 1991). According to the speech-planning account of the MOPE, the orthography–to–phonology computation of the prime need not occur serially; it can occur in parallel. As such, during prime presentation, all of the prime's phonemes (e.g., /m/, /ɒ/, /f/) are activated in parallel and inserted (in a serial, left-to-right manner) into the onset, nucleus, and coda slots, respectively.[1] Then, the target's phonemes (e.g., /s/, /I/, /b/) are activated in parallel, but when they are to be inserted (in a serial, left-to-right manner) into the onset, nucleus, and coda slots, a mismatch in the onset position (e.g., between /m/ and /s/) holds up the segment-to-frame

[1] It is unclear whether according to the speech-planning account all of the prime's segments/phonemes are inserted into the corresponding slots of onset, nucleus, and coda during prime presentation, or whether it is just the phonological onset of the prime that is inserted into the onset slot. If the latter, this account *must* necessarily postulate that there is an additional process that prevents the remaining segments/phonemes of the prime from being inserted into the nucleus and coda slots, given that it is compatible with the idea that the prime's phonemes are activated in parallel during prime presentation. To our knowledge, this additional process has not been described by any of the proponents of the speech-planning account, and so in the present paper we assume that each of the prime's phonemes is inserted into the onset, nucleus, and coda slots during prime presentation.

association process of the target, i.e. insertion of the target's first phoneme into the onset slot. This delay in the unrelated condition (e.g., *mof*-SIB) compared to the onset-related condition (*suf*-SIB) causes the MOPE. Proponents of this view attribute the position of phoneme-overlap effect to the serial left–to–right nature of the segment–to–frame association process.

The aim of the present paper is to determine the locus of serial processing in reading aloud: is it in the orthography–to–phonology computation or during speech planning? If it is during speech planning, the computation of phonology from orthography need not occur serially across letter strings; it could occur in parallel, which is consistent with theories of reading that assume no serial processing in the orthography–to–phonology computation (e.g., Harm & Seidenberg, 2004; Plaut, McClelland, Seidenberg, & Patterson, 1996), and inconsistent with dual-route theories, which posit that a sublexical serially-operating reading mechanism is involved in the print–to–sound translation (Coltheart et al., 2001; Perry et al., 2007; 2010). Therefore, seeking empirical evidence to adjudicate between the dual-route and speech-planning accounts is critical for evaluating extant theories of reading.

One specific prediction of the speech-planning account, for example, is that the unit underlying the MOPE is the syllabic onset rather than a single phoneme (as the DRC account posits). Kinoshita (2000, Experiment 2) tested this prediction using target words that started either with a simple (e.g., PASTE) or a complex onset (e.g., BLISS). A MOPE was observed only for targets with simple onsets, offering support for the speech-planning account. However, another proponent of the speech planning account failed to observe an effect of onset complexity on the MOPE in an experiment that used Dutch disyllabic words, thus concluding: "there is no evidence from this experiment that the word onset as a unit played a role" (Schiller, 2004, p. 485). Moreover, in a series of experiments, Mousikou, Coltheart, Saunders, & Yen (2010b) tested whether there is a MOPE for word and nonword prime-target pairs that share their initial phoneme, but not their onset (e.g., *disc*-DRUM vs. *melt*-DRUM, *drum*-DISC vs. *melt*-DISC, *biln*-BREV vs. *kalt*-BREV, *brev*-BILN vs. *kalt*-BILN). The results from these experiments indicated a significant MOPE in all of the above cases, and the DRC model successfully simulated the human data. The speech-planning account cannot accommodate these findings.

Additional empirical evidence in favor of the DRC account and against the speech-planning account of the MOPE was provided more recently by Timmer, Vahid-Gharavi, and Schiller (2012). In an ERP study that investigated the locus of the MOPE in Persian, the authors observed that early in processing (i.e. in the 80-160 ms time window) there were more negative amplitudes for the unrelated condition than for the onset-related condition. According to a meta-analysis of reading and word production studies (Indefrey, 2011; Indefrey & Levelt, 2004), grapheme–to–phoneme conversion is thought to take place approximately between 150 and 330 ms after target presentation, whereas speech planning has been associated with the 330-600 ms time window. Based on these findings the authors concluded that their results are "in line with an early locus of the MOPE as suggested by the DRC model (Coltheart et al., 2001; Mousikou et al., 2010)" (Timmer et al., 2012, p. 38).

Taken together, the available empirical evidence considered above favors the dual-route account over the speech-planning account of the MOPE. However, there is at least one empirical finding in the literature that is at odds with the dual-route account, but can be readily explained by the speech-planning account. In a study carried out in Spanish (Dimitropoulou, Duñabeita, & Carreiras, 2010, Experiment 3), word targets were preceded by masked word and nonword primes. The nonword primes were either pronounceable or unpronounceable. Although a significant MOPE was observed when the primes were words or pronounceable nonwords (e.g., LOBO preceded by the onset-related prime *lefu* was read aloud faster than when preceded by the unrelated prime *cusi*), the effect disappeared when the nonword primes were unpronounceable (e.g., LOBO preceded by the onset-related prime *lpgz* was read aloud as slow as when preceded by the unrelated prime *mxbf*). According to the dual-route account of the MOPE, there is no reason why the sublexical procedure should be prevented from activating the first phoneme of the prime if the prime is unpronounceable, and so the finding that the MOPE depends on prime pronounceability is inconsistent with the dual-route explanation of the effect. In contrast, this finding can be accommodated within the speech-planning account, because if a prime lacks vowels no syllabic onset will be inserted into the onset slot during phonological encoding. As such, the segment–to–frame association process fails and the MOPE is abolished. The empirical finding observed by Dimitropoulou et al. (2010) is important insofar as it has the potential to falsify the dual-route account of the MOPE. This would have serious implications for dual-route theories of reading (e.g., Coltheart et al., 2001; Perry et al., 2007; 2010), because they offer this effect as primary evidence for serial processing in the print–to–sound translation.

Another well-established empirical phenomenon that is thought to have the same locus as the MOPE, according to dual-route theories of reading, is the Phonological Stroop Effect (PSE). In particular, the PSE (see Coltheart, Woollams, Kinoshita, & Perry, 1999) refers to the finding that color naming of a printed word occurs faster when the word starts with the same phoneme as the color in which it is printed (e.g., *rat* presented in red), compared to when the color name and the word have no phonemes in common (e.g., *tip* presented in red). Coltheart and colleagues additionally observed that color naming was facilitated when the color name and the printed word shared their *last* phoneme (e.g., *cod* presented in red) compared to when there was no phoneme overlap between the color name and the printed word (e.g., *sat* presented in red). However, such facilitation was much smaller than when color names and printed words shared their initial phoneme. According to Coltheart et al. (1999), the printed words activated their phonological representations via both the lexical and sublexical procedures. Because the lexical procedure operates in parallel, initial and final phonemes were equally activated via this route, facilitating color naming when printed words and color names shared either their initial or final phoneme. Because the sublexical procedure operates serially, from left to right, by the time color naming occurred, initial phonemes would be more activated via this procedure than final phonemes, producing more facilitation in color naming when printed words and color names shared their initial phoneme. The net result of the phoneme activations produced by the joint action of the two procedures was facilitation for both initial and final phoneme overlap, with the effect being larger when the phoneme overlap was in the initial position than when it was in the final position. The DRC model, additionally equipped with a rudimentary semantic system to allow the model to do color naming (Coltheart, Curtis, Atkins, & Haller, 1993), successfully simulated these empirical findings.

Dual-route theories of reading assume that the locus of the MOPE and the PSE is the same. But if the MOPE is abolished when the primes are unpronounceable indicating that the effect occurs during speech planning, as Dimitropoulou et al. (2010) claim, the PSE may also disappear when the printed letter strings are unpronounceable. In other words, if the PSE occurs during speech planning *RZF* presented in red should be color-named no faster than *RZF* presented in blue. This is because the lack of a syllabic onset in *RZF* will result in a failure of the segment–to–frame association process, thus abolishing the PSE. We tested this idea in Experiment 1 using the PSE paradigm with pronounceable and unpronounceable nonwords in English. If our results were consistent with the Dimitropoulou et al. (2010) results, so that unpronounceable nonwords yielded no PSE, the claim that a serially-operating sublexical reading mechanism is involved in the orthography–to–phonology computation would be seriously challenged.

EXPERIMENT 1

Method

Participants. Twenty undergraduate students from the University of Waterloo participated in the study for course credit. Participants were native speakers of Canadian English and reported no visual, reading, or language difficulties.

Materials and Design. Half of the trials (N = 144) consisted of stimuli that were CVC and CCVC nonwords printed in six colors (red, blue, brown, green, pink, and white). These stimuli formed the pronounceable nonword set. Half of the nonwords in this set began with the same phoneme as the color in which they were printed, but shared no other phonemes with the color name (congruent condition). The remaining half began with a phoneme that corresponded to the initial phoneme of a color that was not the one in which they were printed, and had no phonemes in common with the color name in which they were printed (incongruent condition). The other half of the trials consisted of stimuli that were constructed from the pronounceable nonword set by replacing the vowel with a consonant (i.e. unpronounceable nonword set). Half of the nonwords in this set were congruent and the remaining half were incongruent (see Appendix A).[2] Twenty-four nonwords that matched the experimental stimuli on the same criteria served as practice items.

Apparatus and Procedure. Participants were tested individually, seated approximately 40 cm in front of a Dell Pentium 4 computer. Stimulus presentation and data recording were controlled by DMDX software (Forster & Forster, 2003). Verbal responses were recorded by a microphone and participants were instructed to name the color in which the printed stimuli were presented as quickly and as accurately as possible. Each trial began with a fixation point (+ sign) that remained on the screen for 753 ms, followed by a blank screen for 335 ms, followed by a colored nonword. Colored nonwords were presented in uppercase letters on a black background (14-point Times New Roman font) and remained on the screen for 1500 ms or until participants responded, whichever happened first. The 288 experimental stimuli were presented to each participant in a different random order, following the 24 practice trials.

[2] Due to an oversight, five of the pronounceable nonwords and four of the unpronounceable nonwords appeared twice in the same condition. However, the same nonword that appeared twice in the congruent condition also appeared twice in the incongruent condition (e.g., ROZ appeared twice in both 'red' and 'blue'). Therefore, the congruency effect could not have been affected by the double appearance of these items in the same condition. We also re-carried out the analyses after excluding these items, but the results remained the same, hence the analyses we report include all of the items.

Results

The data from three participants were excluded from the analyses, because one participant persistently color-named the nonwords printed in brown as ‘orange’, for another participant the DMDX software produced timing problems, and for the third participant the recording of the sound files malfunctioned. Participants’ responses (N = 17) were hand marked using Cool Edit. We marked the acoustic onset of the responses as described in Rastle, Croot, Harrington, and Coltheart (p. 1088, 2005). In particular, the onset of acoustic energy (excluding lip pops and lip smacking) was denoted by a clear increase in amplitude on the speech waveform following a period of silence. Incorrect responses, mispronunciations, and hesitations (4.6% of the data) were treated as errors and discarded. To control for temporal dependencies between successive trials (Taylor & Lupker, 2001), reaction time of the previous trial and trial order were included in the analyses, so trials whose previous trial corresponded to an error and participants’ first trial in the experiment (4.6% of the data) were excluded. Extreme outliers (1.1% of the data) were also identified for each participant and removed.

The analyses were performed using linear mixed effects modelling (Baayen, 2008; Baayen, Davidson, & Bates, 2008) and the *languageR* (Baayen, 2008), *lme4* 1.0-5 (Bates, Maechler, Bolker, & Walker, 2013), and *lmerTest* (Kuznetsova, Brockhoff, & Christensen, 2013) packages implemented in R 3.0.2 (2013–09–25) – “Frisbee Sailing” (R Core Team, 2013). The linear mixed-effects model we report was created using a backward stepwise model selection procedure. Model comparison was performed using chi-squared log-likelihood ratio tests with maximum likelihood. The Box-Cox procedure indicated that inverse RT (-1000/RT) was the optimal transformation to meet the precondition of normality. The model we report included inverse RT (invRT) as the dependent variable, and as fixed effects the interaction between congruency (onset related vs. unrelated) and pronounceability (pronounceable vs. unpronounceable), RT of previous trial (PrevRT), and trial order. Intercepts for subjects and items were included as random effects and so were random slopes for items for the effect of congruency[3]: invRT ~ congruency*pronounceability + PrevRT + trial order + (1 | subject) + (1 + congruency | target).

Outliers with a standardized residual greater than 2.5 standard deviations from zero were removed from the fitted model (2% of the data). The results indicated a significant congruency effect, so that color-naming latencies were significantly faster in the onset-related condition compared to the unrelated condition. This was the case for both pronounceable and unpronounceable nonwords (t = -6.820, p < .001 and t = -6.555, p < .001, respectively). Importantly, congruency did not interact with pronounceability (t < 1). Also, unpronounceable nonwords yielded significantly faster color-naming latencies than pronounceable nonwords in the incongruent condition (t = -3.040, p < .01).

The error analysis was performed using a logit mixed model (Jaeger, 2008) with the congruency by pronounceability interaction as a fixed effect and intercepts for subjects and items as random effects. The incongruent condition yielded significantly more errors than the congruent condition. This was the case for both pronounceable and unpronounceable nonwords (z = 3.829, p < .001 and z = 4.646, p < .001, respectively). Mean RTs (calculated from a total of 4319 observations) and percentage of errors for each condition are presented in Table 1.

–Insert Table 1 about here–

To quantify evidence for the null interaction (see Rouder, Speckman, Sun, Morey & Iverson, 2009), we calculated the Bayes factor to compare the model we report against the model that did not include the congruency by pronounceability interaction. The model without the interaction term was preferred by a factor of about 11, which according to Jeffreys (1961)

[3] Random slopes are included to remove the assumption that either all subjects or all items (or both) show the same sensitivity to the experimental effects being tested.

provides “strong evidence” for the hypothesis that the congruency effect does not depend on the pronounceability of the printed nonwords.

Discussion

Experiment 1 investigated whether the PSE disappears when the printed letter strings are unpronounceable. The results indicated that this was not the case: irrespective of the pronounceability of the stimuli, nonwords whose initial sound was the same as the initial sound of the color in which they were printed were color-named faster than nonwords whose initial sound did not match the initial sound of the color in which they were printed. The dual-route account of the PSE can accommodate these findings. In addition, we observed that unpronounceable nonwords yielded faster color-naming latencies than pronounceable nonwords. This finding is discussed in detail in the General Discussion.

The dual-route account predicts that the MOPE will also occur irrespective of the pronounceability of the primes. However, this prediction is inconsistent with the findings that Dimitropoulou et al. (2010) obtained in a MOPE experiment conducted in Spanish. Thus, in Experiment 2 we sought to determine whether the MOPE depends on prime pronounceability in English using monosyllabic nonword targets preceded by pronounceable and unpronounceable monosyllabic nonword primes. The choice of monosyllabic nonword stimuli in our experiment was deliberate since a robust MOPE is typically observed with such stimuli (Kinoshita, 2000; Mousikou et al., 2010a; Mousikou et al., 2010b; Mousikou et al., 2010c; Mousikou, Roon, & Rastle, in press). As such, the potential absence of a MOPE with unpronounceable nonword primes in the presence of a robust MOPE with pronounceable nonword primes would provide very strong evidence against the dual-route account of the MOPE and in favour of the speech-planning account.

EXPERIMENT 2

Method

Participants. Twenty-four undergraduate students from Macquarie University participated in the study for course credit. Participants were native speakers of Australian English and reported no visual, reading, or language difficulties.

Materials. Most of the stimuli from Experiment 1 were used in Experiment 2. Items that started with BW were replaced with items that started with BR, because BW onsets do not exist in English and introducing ambiguity/conflict in target reading aloud could influence the MOPE (see Kinoshita & Woollams, 2002). Thirty-six CVC nonwords and thirty-six CCVC nonwords served as target items. Another 144 nonwords with similar structures served as onset-related and unrelated primes. Prime *N* (Coltheart, Davelaar, Jonasson, & Besner, 1977) was 8.75 for the onset-related primes and 8.88 for the unrelated primes. An additional 144 nonwords with no vowels served as unpronounceable onset-related and unrelated primes. Four groups of 72 prime-target pairs were formed with the targets remaining the same in all groups. Two experimental conditions were tested. In the onset-related condition pronounceable and unpronounceable nonword primes shared their first phoneme with the targets (e.g., *reg*-RAV and *rnz*-RAV). In the unrelated condition pronounceable and unpronounceable nonword primes shared no phonemes with the target in the same position (e.g., *mub*-RAV and *cnz*-RAV). A total of 288 prime-target pairs formed the experimental stimuli (see Appendix B) and four prime-target pairs with similar characteristics served as practice items.

Design. Each experimental condition (onset related and unrelated) for each type of nonword prime (pronounceable and unpronounceable) consisted of 72 prime-target pairs, making a total of 288 trials per participant in a fully counterbalanced design (as in Mousikou et al., 2010a; 2010b). Every participant saw the 72 targets four times, each time preceded by a different type of prime. The 288 trials were divided into four blocks so that the same target would not appear more than once within the same block. A short break was administered between the blocks. The blocks were constructed in a way that at least 36 trials intervened before the same item reappeared. Four lists were constructed to counterbalance the order of block presentation. An equal number of participants (N = 6) were tested on each list.

Apparatus and Procedure. Participants were tested individually, seated approximately 40 cm in front of a Dell CRT monitor in a dimly lit room. Stimulus presentation and data recording were controlled by DMDX software (Forster & Forster, 2003). Verbal responses were recorded by a microphone and participants were instructed to read aloud the nonwords presented on the screen as quickly as possible. The presence of primes was not mentioned to the participants. Each trial started with the presentation of a forward mask (####), which remained on the screen for 500 ms. The prime was then presented in lowercase letters for 50 ms (five ticks based on the monitor's refresh rate of 10 ms), followed by the target that was presented in uppercase letters and acted as a backward mask to the prime. The target nonwords appeared in white on a black background (12-point Courier New font) and remained on the screen for 2000 ms or until participants responded, whichever happened first. Following the four practice trials, the order of trial presentation within blocks and lists was randomized across participants.

Results

Participants' responses (N = 24) were hand marked using CheckVocal (Protopapas, 2007). The acoustic onset of the responses was marked in the same way as in Experiment 1. Incorrect responses, mispronunciations, and hesitations (.5% of the data), trials that were presented first in each of the blocks, and trials whose previous trial corresponded to an error (1.9% of the data), as well as extreme outliers that were identified separately for each participant (.6% of the data) were discarded.[4]

The analyses were performed in the same way as in Experiment 1. The Box-Cox procedure indicated that inverse RT (-1000/RT) was the optimal transformation, so the model we report included invRT as the dependent variable, and the interaction between prime relatedness (onset related vs. unrelated) and prime pronounceability (pronounceable vs. unpronounceable), RT of previous trial, and trial order as fixed effects. Intercepts for subjects and items were included as random effects, and so were by-subject random slopes for the effect of prime relatedness to remove the assumption that all participants showed the same amount of MOPE: invRT ~ prime relatedness*prime pronounceability + PrevRT + trial order + (1 + prime relatedness | subject) + (1 | target).

Outliers with a standardized residual greater than 2.5 standard deviations from zero were removed from the fitted model (2.1% of the data). The results showed a significant MOPE, so that target reading aloud latencies were faster in the onset-related condition compared to the unrelated condition for both pronounceable and unpronounceable nonword primes (t = -6.601, p < .001 and t = -6.589, p < .001, respectively). Importantly, the MOPE did not interact with prime pronounceability (t < 1). There was also a significant pronounceability effect, so that pronounceable primes yielded faster target reading aloud latencies than unpronounceable primes both in the onset-related and unrelated conditions (both ts = -3.202, p < .01). The error rate in this experiment was too low to perform an informative error analysis, hence errors were not analysed.

[4] Some of the target nonwords yielded more than one plausible pronunciations. For these items, we considered alternative responses as correct. All acceptable pronunciations per item are shown in Appendix B. The overall low error rate in this experiment (.5%) indicates that the majority of the responses that participants gave matched the pronunciations that we considered as acceptable.

Mean RTs (calculated from a total of 6567 observations), and percentage of errors for each condition are presented in Table 2.

–Insert Table 2 about here–

Given the null interaction, as in Experiment 1, we calculated the Bayes factor to compare the model we report against the model that did not include the MOPE by prime pronounceability interaction. The model without the interaction term was preferred by a factor of about 25, which according to Jeffreys (1961), provides “strong to very strong evidence” for the hypothesis that the MOPE does not depend on prime pronounceability.

Discussion

Experiment 2 was carried out to determine whether the MOPE depends on prime pronounceability in English, as the speech planning account predicts (Kinoshita, 2000; Dimitropoulou et al., 2010). We observed a MOPE of equal size for both pronounceable and unpronounceable nonword primes, a result that contrasts sharply with the Dimitropoulou et al. (2010) findings, which showed no MOPE when the primes were unpronounceable. Thus, our finding cannot be accommodated within the speech-planning account but provides strong support in favor of the dual-route account of the MOPE, according to which the sublexical procedure activates the first phoneme of the prime during prime presentation irrespective of the prime’s pronounceability, thus influencing the processing of the first phoneme of the target and yielding a MOPE.

To assess whether the DRC model can simulate our data we ran our stimuli through DRC 1.2.1 (http://www.cogsci.mq.edu.au/~ssaunder/DRC/category/builds/). With the default parameters and a prime duration of 26 cycles (see Mousikou et al., 2010b) the model made no errors and produced a significant MOPE for both pronounceable and unpronounceable primes, both *ts*(71) = 71.0, $p < .001$ (see Table 3). Thus, the DRC simulations agreed with the human results.[5] The model's pronunciations of the target stimuli and its RTs (in cycles) for each item are shown in Appendix C. Similarly, we ran our stimuli through the CDP++ model of reading aloud (Perry et al., 2010), which also attributes the MOPE to the left–to–right processing of the prime by the sublexical procedure. With the default parameters and a prime duration of 25 cycles (as per Perry et al., 2010) the model mispronounced 17 target nonwords both in the onset-related and unrelated conditions, and two target nonwords in the onset-related condition. This was the case for both pronounceable and unpronounceable primes (see Appendix D).[6] Importantly though, the model produced a significant MOPE for both pronounceable and unpronounceable primes ($t(52) = 5.269$ and $t(52) = 8.12$, both *ps* < .001), hence, the CDP++ model successfully simulated the human data.[7] The DRC and CDP++ pronunciation symbols, their corresponding symbols in IPA, and example words containing the corresponding sounds are provided in Appendix E.

–Insert Tables 3 and 4 about here–

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[5] The differences between DRC 1.2.1 and DRC 1.2 (Mousikou et al., 2010b) are documented here: http://www.cogsci.mq.edu.au/~ssaunder/DRC/category/builds/

[6] Given that the participants' pronunciations of the target nonwords agreed overall with the pronunciations that we considered as acceptable, we only considered as erroneous the model's pronunciations that did not match any of the acceptable pronunciations (see Appendix B). In the analyses we only included the items that the model pronounced correctly both in the onset-related and unrelated conditions for each type of prime.

[7] It is worth mentioning that we also ran the stimuli from Experiment 2 through CDP+ (Perry et al., 2007). With the default parameters and a prime duration of 25 cycles (as per Perry et al., 2007, p. 294) the model made a significant number of errors (35% across all conditions) and failed to produce a MOPE for both pronounceable and unpronounceable primes ($t(44) < 1$ and $t(43) = 0$, respectively).

The remaining issue concerns how to explain the discrepancy between the findings by Dimitropoulou et al. (2010, Experiment 3) and our findings in Experiment 2. A major difference between their study and our study is that ours was conducted in English, whereas theirs was conducted in Spanish. However, we see no basis for assuming that the two proposed accounts would make different predictions in relation to an effect of prime pronounceability on the MOPE on the basis of the language being processed. Another major difference between the two studies was that in our experiment participants read aloud monosyllabic nonwords (preceded by pronounceable and unpronounceable nonword primes), whereas in the Dimitropoulou et al. (2010) experiment participants read aloud multisyllabic words (preceded by word primes and pronounceable and unpronounceable nonword primes). Hence, the effect of prime pronounceability on the MOPE may depend on the lexical status and/or syllable length of the stimuli. In principle, independently of whether the stimuli are words or nonwords, and whether they consist of one or multiple syllables, the dual-route account predicts that a MOPE should be observed for both pronounceable and unpronounceable primes. For this reason, in Experiment 3 we sought to determine whether there is a MOPE for both types of primes when the stimuli consist of multisyllabic target words. As such, Experiment 3 was an attempt to replicate the Dimitropoulou et al. (2010) results in the English language using the same type of stimuli and experimental design that they used.

EXPERIMENT 3

Method

Participants. Thirty undergraduate students from Royal Holloway, University of London, participated in the study for course credit. Participants were native speakers of Southern British English and reported no visual, reading, or language difficulties.

Materials. We chose our stimuli using the same selection criteria that Dimitropoulou et al. (2010, Experiment 3) used. In particular, 150 disyllabic English words from the English Lexicon Project (ELP) database (Balota, Yap, Cortese, Hutchison, Kessler, Loftis,…Treiman, 2007) were selected as target items. Target words were of low–to–moderate frequency (log frequency on the Zipf scale *M* = 2.81)[8] according to SUBTLEX-UK (van Heuven, Mandera, Keuleers, & Brysbaert, 2014), consisted of five to seven letters (*M* = 6), and had a mean *N* (orthographic neighbourhood) of 1.38. Given that Spanish is a transparent language with regular/consistent grapheme–to–phoneme mappings, we ensured that the target words in our experiment also contained regular/consistent pronunciations. In particular, we ran a large set of words from the ELP database through CDP++ (Perry et al., 2010), and a disyllabic version of the DRC model that contains only a sublexical procedure (Rastle & Coltheart, 2000) and therefore produces only regular pronunciations. We then selected the items for which the pronunciations of the two models matched, thus ensuring that the grapheme–to–phoneme mappings in these words were regular/consistent. Furthermore, given that stress in Spanish is marked, whereas in English it is not, we opted for using only first-syllable stressed words as targets, so that the English target words in our experiment would be comparable to the Spanish target words in the Dimitropoulou et al. experiment in terms of stress regularity/predictability.[9]

As in the Dimitropoulou et al. study, for each target word three types of primes were chosen (high-frequency words, pronounceable nonwords, and unpronounceable nonwords) in two conditions (onset-related and unrelated). The high-frequency word primes (log frequency on the Zipf scale *M* = 4.08 and *M* = 3.99, mean *N* = 1.29 and *N* = 1.55, for onset-related and unrelated primes, respectively) were selected using the same procedure as that used for the targets. We

[8] Values 1-3 correspond to low-frequency words and values 4-7 correspond to high-frequency words.

[9] We opted for choosing items with no more than two syllables so that we could tightly control for their properties using the available computational models of disyllabic reading.

obtained the pronounceable nonword primes (mean $N = 1.13$ and $N = 1.15$, for onset-related and unrelated primes, respectively) by submitting the disyllabic words from the ELP database to Wuggy (Keuleers & Brysbaert, 2010). The unpronounceable nonword primes were created by generating random consonant sequences. Primes and targets in the onset-related condition shared their first letter and phoneme but had no other letters/phonemes in common in the same position. In the unrelated condition primes and targets shared no letters/phonemes in the same position. Prime-target pairs were also matched on number of letters and phonemes. The stimuli used in Experiment 3 are shown in Appendix F. In addition, six target words with their corresponding primes (36 in total), which had the same characteristics as the experimental stimuli, were selected and used as practice items.[10]

Design. Each experimental condition (onset-related and unrelated) for each type of prime (words, pronounceable nonwords, and unpronounceable nonwords) consisted of 25 prime-target pairs for a total of 150 trials per participant. Six lists were created with each target word appearing only once in each list. The priming conditions were counterbalanced across lists (e.g., the target word SANDAL was preceded by the onset-related word prime *stigma* in List A, the unrelated word prime *recent* in List B, the onset-related pronounceable nonword prime *soslin* in List C, the unrelated pronounceable nonword prime *ticlet* in List D, the onset-related unpronounceable nonword prime *sjxlqk* in List E, and the unrelated unpronounceable nonword prime *tvwmhf* in List F).

[10] Due to the restrictions we had in selecting our stimuli, five of the primes were monosyllables (i.e. *mosque*, *bless*, *prawn*, *glance*, and *floon*). However, this was also the case in the Dimitropoulou et al. (2010) stimulus set. For example, the primes *piel*, *diez*, *buen*, *dios*, *juez*, *bien*, and *buil*, are monosyllabic in Spanish.

Apparatus and Procedure. Participants were tested individually, seated approximately 40 cm in front of a CRT monitor in a dimly lit room. Stimulus presentation and data recording were controlled by DMDX software (Forster & Forster, 2003). Verbal responses were recorded by a head-worn microphone. Participants were told that they would see a series of hash tags (#######) followed by words presented in uppercase letters, and that they had to read aloud the words as quickly and as accurately as possible. The presence of primes was not mentioned to the participants. Stimuli were presented to each participant in a different random order, following six practice trials. Each trial started with the presentation of a forward mask (#######) that remained on the screen for 500 ms. The prime was then presented in lowercase letters for 50 ms (three ticks based on the monitor's refresh rate of 16.67 ms), followed by the target, which was presented in uppercase letters and acted as a backward mask to the prime. The stimuli appeared in white on a black background (12-point Courier New font) and remained on the screen for 2000 ms or until participants responded, whichever happened first. The order of trial presentation was randomized across participants in all lists.

Results

Participants' responses (N = 30) were hand marked using CheckVocal (Protopapas, 2007). The acoustic onset of the responses was marked in the same way as in Experiments 1 and 2. Incorrect responses, mispronunciations, and hesitations (6.7% of the data), trials that were presented first and trials whose previous trial corresponded to an error (7.4% of the data), as well as extreme outliers that were identified separately for each participant (.8% of the data) were discarded. The analyses were performed in the same way as in Experiments 1 and 2. The model we report included invRT as the dependent variable, and the interaction between prime relatedness (onset related vs. unrelated) and prime type (word vs. pronounceable nonword vs. unpronounceable nonword), RT of previous trial, and trial order as fixed effects. Intercepts for subjects and items were included as random effects, and so were by-item random slopes for the effect of prime relatedness: invRT ~ prime relatedness*prime type + PrevRT + trial order + (1 | subject) + (1 + prime relatedness | target).

Outliers with a standardized residual greater than 2.5 standard deviations from zero were removed from the fitted model (1.8% of the data). The results indicated a significant MOPE, so that reading aloud latencies were faster in the onset-related condition compared to the unrelated condition for word primes (t = -2.846, p < .01), pronounceable nonword primes (t = -5.483, p < .001), and unprounceable nonword primes (t = -1.992, p < .05). The significant MOPE for unpronounceable nonword primes contrasts sharply with the Dimitropoulou et al. (2010) results, which showed no MOPE when the primes were unpronounceable. There was also a significant interaction between prime relatedness and prime type when the MOPE for pronounceable nonword primes was compared to the MOPE for word primes and unpronounceable nonword primes. In particular, pronounceable nonword primes yielded a significantly bigger MOPE than word primes (t = 1.965, p < .05) and unpronounceable nonword primes (t = 2.604, p < .01). However, the interaction between prime relatedness and prime type was not significant when the MOPE for unpronounceable nonword primes was compared to the MOPE for word primes (t < 1). The latter result also conflicts with the Dimitropoulou et al. (2010) results, which indicated a bigger MOPE for word primes compared to unpronounceable nonword primes. In addition, our results indicated a significant pronounceability effect: word primes yielded significantly faster target reading aloud latencies than unpronounceable nonword primes, both in the onset-related and unrelated conditions (t = -3.495, p < .001 and t = -2.605, p < .01, respectively), and pronounceable nonword primes yielded significantly faster target reading aloud latencies than unpronounceable nonword primes in the onset-related condition (t = -4.493, p < .001).

The error analysis was performed using a logit mixed model with the prime relatedness by prime type interaction as a fixed effect and intercepts for subjects and items as random effects. The onset-related condition yielded significantly fewer errors than the unrelated condition when the primes were unpronounceable nonwords (z = -2.288, p < .05). Also, word primes and pronounceable nonword primes yielded significantly fewer errors than unpronounceable nonword primes in the unrelated condition (z = -2.325, p < .05 and z = -2.667, p < .01, respectively). The error rate difference between the onset-related and unrelated condition was also significantly bigger for unpronounceable nonword primes, compared to word primes (z = 2.742, p < .01) and pronounceable nonword primes (z = 2.052, p < .05). Mean RTs for each condition (calculated from a total of 3787 observations), and percentage of errors (based on the total number of trials in each condition), are presented in Table 5.

–Insert Table 5 about here–

Discussion

We carried out a MOPE experiment using the same experimental design and type of stimuli that Dimitropoulou et al. (2010) used in the English language. In contrast to their findings and in agreement with our results from Experiment 2 we observed a significant MOPE for both pronounceable and unpronounceable primes. However, it is worth noting that the MOPE was significantly bigger for pronounceable nonword primes compared to word primes. We hypothesize that this could be because word primes are likely to activate their lexical representations during prime presentation. The lexical representations of the onset-related word primes share more phonemes with the targets in the same position, compared to unrelated word primes (e.g., ***s**tigma*-**S**ANDAL vs. *recent*-SANDAL), thus yielding a significant MOPE. However, competition between the primes' and targets' lexical representations could significantly reduce the size of the effect.

Also, the MOPE was significantly bigger for pronounceable nonword primes compared to unpronounceable nonword primes, which contrasts with our finding in Experiment 2, where equal MOPE was observed for both types of primes. However, the stimuli in Experiment 2 were monosyllabic, whereas the ones used in Experiment 3 were disyllabic. Perhaps the syllable becomes a prominent representational unit in reading aloud when the printed letter strings are multisyllabic. In the case of pronounceable nonword primes there was more phoneme overlap between the first syllable of the onset-related primes and the first syllable of the targets, compared to unrelated prime-target pairs (e.g., ***s****o.slin*-**S**AN.DAL vs. *ti.clet*-SAN.DAL), thus yielding a robust MOPE. In the case of unpronounceable nonword primes, there was also more phoneme overlap between the primes and the targets in the onset-related condition compared to the unrelated condition (e.g., ***s****jxlqk*-**S**ANDAL vs. *tvwmhf*-SANDAL), thus yielding a significant MOPE. However, an attempt to process the first syllable of an unpronounceable prime would result in processing a phonotactically illegal sequence of letters, which would induce conflict or ambiguity, thus reducing significantly the size of the effect. This explanation is compatible with the results from the error analysis, which revealed many more reading aloud errors when the primes were unpronounceable.

The CDP++ model (Perry et al., 2010) explains the MOPE as result of left–to–right processing of the prime by the sublexical procedure. Hence, we ran the stimuli from Experiment 3 through this model to assess whether it can simulate our findings. With the default parameters and a prime duration of 25 cycles (as per Perry et al., 2010) the model produced one error in the onset-related condition and a significant MOPE for all three types of primes, $t(148) = 23.422$ for word primes, $t(148) = 28.767$ for pronounceable nonword primes, and $t(148) = 25.123$ for unpronounceable nonword primes, all $ps < .001$ (see Table 6). Thus, the CDP++ model successfully simulated a significant MOPE for all three types of primes. It is also worth noting that the size of the MOPE was numerically smaller when the primes were words (2.2 cycles) compared to when they were pronounceable nonwords (2.4 cycles), which is consistent with the human results. However, the size of the MOPE was numerically bigger when the primes were unpronounceable nonwords (2.5 cycles) compared to when they were pronounceable nonwords, which is inconsistent with the human data. The model's pronunciations of the target stimuli and its RTs (in cycles) for each item are provided in Appendix G.

–Insert Table 6 about here–

General Discussion

Recent computational instantiations of the dual-route theory of reading (e.g., Coltheart et al., 2001; Perry et al., 2007; 2010) posit that a serially-operating sublexical reading mechanism is involved in the orthography–to–phonology computation. Such theories attribute the MOPE to the serial left–to–right nature of operation of this mechanism. However, the speech-planning account (Kinoshita, 2000; Dimitropoulou et al., 2010) attributes the MOPE to the serial left–to–right nature of the segment–to–frame association process, which occurs further downstream, during phonological encoding. Thus, according to the speech-planning account, the orthography–to–phonology computation need not occur serially; it may occur in parallel. Recently, a study that was carried out in Spanish (Dimitropoulou et al., 2010) offered new evidence in favor of the speech-planning account of the MOPE and against the dual-route account. In particular, Dimitropoulou et al. (2010) failed to obtain a MOPE when target words were preceded by unpronounceable primes. According to the speech-planning account, if a prime is unpronounceable its syllabic onset cannot be identified, and so the segment–to–frame process fails and the MOPE is abolished. The dual-route account cannot explain this finding. In the present paper we sought to determine whether serial processing in reading aloud occurs indeed during speech planning, rather than in the orthography–to–phonology computation as dual-route theories of reading postulate.

Three experiments were carried out using the PSE and the MOPE paradigms. According to dual-route theories of reading, both effects are due to the serial left–to–right nature of operation of the sublexical reading mechanism. In Experiment 1 the printed stimuli consisted of phonologically congruent/incongruent pronounceable and unpronounceable nonwords that participants had to color-name. We observed a robust PSE irrespective of the pronounceability of the stimuli. In Experiments 2 and 3 target nonwords/words were preceded by onset-related/unrelated pronounceable and unpronounceable primes. We observed a significant MOPE for both types of primes in both experiments. These results contrast sharply with the Dimitropoulou et al. findings providing evidence against the idea that the PSE and the MOPE arise during speech planning.

But how could one explain the discrepancy between our data and the Dimitropoulou et al. (2010) data? In Experiment 3 we used the same experimental design and type of stimuli that Dimitropoulou et al. used, hence the only major difference between our study and the Dimitropoulou et al. study was that ours was in English, whereas theirs was in Spanish. A possible explanation is that the syllabic onset is a functional unit in Spanish. If that were the case, the orthography-to-phonology translation of the unpronounceable prime's syllabic onset would have failed during prime presentation (given that unpronounceable primes lack a syllabic onset), and so no MOPE would be expected in the Spanish language. As it has already been mentioned in the introduction, Mousikou et al. (2010b) investigated this issue in English using prime-target pairs with shared initial phoneme, but not syllabic onset (e.g., *disc*-DRUM vs. *melt*-DRUM, *drum*-DISC vs. *melt*-DISC, *biln*-BREV vs. *kalt*-BREV, *brev*-BILN vs. *kalt*-BILN). They observed a significant MOPE in all cases, which indicated that the syllabic onset is not a functional unit in the English language. Similar results were obtained in Dutch (Schiller, 2004). Such an experiment in Spanish could determine whether syllabic onsets play a functional role in this language and could potentially explain the discrepancy between our findings and the Dimitropoulou et al. (2010) findings.

The question of whether the MOPE disappears when the primes are unpronounceable provides the only direct test of the contrasting predictions of the dual-route and speech-planning accounts. However, two other empirical phenomena in the MOPE literature have been explained within the speech-planning account. These are the presence of a MOPE in picture naming (Schiller, 2008) and the absence of a MOPE with irregular word targets (Kinoshita & Woollams, 2002). In relation to these phenomena Mousikou et al. (2010c, p 743) noted: “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).” Hence, the dual-route account indeed predicts a MOPE in picture naming, which is consistent with the empirical findings (Schiller, 2008), but in principle, it also predicts a MOPE with irregular word targets, which is inconsistent with the available empirical evidence (Forster & Davis, 1991; Kinoshita & Woollams, 2002). Mousikou et al. (2010c) investigated this issue with the DRC model using regular and irregular word targets preceded by onset-related and unrelated masked primes. Although the model showed a significant regularity effect, so that regular word targets were read aloud significantly faster than irregular word targets (as it was also the case in the Kinoshita and Woollams data), it failed to show a MOPE with irregular word targets. This was because of very strong competition between the incorrect ‘regularised’ pronunciation of the irregular phoneme of the target (produced by the sublexical procedure) and its correct irregular pronunciation (produced by the lexical procedure), which was not resolved until the target word was named by the model. Thus, target reading aloud latencies were determined by the time the irregular target phoneme reached threshold, which happened at the same time for targets preceded by onset-related and unrelated primes. In other words, any influence of the first phoneme of the prime on the speed of processing of the first phoneme of the target did not affect overall target reading aloud latencies, thus resulting in the absense of a MOPE. Therefore, no empirical phenomenon in the literature can be explained by the speech-planning account, but not the dual-route account. Yet, the findings from the three experiments we report in this paper can be explained by the dual-route account but not the speech-planning account, providing strong support for the claim that a sublexical reading mechanism that operates serially and from left to right is involved in the orthography–to–phonology computation.

Although the dual-route account seems to be the only account that can accommodate these findings, it is worth noting that on the assumption that a response can be initiated as soon as the initial phoneme has been computed (Kawamoto, Kello, Jones, & Bame, 1998), an account that posits parallel computation of phonology from orthography across the letter string can also explain the serial nature of the MOPE. In particular, according to this account, the orthography–to–phonology computation of the prime's letters could occur in parallel, but if readers initiate articulation as soon as the initial phoneme of the target letter string 'becomes known' (rather than when *all* of the phonemes of the target letter string become known), savings in target reading aloud will only occur if the phoneme overlap between the prime and the target is in the initial position.

However, the idea that a response can be initiated as soon as the initial phoneme has been computed is incompatible with several empirical findings in the reading aloud and speech production literature. For example, in a large-scale multiple regression study, Spieler & Balota (1997) found that word length (defined in terms of number of letters) was one of the primary predictors of word reading aloud latency. If people initiate articulation as soon as they have computed the initial phoneme of a word, a word-length effect on reading aloud latency should not have been observed. Further, anticipatory coarticulatory effects in speeded reading aloud, i.e. the lip protrusion in articulating the vowel of *spoon* extends to the initial phoneme /s/ (Rastle et al., 2000), cannot be explained if one assumes that articulation begins as soon as the initial phoneme becomes known. Moreover, recently, Cholin, Dell, and Levelt (2011) observed that English speakers are faster in producing high-frequency syllables (e.g., /kæl/) compared to low-frequency syllables (e.g., /kæk/). If speakers started articulation as soon as the initial phoneme (i.e. /k/) became known, syllable-frequency effects would not have been observed in this study. Last, our own results from the present study are incompatible with the initial-phoneme criterion hypothesis.

For example, according to Kawamoto et al. (1998, p. 881), “the plosivity of the IP should affect the magnitude of the onset effect. In particular, we would expect a larger onset effect (i.e. more priming) based on acoustic latencies when the IP of the target was a nonplosive than when it was a plosive because with plosive initial consonants, the release of the plosive would be delayed until the vowel is identified.” The initial phonemes of the target nonwords in Experiment 2 were mainly plosives (48 items started with plosives and 24 items started with non-plosives). We calculated the MOPE for plosives and non-plosives separately and the results indicated similar size of MOPE for both types of consonants (i.e. for plosives, the MOPE for pronounceable and unpronounceable nonword primes was 17 and 15 ms, respectively; for non-plosives, it was 11 and 17 ms for pronounceable and unpronounceable nonword primes, respectively). Hence, the claim that a response can be initiated as soon as the initial phoneme has been computed is not supported by several lines of evidence. As such, the only account that offers a valid explanation for the present findings is the dual-route account.

We explicitly tested the dual-route account by simulating the behavioral data on the MOPE with the DRC and CDP++ computational models of reading, which are computational instantiations of the dual-route theory of reading. Both models simulated successfully a MOPE for nonword targets preceded by pronounceable and unpronounceable nonword primes (Experiment 2). Also, the CDP++ model simulated successfully a MOPE for disyllabic word targets preceded by word primes, pronounceable nonword primes and unpronounceable nonword primes. These simulation results provide additional support for the claim that the MOPE is due to the processing of the primes by a sublexical serially-operating reading mechanism.

Finally, an additional effect that we observed in all three experiments and we have not discussed so far is the pronounceability effect. In Experiment 1 unpronounceable nonwords yielded significantly faster color-naming latencies than pronounceable nonwords in the incongruent condition. In the congruent condition the effect was smaller but in the same direction. This result suggests that participants must have generated the phonology of the nonwords when these were pronounceable, which would interfere with the phonology of the color name they had to utter, thus slowing down color-naming latencies. Such interference would not be present with unpronounceable nonwords because their phonology cannot be generated. This finding is consistent with Bakan and Alperson's (1967) observation that consonantal letter strings such as FJQ produce less interference than pronounceable letter strings such as EKL or DAP when color-named. However, the pronounceability effect observed in Experiments 2 and 3 was in the opposite direction: unpronounceable primes yielded significantly slower target reading aloud latencies than pronounceable primes. Critically, the primes were masked so participants could not see them. A potential explanation for this finding is that participants (at least sometimes or some of them) may process more letters of the prime than just the first. This idea was initially proposed by Mousikou et al. (2010a) who observed more priming when primes and targets shared their first two letters/phonemes (*sif*-SIB) compared to when they only shared their first letter/phoneme (*suf*-SIB). The difference in priming between the two conditions was very small (3 ms) but significant, leading the authors to suggest that the sublexical reading procedure may be operating at different speeds across individuals (or on some trials). Thus, on some occasions more letters of the prime than the first could be processed. If that were the case, when the primes were unpronounceable, the phonotactical illegality at the beginning of the primes could potentially conflict with the orthography–to–phonology computation process, thus slowing down target reading aloud in this condition. This idea is further supported by the error analysis in Experiment 3: unpronounceable nonword primes yielded significantly more errors than word primes and pronounceable nonword primes suggesting more interference in target reading aloud in this condition. Neither the DRC nor the CDP++ models were able to simulate this pronounceability effect that people showed in the MOPE experiments. Further empirical work is required to determine the nature of this effect.

Conclusion

The findings from the present experiments falsify the idea that the MOPE and the PSE arise during speech planning and corroborate the original dual-route interpretation of both effects, providing strong support for the claim that serial processing is involved in the orthography–to–phonology computation.

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Table 1. *Mean Colour-naming Latencies (RTs in ms) with Standard Deviations (in parentheses) and Percent Error Rates (%E) for each condition in Experiment 1.*

	Pronounceable		Unpronounceable		Pronounceability effect
	RTs (SDs)	%E	RTs (SDs)	%E	
Congruent	617 (154)	2.9	608 (161)	2.5	-9
Incongruent	675 (167)	6.2	662 (177)	6.5	-13
Congruency effect	58		54		

Table 2. *Human Mean Reading Aloud Latencies (RTs in ms) with Standard Deviations (in parentheses) and Percent Error Rates (%E) for each condition in Experiment 2.*

	Pronounceable primes		Unpronounceable primes		Pronounceability effect
	RTs (SDs)	%E	RTs (SDs)	%E	
Onset related	502 (79)	.4	508 (81)	.8	6
Unrelated	517 (78)	.2	523 (80)	.6	6
MOPE	15		15		

Table 3. *DRC Mean Reading Aloud Latencies (RTs in cycles) with Standard Deviations (in parentheses) in Experiment 2 (Prime Duration = 26 cycles).*

	Pronounceable primes	Unpronounceable primes	Pronounceability effect
	RTs (SDs)	RTs (SDs)	
Onset related	132.4 (3.6)	132.4 (3.6)	0
Unrelated	133.4 (3.6)	133.4 (3.6)	0
MOPE	1	1	

Table 4. *CDP++ Mean Reading Aloud Latencies (RTs in cycles) with Standard Deviations (in parentheses) in Experiment 2 (Prime Duration = 25 cycles).*

	Pronounceable primes	Unpronounceable primes	Pronounceability effect
	RTs (SDs)	RTs (SDs)	
Onset related	103.2 (15.2)	103.2 (15.4)	0
Unrelated	106.6 (16.2)	105.4 (16.1)	-1.2
MOPE	3.4	2.2	

Table 5. *Human Mean Reading Aloud Latencies (RTs in ms) with Standard Deviations (in parentheses) and Percent Error Rates (%E) for each condition in Experiment 3.*

	Word primes		Pronounceable nonword primes		Unpronounceable nonword primes		Pronounceability effect	
	RTs (SDs)	%E	RTs (SDs)	%E	RTs (SDs)	%E	Words	Nonwords
Onset related	522 (100)	7.7	518 (96)	6.3	529 (98)	6	7	11
Unrelated	531 (102)	5.9	535 (103)	5.5	538 (96)	8.8	7	3
MOPE	9		17		9			

Table 6. *CDP++ Mean Reading Aloud Latencies (RTs in cycles) with Standard Deviations (in parentheses) in Experiment 3 (Prime Duration = 25 cycles).*

	Word primes	Pronounceable nonword primes	Unpronounceable nonword primes	Pronounceability effect	
	RTs (SDs)	RTs (SDs)	RTs (SDs)	Words	Nonwords
Onset related	84.4 (7.6)	84.2 (7.5)	84.2 (7.5)	-0.2	0
Unrelated	86.6 (7.3)	86.6 (7.2)	86.7 (7.3)	0.1	0.1
MOPE	2.2	2.4	2.5		

Appendix A. Experimental stimuli used in Experiment 1.

Congruent			Incongruent		
Pronounceable	Unpronounceable	Color	Pronounceable	Unpronounceable	Color
BWAC	BWFC	blue	BWAC	BWFC	red
BWAM	BWFM	blue	BWAM	BWFM	red
BWAZ	BWFZ	blue	BWAZ	BWFZ	red
BWIF	BWGF	blue	BWIF	BWGF	red
BWIK	BWGM	blue	BWIK	BWGM	red
BWIV	BWGS	blue	BWIV	BWGS	red
BWIZ	BWVK	blue	BWIZ	BWVK	red
BWOC	BWVV	blue	BWOC	BWVV	red
BWOG	BWVZ	blue	BWOG	BWVZ	red
BWOM	BWZC	blue	BWOM	BWZC	red
BWOS	BWZG	blue	BWOS	BWZG	red
BWOT	BWZT	blue	BWOT	BWZT	red
BLAG	BLFG	brown	BLAG	BLFG	white
BLAJ	BLFM	brown	BLAJ	BLFM	white
BLAM	BLFP	brown	BLAM	BLFP	white
BLAP	BLGP	brown	BLAP	BLGP	white
BLEB	BLGV	brown	BLEB	BLGV	white
BLEF	BLGZ	brown	BLEF	BLGZ	white
BLEP	BLNB	brown	BLEP	BLNB	white
BLUC	BLNF	brown	BLUC	BLNF	white
BLUP	BLNP	brown	BLUP	BLNP	white
BLUS	BLZC	brown	BLUS	BLZC	white
BLUV	BLZJ	brown	BLUV	BLZJ	white
BLUZ	BLZZ	brown	BLUZ	BLZZ	white
GLAB	GLFF	green	GLAB	GLFF	pink
GLAF	GLGB	green	GLAF	GLGB	pink
GLAJ	GLGJ	green	GLAJ	GLGJ	pink
GLOM	GLGK	green	GLOM	GLGK	pink
GLOP	GLNB	green	GLOP	GLNB	pink
GLOT	GLNJ	green	GLOT	GLNJ	pink
GLOV	GLNZ	green	GLOV	GLNZ	pink
GLOZ	GLZM	green	GLOZ	GLZM	pink
GLOZ	GLZP	green	GLOZ	GLZP	pink
GLUB	GLZT	green	GLUB	GLZT	pink
GLUJ	GLZV	green	GLUJ	GLZV	pink
GLUK	GLZZ	green	GLUK	GLZZ	pink
PAF	PFF	pink	PAF	PFF	green
PAF	PFV	pink	PAF	PFV	green
PAV	PFV	pink	PAV	PFV	green
PAV	PGJ	pink	PAV	PGJ	green
PAZ	PGM	pink	PAZ	PGM	green
POB	PGV	pink	POB	PGV	green
POF	PNF	pink	POF	PNM	green
POL	PNF	pink	POL	PNM	green
POZ	PNZ	pink	POZ	PNZ	green
PUJ	PZB	pink	PUJ	PZB	green
PUM	PZF	pink	PUM	PZF	green
PUV	PZL	pink	PUV	PZL	green
RAF	RFF	red	RAF	RFF	blue
RAS	RFS	red	RAS	RFS	blue

RAV	RFV	red	RAV	RFV	blue
RAZ	RNM	red	RAZ	RNM	blue
RIT	RNM	red	RIT	RNM	blue
RIV	RNZ	red	RIV	RNZ	blue
RIZ	RVN	red	RIZ	RVN	blue
ROF	RVN	red	ROF	RVN	blue
ROF	RVZ	red	ROF	RVZ	blue
ROV	RZF	red	ROV	RZF	blue
ROZ	RZV	red	ROZ	RZV	blue
ROZ	RZZ	red	ROZ	RZZ	blue
WAF	WFF	white	WAF	WFF	brown
WAV	WFV	white	WAV	WFV	brown
WAZ	WFZ	white	WAZ	WFZ	brown
WEC	WGF	white	WEC	WGF	brown
WEM	WGM	white	WEM	WGM	brown
WEP	WGP	white	WEP	WGP	brown
WEV	WNC	white	WEV	WNC	brown
WID	WNM	white	WID	WNM	brown
WUF	WNP	white	WUF	WNP	brown
WUJ	WVD	white	WUJ	WVD	brown
WUM	WVJ	white	WUM	WVJ	brown
WUP	WVV	white	WUP	WVV	brown

Appendix B. Experimental stimuli used in Experiment 2 and acceptable target pronunciations.

Targets	Acceptable pronunciations	Pronounceable primes		Unpronounceable primes	
		Onset related	Unrelated	Onset related	Unrelated
BLAG	blæg	bomp	zost	bnfz	vnfz
BLAJ	blædʒ	bisp	semp	bngs	qngs
BLAM	blæm	boft	crin	bnvv	cnvv
BLAP	blæp	besk	stit	bngf	vngf
BLEB	bleb	bonk	fonk	bnzc	fnzc
BLEF	blef	bant	tump	bnvz	knvz
BLEP	blep	baft	dand	bnfm	rnfm
BLUC	blʌk; blʊk	basp	spid	bnzg	mnzg
BLUP	blʌp; blʊp	bist	trin	bnzt	rnzt
BLUS	blʌs; blʊs; blʌz; blʊz	bect	neft	bngm	zngm
BLUV	blʌv; blʊv	bimp	smed	bnfc	rnfc
BLUZ	blʌz; blʊz	beft	mond	bnvk	cnvk
BRAK	bræk	belf	lipt	bjgv	fjgv
BRAV	bræv	belk	slig	bjzc	mjzc
BREF	bref	binc	kulp	bjgp	kjgp
BREK	brek	bamp	nint	bjfp	ljfp
BREP	brep	bont	jand	bjfg	vjfg
BRET	bret	bolf	zold	bjgz	mjgz
BREV	brev	balf	dact	bjnf	tjnf
BRID	brɪd	bemp	yolf	bjnz	pjnz
BRIV	brɪv	bulp	lelt	bjzz	njzz
BRIZ	brɪz	beld	colk	bjnp	gjnp
BROG	brɒg	balp	kaft	bjfm	kjfm
BROT	brɒt	belp	kisk	bjzj	vjzj
GLAB	glæb	goft	hisk	gpzv	mpzv
GLAF	glæf	gont	munt	gpnz	kpnz
GLAJ	glædʒ	gond	comp	gpzt	rpzt
GLOD	glɒd	greb	frim	gpvk	tpvk
GLOM	glɒm	guct	sisp	gpvj	srvj
GLOP	glɒp	gank	zast	gvfb	wvfb
GLOT	glɒt	gusk	vink	gpnj	bpnj
GLOV	glɒv	gund	yesk	gpnb	rpnb
GLOZ	glɒz	gapt	drup	gpff	vpff
GLUB	glʌb; glʊb	gask	vint	gpzp	dpzp
GLUJ	glʌdʒ; glʊdʒ	gact	vomp	gpzm	fpzm
GLUK	glʌk; glʊk	grat	zent	gpzz	npzz
PAB	pæb	pim	feg	pgj	mgj
PAF	pæf	pid	lig	pkm	gkm
PAK	pæk	pef	nom	pzl	vzl
PAV	pæv	ped	dob	pgm	bgm
PAZ	pæz	piv	mec	pff	jff
POB	pɒb	piz	lef	pnz	knz
POF	pɒf	pag	san	pzb	nzb
POL	pɒl	pev	ned	pfv	dfv
POZ	pɒz	pel	kun	pnf	rnf
PUJ	pʌdʒ; pʊdʒ	pem	seb	pzf	lzf
PUM	pʌm; pʊm	pez	zeg	pgv	fgv
PUV	pʌv; pʊv	pog	nen	psl	zsl
RAF	ræf	res	mep	rvz	qvz

RAS	ræs; ræz	reb	deg	rff	gff
RAV	ræv	reg	mub	rnz	cnz
RAZ	ræz	rem	fod	rnm	pnm
RIT	rɪt	ral	sof	rzf	szf
RIV	rɪv	rup	yop	rfs	mfs
RIZ	rɪz	rel	hof	rtv	ptv
ROF	rɒf	rab	tad	rvn	kvn
ROG	rɒg	ruv	teb	rzz	nzz
ROP	rɒp	rud	yig	rfv	lfv
ROV	rɒv	rez	jeb	rzl	dzl
ROZ	rɒz	rid	kag	rbk	tbk
WAF	wæf; wɒf	wom	tem	wnp	dnp
WAV	wæv; wɒv	wez	liz	wnm	jnm
WAZ	wæz; wɒz	wof	kiv	wgf	kgf
WEC	wek	wib	zab	wfv	zfv
WEM	wem	wub	tav	wvd	lvd
WEP	wep	wut	nim	wfz	gfz
WEV	wev	wos	kug	wgm	cgm
WID	wɪd	wef	nuv	wnc	lnc
WUF	wʌf; wʊf	wob	tog	wgp	rgp
WUJ	wʌdʒ; wʊdʒ	wek	fek	wff	sff
WUM	wʌm; wʊm	wal	cav	wvj	nvj
WUP	wʌp; wʊp	wes	ved	wvv	bvv

Appendix C. DRC pronunciations and RTs (in cycles) per item at a prime duration of 26 cycles (Experiment 2).

Target		Pronounceable		Unpronounceable	
		Onset related	Unrelated	Onset related	Unrelated
BLAG	bl{g	136	137	136	137
BLAJ	bl{_	136	137	136	137
BLAM	bl{m	136	137	136	137
BLAP	bl{p	136	137	136	137
BLEB	blEb	136	137	136	137
BLEF	blEf	136	137	136	137
BLEP	blEp	136	137	136	137
BLUC	blVk	136	137	136	137
BLUP	blVp	136	137	136	137
BLUS	blVs	136	137	136	137
BLUV	blVv	136	137	136	137
BLUZ	blVz	136	137	136	137
BRAK	br{k	136	137	136	137
BRAV	br{v	136	137	136	137
BREF	brEf	136	137	136	137
BREK	brEk	136	137	136	137
BREP	brEp	136	137	136	137
BRET	brEt	136	137	136	137
BREV	brEv	136	137	136	137
BRID	brId	136	137	136	137
BRIV	brIv	136	137	136	137
BRIZ	brIz	136	137	136	137
BROG	brQg	136	137	136	137
BROT	brQt	136	137	136	137
GLAB	gl{b	136	137	136	137
GLAF	gl{f	136	137	136	137
GLAJ	gl{_	136	137	136	137
GLOD	glQd	136	137	136	137
GLOM	glQm	136	137	136	137
GLOP	glQp	136	137	136	137
GLOT	glQt	136	137	136	137
GLOV	glQv	136	137	136	137
GLOZ	glQz	136	137	136	137
GLUB	glVb	136	137	136	137
GLUJ	glV_	136	137	136	137
GLUK	glVk	136	137	136	137
PAB	p{b	129	130	129	130
PAF	p{f	129	130	129	130
PAK	p{k	126	127	126	127
PAV	p{v	129	130	129	130
PAZ	p{z	129	130	129	130
POB	pQb	129	130	129	130
POF	pQf	129	130	129	130
POL	pQl	129	129	129	129
POZ	pQz	129	130	129	130
PUJ	pV_	129	130	129	130
PUM	pVm	129	130	129	130
PUV	pVv	129	130	129	130

RAF	r{f	129	130	129	130
RAS	r{s	129	130	129	130
RAV	r{v	129	130	129	130
RAZ	r{z	129	130	129	130
RIT	rIt	128	129	128	129
RIV	rIv	129	130	129	130
RIZ	rIz	129	130	129	130
ROF	rQf	129	130	129	130
ROG	rQg	129	130	129	130
ROP	rQp	129	130	129	130
ROV	rQv	129	130	129	130
ROZ	rQz	129	130	129	130
WAF	w{f	129	130	129	130
WAV	w{v	129	130	129	130
WAZ	w{z	129	130	129	130
WEC	wEk	129	130	129	130
WEM	wEm	129	130	129	130
WEP	wEp	129	130	129	130
WEV	wEv	129	130	129	130
WID	wId	129	130	129	130
WUF	wVf	129	130	129	130
WUJ	wV_	129	130	129	130
WUM	wVm	129	130	129	130
WUP	wVp	129	130	129	130

Appendix D. CDP++ pronunciations, accuracy (C = Correct; W = Wrong), and RTs (in cycles) per item at a prime duration of 25 cycles (Experiment 2). RTs of erroneous pronunciations have been removed.

Target	Pronounceable						Unpronounceable					
	Onset			Unrelated			Onset			Unrelated		
BLAG	bl{g	C	102	bl{g	C	104	bl{g	C	102	bl{g	C	104
BLAJ	bl{	W		bl{	W		bl{	W		bl{	W	
BLAM	bl{m	C	100	bl{m	C	102	bl{m	C	100	bl{m	C	102
BLAP	bl{p	C	100	bl{p	C	102	bl{p	C	100	bl{p	C	102
BLEB	blEb	C	113	blEb	C	114	blEb	C	113	blEb	C	114
BLEF	blEf	C	106	blEf	C	106	blEf	C	106	blEf	C	108
BLEP	blEp	C	109	blEp	C	116	blEp	C	109	blEp	C	110
BLUC	blVk	C	130	blVk	C	132	blVk	C	130	blVk	C	132
BLUP	blVp	C	100	blVp	C	103	blVp	C	100	blVp	C	102
BLUS	blVz	C	130	blVz	C	132	blVz	C	130	blVz	C	131
BLUV	blVv	C	101	blVv	C	103	blVv	C	101	blVv	C	103
BLUZ	blVz	C	102	blVz	C	104	blVz	C	102	blVz	C	104
BRAK	br1k	W		br1k	W		br1k	W		br1k	W	
BRAV	br{v	C	101	br{v	C	103	br{v	C	101	br{v	C	103
BREF	brEf	C	103	brEf	C	105	brEf	C	103	brEf	C	105
BREK	brEkf@st	W		brEkf@st	W		brEkf@st	W		brEkf@st	W	
BREP	brEp	C	105	brEp	C	106	brEp	C	105	brEp	C	106
BRET	brEt	C	104	brEt	C	103	brEt	C	104	brEt	C	104
BREV	brEv	C	118	brEv	C	125	brEv	C	118	brEv	C	117
BRID	brId	C	101	brId	C	106	brId	C	101	brId	C	103
BRIV	brIv	C	101	brIv	C	103	brIv	C	101	brIv	C	103
BRIZ	brIz	C	101	brIz	C	103	brIz	C	101	brIz	C	103
BROG	brQg	C	101	brQg	C	103	brQg	C	101	brQg	C	103
BROT	brQt	C	101	brQt	C	103	brQt	C	101	brQt	C	103
GLAB	gl{b	C	100	gl{b	C	103	gl{b	C	100	gl{b	C	103
GLAF	gl#f	W		gl#f	W		gl#f	W		gl#f	W	
GLAJ	gl{	W		gl{	W		gl{	W		gl{	W	
GLOD	glQd	C	106	glQd	C	107	glQd	C	106	glQd	C	108
GLOM	glQm	C	121	glQm	C	123	glQm	C	120	glQm	C	123
GLOP	glQp	C	102	glQp	C	103	glQp	C	102	glQp	C	102
GLOT	glQt	C	102	glQt	C	104	glQt	C	102	glQt	C	103
GLOV	glVv	W		glVv	W		glVv	W		glVv	W	
GLOZ	gl5z	W		gl5z	W		gl5z	W		gl5z	W	
GLUB	glVb	C	100	glVb	C	103	glVb	C	100	glVb	C	103
GLUJ	glV	W		glV	W		glV	W		glV	W	
GLUK	glVk	C	100	glVk	C	102	glVk	C	100	glVk	C	102
PAB	p{b	C	90	p{b	C	95	p{b	C	90	p{b	C	93
PAF	p#f	W		p#f	W		p#f	W		p#f	W	
PAK	p{k	C	106	p{k	C	113	p{k	C	106	p{k	C	112
PAV	p{v	C	91	p{v	C	93	p{v	C	91	p{v	C	93
PAZ	p{z	C	134	p{z	C	140	p{z	C	135	p{z	C	139
POB	pQb	C	94	pQb	C	96	pQb	C	94	pQb	C	97
POF	pQf	C	95	pQf	C	97	pQf	C	95	pQf	C	97
POL	p5l	W		p5l	W		p5l	W		p5l	W	
POZ	p5z	W		p5z	W		p5z	W		p5z	W	
PUJ	pju	W		pju	W		pju	W		pju	W	
PUM	pVm	C	93	pVm	C	96	pVm	C	93	pVm	C	98
PUV	pVv	C	91	pVv	C	93	pVv	C	91	pVv	C	93

RAF	r#f	W		r#f	W		r#f	W		r#f	W	
RAS	r{z	C	162	r{z	C	167	r{z	C	164	r{z	C	166
RAV	r{v	C	91	r{v	C	93	r{v	C	91	r{v	C	93
RAZ	r{z	C	158	r{z	C	167	r{z	C	158	r{z	C	170
RIT	rIt	C	91	rIt	C	93	rIt	C	91	rIt	C	93
RIV	rIv	C	92	rIv	C	102	rIv	C	92	rIv	C	93
RIZ	rIz	C	91	rIz	C	94	rIz	C	91	rIz	C	99
ROF	rQf	C	91	rQf	C	93	rQf	C	90	rQf	C	93
ROG	rQg	C	95	rQg	C	96	rQg	C	94	rQg	C	96
ROP	rQp	C	96	rQp	C	109	rQp	C	95	rQp	C	97
ROV	rVv	W		rVv	W		rVv	W		rVv	W	
ROZ	r5z	W		r5z	W		r5z	W		r5z	W	
WAF	wQz	W		wQf	C	151	wQz	W		wQf	C	144
WAV	wQz	W		w{v	C	184	wQz	W		w{v	C	181
WAZ	wQz	C	53	w1z	W		wQz	C	53	w1z	W	
WEC	wEk	C	96	wEk	C	96	wEk	C	92	wEk	C	96
WEM	wEm	C	91	wEm	C	92	wEm	C	94	wEm	C	93
WEP	wEp	C	91	wEp	C	94	wEp	C	91	wEp	C	93
WEV	wEv	C	94	wEv	C	97	wEv	C	94	wEv	C	97
WID	wId	C	103	wId	C	105	wId	C	103	wId	C	103
WUF	wVf	C	91	wVf	C	122	wVf	C	91	wVf	C	92
WUJ	wV	W		wV	W		wV	W		wV	W	
WUM	wVm	C	93	wVm	C	92	wVm	C	91	wVm	C	94
WUP	wVp	C	91	wVp	C	92	wVp	C	92	wVp	C	92

Appendix E. DRC and CDP++ pronunciation symbols, their corresponding IPA symbols, and example words containing the corresponding sounds (in bold).

DRC/CDP++ symbol	IPA symbol	Example word
1	eɪ	b**ay**
3	ɜ:	b**ur**n
5	oʊ	n**o**
7	ɪə	p**ee**r
9	ɔ:	p**oor**
E	e	p**e**t
J	tʃ	**ch**eap
Q	ɒ	p**o**t
T	θ	**th**in
V	ʌ	p**u**tt
b	b	**b**ad
f	f	**f**at
h	h	**h**ad
j	j	**y**ank
l	l	**l**ad
n	n	**n**at
r	r	**r**at
t	t	**t**ack
v	v	**v**at
z	z	**z**ap
{	æ	p**a**t
2	aɪ	b**uy**
4	ɔɪ	b**oy**
6	aʊ	br**ow**
8	eə	p**air**
D	ð	**th**en
I	ɪ	p**i**t
N	ŋ	ba**ng**
S	ʃ	**sh**eep
U	ʊ	p**u**t
Z	ʒ	mea**s**ure
d	d	**d**ad
g	g	**g**ame
i	i:	b**ea**n
k	k	**c**ad
m	m	**m**ad
p	p	**p**at
s	s	**s**ap
u	u:	b**oo**n
w	w	**w**hy
#	ɑ:	b**ar**n
_	dʒ	**j**eep

Appendix F. Experimental stimuli used in Experiment 3 and target pronunciations in IPA.

Targets		Word primes		Pronounceable nonword primes		Unpronounceable nonword primes	
		Onset related	Unrelated	Onset related	Unrelated	Onset related	Unrelated
BANISH	‘bænɪʃ	beetle	common	bellap	mibble	bfhsvf	hxmsrl
BOBBIN	‘bɒbɪn	battle	parcel	banfer	liggle	bhdzpk	fmspjp
FERMENT	‘fɜmənt[11]	fragile	plaster	finsood	bostard	fkdkxgz	dswrdxz
BELLOW	‘beloʊ	butter	suffer	babber	codder	bpfkfp	fsqpqh
BODIED	‘bɒdɪd	button	kettle	barbot	furgle	bmkhvx	hkvfrs
BECKON	‘bekən	budget	fillet	bamper	fudish	bzhfnq	lbnslk
CARPAL	‘kɑpəl	county	winter	cullin	debort	cpxhtj	djpwwf
GAMBIT	‘gæmɪt	gospel	frenzy	glorag	mespel	gvwdlx	hndfkp
BIGOT	‘bɪgət	banjo	comic	bafin	melid	bfkzb	mftsq
CLOVER	‘kloʊvə	cannon	novice	carful	buggle	cfqhzd	lqhlxk
FLOOZY	‘fluzi	finish	kitten	fander	mobble	fkmqhv	dmzkph
TATTLE	‘tætəl	ticket	pocket	tilber	codern	tqzhpr	mfhdrd
BAFFLE	‘bæfəl	bucket	timber	bossin	dosset	bxntmk	lnjwpq
TOGGLE	‘tɒgəl	tennis	bumper	telish	melder	tzzsjd	pktnzf
DOGMA	‘dɒgmə	disco	habit	defil	pevol	dnqqt	lpbdn
FELON	‘felən	fancy	drama	fibet	pobid	fxpzl	mxnjl
HENNA	‘henə	hobby	lobby	harty	rilly	hzvzx	ltwsh
LIVID	‘lɪvɪd	lemon	madam	lacot	naral	lfmhv	bczfq
MAGMA	‘mægmə	medal	coral	mendy	nolid	mjdqf	lpsxn
MIMIC	‘mɪmɪk	metal	pasta	manty	tasel	mnpdj	pxlmr
MUTTER	‘mʌtə	mosque	willow	miseau	welloy	mbkqqn	hvrsrk
PESKY	‘peski	panda	limit	pamic	tafet	pjkbw	fzvrb
SURLY	‘sɜli	sober	lever	samer	biver	sxnbq	dxqdm
TARRY	‘tɑri	tiger	fever	tover	moger	txlwx	vkcvp
TIMID	‘tɪmɪd	token	robot	tozal	sofen	tqkwx	rlvjf
DAMASK	‘dæməsk	dragon	victim	dredel	gragon	dnxxqw	hsprhb
DOLLOP	‘dɒləp	damage	crater	dunnet	speezy	dbhjwz	jbpnbf
GAGGLE	‘gægəl	gossip	puffin	golter	preedy	gbkxfx	mhpmtq
HIPPIE	‘hɪpi	hammer	banner	hasser	gonner	hklbxh	mzbjsk
HERMIT	‘hɜmɪt	happen	nibble	hoggle	paggle	hxmnbv	pdltvk
JIGGLE	‘dʒɪgəl	jacket	butler	jelber	burrip	jbkwhf	pdndmm
LOCKET	‘lɒkɪt	lizard	bundle	lirall	pittle	lbtnwv	mcqjtx
MAGGOT	‘mægət	member	bounty	misack	romber	mjsppw	rfqjmx
MUSKET	‘mʌskɪt	mental	simple	momble	vongle	mkzpsz	rvbzww
NUGGET	‘nʌgɪt	needle	ribbon	nenack	sothod	nblhwq	pvwmzn
PAMPER	‘pæmpə	polish	cuddle	peresh	lorrod	pkwjpd	dmnbsk
PANTRY	‘pæntri	public	treble	pedlin	lompod	pqsbxj	fkjplt
PONCHO	‘pɒntʃoʊ	puppet	wiggle	pecket	dissil	pvlzjj	rndzrk
MIDGET	‘mɪdʒɪt	marble	purple	menshy	goftar	mpvqpv	sjzqmj
PONDER	‘pɒndə	puzzle	tickle	pessin	sivish	pjbjsf	hpmwlk
ROSTER	‘rɒstə	rabbit	method	rallod	tazzle	rnvqhm	tpklwt

[11] Two of the target items (*ferment*, *segment*) could either receive first- or second-syllable stress. None of the participants pronounced *segment* with a second-syllable stress, but some of the participants pronounced *ferment* with second-syllable stress. These pronunciations were counted as correct.

RIDDLE	‘rɪdəl	racket	banter	roshet	clorry	rqhlfb	fhvbvs
RIPPLE	‘rɪpəl	rocket	tender	rucket	carish	rpqnbz	pxqwxn
RENDER	‘rendə	rustic	tackle	rallom	coggle	rzsqqz	msjxbz
RADISH	‘rædɪʃ	rubble	turtle	revall	millen	rzmdnm	tqvqdm
SERMON	‘sɜmən	silver	mullet	sivage	cander	sxkkjl	pbvhdf
SNAZZY	‘snæzi	spider	poison	secket	mertle	sxdvxb	mrvxhp
SIZZLE	‘sɪzəl	summit	temper	scover	mollet	sxvkjs	lnrkvz
TENDON	‘tendən	tactic	profit	tamant	fampet	tkplzb	lvqwwq
TODDLE	‘tɒdəl	target	lavish	tancar	ricket	tlqxxn	szhlhw
TUSSLE	‘tʌsəl	toilet	vermin	talder	comper	tmfvbp	fkppvb
CRIPPLE	‘krɪpəl	cluster	verdict	comboss	smender	cmhbfjx	vpwzfsz
PLACID	‘plæsɪd	petrol	talent	ponest	sumple	pfbdjq	hpfqwv
RAVAGE	‘rævɪdʒ	reckon	sudden	ronnel	tember	rdwrfm	sfhpsq
BEATNIK	‘bitnɪk	blossom	hamster	bloster	snuddle	bfvqhbx	tpqgsvz
BLEMISH	‘blemɪʃ	bonkers	truffle	brackle	spanter	bxbdtbv	vhnlhdq
PIGMENT	‘pɪgmənt	plastic	scalpel	preslem	domslin	pxtnwvd	lnjhvrx
SEGMENT	‘segmənt	scandal	pumpkin	spestic	fulprom	szbrvkx	fxkhppm
BELFRY	‘belfri	basket	ransom	bandle	mindal	bztrvb	ndmjkw
PLATTER	‘plætə	paddock	luggage	perpoll	torrish	pqhxmkv	dsdxwjk
SAUNA	‘sɔnə	silly	petty	setty	tully	sdrqm	vhdkt
PIVOT	‘pɪvət	panic	cumin	pango	duril	pzxdf	rqdhs
BISTRO	‘bɪstroʊ	brandy	temple	bengle	domble	bkxjbm	mjqxhl
WAVER	‘weɪvə	widow	soggy	wicko	cully	wfzst	pskzn
CANDID	‘kændɪd	custom	modest	comnel	fragot	cvkfps	hmkvhf
SUPPLE	‘sʌpəl	sister	wicket	soster	totish	sxvbsq	mrrsmq
FIGMENT	‘fɪgmənt	frantic	problem	flastif	spolsam	fxjlzbl	rqxppwb
CULPRIT	‘kʌlprɪt	crystal	grumble	comband	strubal	cthfndz	vfzbzrx
DWINDLE	‘dwɪndəl	drastic	trumpet	destand	lampist	dqmhxsp	rmxbxbv
HACKSAW	‘hæksɔ	herring	village	hedding	dretter	hqblkdb	mzqwptb
VISTA	‘vɪstə	valid	magic	vonit	pamfy	vprpl	nfjhw
CRONY	‘kroʊni	cabin	zebra	casal	meval	cftvk	wfdzj
DAZZLE	‘dæzəl	doctor	mentor	doster	pitish	dklbxh	rxlkqb
COBBLE	‘kɒbəl	carpet	margin	crarry	sester	cnrfpt	nrkjdk
VANDAL	‘vændəl	velvet	planet	viptex	metest	vftmnj	sztqwz
TALLOW	‘tæloʊ	toffee	bitter	toopie	hiddie	txhvjz	pmnjdx
WAGGLE	‘wægəl	window	trauma	wilber	pirpit	wjfbqx	nrlpmp
POODLE	‘pudəl	picket	relish	pesset	mellit	pktjfq	rkwznb
SANDAL	‘sændəl	stigma	recent	soslin	ticlet	sjxlqk	tvwmhf
CAMBER	‘kæmbə	cotton	bottle	corash	joddle	cnpxlq	rkfzkl
NETTLE	‘netəl	number	hamper	narrip	finser	nsfnbw	vqwkxv
PALLID	‘pælɪd	pickle	middle	picter	mervon	pmvftb	nhjpsf
SONNET	‘sɒnɪt	settle	rattle	savack	muffon	sxpsds	rfxhms
PUNDIT	‘pʌndɪt	pistol	clumsy	plovel	ramand	pvxhsm	wjthhx
CUTLET	‘kʌtlɪt	canvas	prison	corand	segral	cmvxnx	wvzrbp
FETISH	‘fetɪʃ	filter	saddle	fallom	carble	fjprhw	lxjskb
TWIDDLE	‘twɪdəl	traffic	witness	tortant	prosash	tzfkfsb	rdlmrzx
TRINKET	‘trɪŋkɪt	textile	stumble	tanglom	bastond	tdjdbpz	vhxbqrz
TREMOR	‘tremə	tariff	bubble	tissil	dollet	tlsfnx	vwhplb
TERMITE	‘tɜmaɪt	trigger	haddock	traffer	flobber	tpqfmkb	sxnhvwp
CREVICE	‘krevɪs	custard	mustard	congool	tolster	cvmwmpf	rvwrpdx
FLICKER	‘flɪkə	fertile	rubbish	forring	narrock	fnldnsm	sxnpmwk
FURNISH	‘fɜnɪʃ	flutter	glitter	frotter	collock	fvqztmb	tbxrkqz
PELLET	‘pelɪt	pardon	wobble	pipple	mososh	pnjrkz	tlvbps

PECTIN	‘pektın	patent	handle	pandle	combal	pmbkpx	sfsdrx
PELVIC	‘pelvık	plenty	mascot	potest	gandle	pzbkdw	wpdzbm
SODDEN	‘sɒdən	savage	glance	snapar	pimage	sjwflb	pvwfbk
ZENITH	‘zenıθ	zombie	pollen	zompee	barrol	zvclvs	jhtzdw
DRIBBLE	‘drıbəl	dolphin	monster	destard	clender	dqhdfhx	mjnqzdf
TRICKLE	‘trıkəl	tabloid	bunting	tartand	ploster	tbfwzdv	lvwjqrb
GROTTO	‘grɒtoʊ	gallop	puddle	gapple	flimer	gbkpjx	dvqnzx
HUDDLE	‘hʌdəl	hornet	nectar	harpit	pancer	hnqtbk	dxtvwq
HINDER	‘hındə	hassle	fossil	hottle	blerry	hqkblm	rbmxkh
GOODIE	‘gudi	gutter	dinner	gaupha	sipper	gbvmth	fszfkj
MORBID	‘mɔbıd	mammal	buckle	manser	pettle	mshdrf	lphnlz
MEDDLE	‘medəl	market	vanish	milmer	pliper	mtjbrh	brkvhm
BONNY	‘bɒni	bless	cargo	bimer	teser	bpjzt	fvlxd
SERPENT	‘sɜpənt	saffron	council	smuttle	combiss	sxjzpwc	vnmjkpf
PRICKLE	‘prıkəl	publish	lobster	platoof	noodish	pbmtlmz	dsnhpqb
TOOTLE	‘tutəl	turnip	kidney	tassit	beriph	tqrdqb	fpqzmz
HOOKY	‘huki	hippo	paper	hiver	teler	hblxr	bsdxp
SAVVY	‘sævi	super	fella	soder	floon	sxfjq	fbzls
BURGLE	‘bɜgəl	bonnet	tinker	basber	fivish	bdvnmz	fpwqzs
CACKLE	‘kækəl	coffin	muster	cobeen	hennet	czvbtr	njmhvz
CASHEW	‘kæʃu	collar	horror	cullur	middor	cflxzv	fzdprz
CRANNY	‘kræni	cattle	burden	cuckon	sonter	cswrmq	sxzkzf
FRESCO	‘freskoʊ	fabric	napkin	flagot	gambel	fqmlpb	dldbqm
FROLIC	‘frɒlık	fiscal	parent	fimpad	mascon	fdxkjq	njnqrk
GOGGLE	‘gɒgəl	garlic	dainty	gaddit	pimper	gkbxzs	tjfbrv
FACILE	‘fæsaıl	finger	beacon	ferrom	beroof	fbxkrv	pbrxkv
SKILLET	‘skılıt	sparkle	hostile	spabble	garrand	szdbprk	dqrbdzn
PILLAGE	‘pılıdʒ	partner	turmoil	prooser	flussom	pzvtbmq	tlmhxns
GLIMMER	‘glımə	garnish	message	garbock	tartack	gcpsrhz	hpnrbmq
PUDGY	‘pʌdʒi	prawn	meter	petto	teper	pvrvz	lkmxh
COMBO	‘kəmboʊ	candy	salon	cadin	lafit	cxspt	pdqvp
MUSSEL	‘mʌsəl	manage	homage	mallod	grimmy	mrbxvf	rlnvrb
SMUGGLE	‘smʌgəl	sponsor	cricket	spacket	forsund	sjbmvrq	tdvwlzc
PERISH	‘perıʃ	paddle	wizard	potten	daggle	pqbmfd	mrvpnb
MANGO	‘mæŋgoʊ	melon	solid	meriz	vimel	mjszf	rvqwt
DINGO	‘dıŋgoʊ	devil	salad	doldy	pasby	dmrjz	wlsxs
FEEBLE	‘fibəl	format	socket	flinny	durish	fhdwpq	djwfdq
CRETIN	‘kretın	cancel	humble	clanab	pendry	cspmqz	vnknkx
STINGY	‘stındʒi	symbol	pencil	sandit	bedrop	sxsvcr	vlgzws
HICCUP	‘hıkʌp	hunger	garden	hoddle	lomper	hzdprx	blfxmn
PEDDLE	‘pedəl	parish	cancer	pammit	flanny	pzslhk	rjshrb
MUZZLE	‘mʌzəl	master	wonder	mecter	febush	mrrqkb	vghsfk
STUTTER	‘stʌtə	session	cabbage	sirning	corrill	szqrnpz	wgnmblq
FRITTER	‘frıtə	fashion	garbage	furdall	dessoll	fmsdkgj	szpqmkc
STAMMER	‘stæmə	sausage	morning	saffill	dodding	sxrtbpq	brvwldb
CODDLE	‘kɒdəl	clever	nephew	clerry	hurrit	cdfpsz	rjqzsb
LIMBER	‘lımbə	lesson	hazard	loogaf	cartle	lpqlnc	hgnvzd
GOBBLE	‘gɒbəl	gadget	clergy	gassit	narrim	gdfhbk	rlvmqx
GARISH	‘gɑrıʃ	giggle	bottom	grooky	loback	gbhjrz	wtbzlb
NIFTY	‘nıfti	novel	camel	natle	rosol	ndhrw	lqjkr
TEPID	‘tepıd	tango	model	tagle	bosan	tbtnq	rnftm
TALON	‘tælən	tempo	visit	tovid	gonty	tvqkx	mpsbf
MANGLE	‘mæŋgəl	moment	helmet	medlin	proody	mftspx	rvvpjb

SORDID	‘sɔdɪd	sturdy	nation	sumble	natath	sbkqlp	lqmzvf
RODENT	‘roʊdənt	random	picnic	rample	mactel	rvwklz	msxjfb
PIDGIN	‘pɪdʒɪn	pebble	marvel	pelker	mososs	psbfmr	rsnblf

Appendix G. CDP++ pronunciations and RTs (in cycles) per item at a prime duration of 25 cycles (Experiment 3). RTs of erroneous pronunciations have been removed.

Targets		Prime types					
		Words		Pronounceable nonwords		Unpronounceable nonwords	
		Onset related	Unrelated	Onset related	Unrelated	Onset related	Unrelated
BANISH	‘b{nIS	78	81	78	81	78	81
BOBBIN	‘bQbIn	87	89	87	89	87	89
FERMENT	‘f3mEnt	87	91	87	89	87	89
BELLOW	‘bEl5	79	82	79	82	80	82
BODIED	‘bQdId	121	122	121	122	121	122
BECKON	‘bEk@n	79	82	79	82	79	82
CARPAL	‘k#p@l	93	95	93	94	93	95
GAMBIT	‘g{mbIt	74	77	74	77	75	76
BIGOT	‘bIg@t	89	94	89	94	89	94
CLOVER	‘kl5v@	76	79	76	78	77	79
FLOOZY	‘fluzI	89	92	89	91	89	91
TATTLE	‘t{t@l	90	92	90	92	90	92
BAFFLE	‘b{f@l	82	85	82	87	82	85
TOGGLE	‘tQg@l	93	95	93	95	93	95
DOGMA	‘dQgm@	74	77	74	77	74	77
FELON	‘fEl@n	79	81	79	82	79	81
HENNA	‘hEn@	82	85	82	87	82	86
LIVID	‘lIvId	74	77	74	77	74	76
MAGMA	‘m{gm@	83	87	83	88	84	86
MIMIC	‘mImIk	74	75	74	76	74	75
MUTTER	‘mVt@	75	78	75	78	75	77
PESKY	‘pEskI	110	112	110	112	110	112
SURLY	‘s3lI	76	76	75	77	75	77
TARRY	‘t#rI[12]		70		70		70
TIMID	‘tImId	70	73	70	73	70	72
DAMASK	‘d{m@sk	81	84	81	84	81	84
DOLLOP	‘dQl@p	87	91	88	90	87	90
GAGGLE	‘g{g@l	86	87	86	88	85	88
HIPPIE	‘hIpI	72	75	72	76	72	76
HERMIT	‘h3mIt	81	84	81	85	81	85
JIGGLE	‘_Ig@l	84	87	84	87	85	87
LOCKET	‘lQkIt	88	91	88	91	88	91
MAGGOT	‘m{g@t	83	86	83	87	83	87
MUSKET	‘mVskIt	99	101	100	102	99	101
NUGGET	‘nVgIt	88	89	88	89	88	89
PAMPER	‘p{mp@	94	99	94	98	94	98
PANTRY	‘p{ntrI	95	89	86	89	86	89
PONCHO	‘pQnJ5	85	86	84	86	84	89
MIDGET	‘mI_It	82	84	82	84	82	84
PONDER	‘pQnd@	76	78	75	78	75	79
ROSTER	‘rQst@	81	83	81	83	81	83
RIDDLE	‘rId@l	79	81	79	81	79	82

[12] This item was errouneously pronounced as /‘t{rI/ in the onset-related condition.

RIPPLE	‘rIp@l	79	81	79	82	78	84
RENDER	‘rEnd@	75	77	75	78	75	78
RADISH	‘r{dIS	84	86	84	86	84	86
SERMON	‘s3m@n	77	79	77	79	77	79
SNAZZY	‘sn{zI	88	90	88	90	88	90
SIZZLE	‘sIz@l	87	89	87	89	87	89
TENDON	‘tEnd@n	77	79	77	80	77	79
TODDLE	‘tQd@l	86	88	86	88	86	88
TUSSLE	‘tVs@l	87	89	86	89	87	88
CRIPPLE	‘krIp@l	84	87	84	86	84	87
PLACID	‘pl{sId	76	79	77	79	76	80
RAVAGE	‘r{vI_	86	89	86	89	86	89
BEATNIK	‘bitnIk	88	90	88	90	88	90
BLEMISH	‘blEmIS	84	87	84	87	84	87
PIGMENT	‘pIgm@nt	83	86	83	86	83	86
SEGMENT	‘sEgm@nt	99	99	98	99	98	99
BELFRY	‘bElfrI	82	84	82	84	82	85
PLATTER	‘pl{t@	80	83	80	83	80	83
SAUNA	‘s$n@	82	84	82	84	82	85
PIVOT	‘pIv@t	79	84	79	83	79	84
BISTRO	‘bistr5	107	109	107	106	107	109
WAVER	‘w1v@	74	78	74	78	75	77
CANDID	‘k{ndId	79	81	79	82	79	81
SUPPLE	‘sVp@l	79	81	79	80	78	81
FIGMENT	‘fIgm@nt	87	91	87	89	87	90
CULPRIT	‘kVlprIt	88	90	89	90	88	90
DWINDLE	‘dwInd@l	86	88	85	88	85	88
HACKSAW	‘h{ks$	90	93	90	93	90	93
VISTA	‘vIst@	74	76	74	76	74	76
CRONY	‘kr5nI	91	92	91	92	90	92
DAZZLE	‘d{z@l	79	81	79	81	78	81
COBBLE	‘kQb@l	87	89	87	89	87	89
VANDAL	‘v{nd@l	85	86	85	87	85	86
TALLOW	‘t{l5	79	81	79	81	79	81
WAGGLE	‘w{g@l	90	92	90	91	90	93
POODLE	‘pud@l	84	89	84	87	84	89
SANDAL	‘s{nd@l	80	82	80	82	80	83
CAMBER	‘k{mb@	88	89	88	90	88	90
NETTLE	‘nEt@l	81	84	83	84	83	84
PALLID	‘p{lId	79	81	79	81	79	82
SONNET	‘sQnIt	83	85	83	85	83	85
PUNDIT	‘pVndIt	88	90	88	93	88	90
CUTLET	‘kVtlIt	100	101	100	101	100	101
FETISH	‘fEtIS	81	84	81	85	81	84
TWIDDLE	‘twId@l	90	91	89	91	88	91
TRINKET	‘trINkIt	102	104	102	103	102	104
TREMOR	‘trEm@	74	77	74	77	74	77
TERMITE	‘t3m2t	96	97	96	98	97	98
CREVICE	‘krEvIs	88	89	88	90	88	89
FLICKER	‘flIk@	77	81	77	81	77	80
FURNISH	‘f3nIS	86	88	86	89	86	88
PELLET	‘pElIt	84	87	84	87	84	87
PECTIN	‘pEktIn	92	94	92	95	92	95

PELVIC	‘pElvIk	77	79	76	79	76	79
SODDEN	‘sQd@n	79	82	79	81	79	81
ZENITH	‘zEnIT	82	84	82	84	82	84
DRIBBLE	‘drIb@l	85	88	85	89	85	88
TRICKLE	‘trIk@l	82	83	81	83	80	83
GROTTO	‘grQt5	82	84	82	84	82	84
HUDDLE	‘hVd@l	81	83	80	83	80	82
HINDER	‘hInd@	76	79	76	78	76	79
GOODIE	‘gUdI	90	91	90	92	89	90
MORBID	‘m$bId	78	80	78	80	79	80
MEDDLE	‘mEd@l	81	84	81	83	82	83
BONNY	‘bQnI	78	81	78	81	78	81
SERPENT	‘s3p@nt	85	86	85	86	85	86
PRICKLE	‘prIk@l	89	91	89	91	88	90
TOOTLE	‘tut@l	93	95	92	94	93	95
HOOKY	‘hUkI	86	89	86	88	86	88
SAVVY	‘s{vI	84	86	84	86	84	86
BURGLE	‘b3g@l	89	91	89	91	89	91
CACKLE	‘k{k@l	85	86	85	86	84	87
CASHEW	‘k{Su	86	88	86	88	86	89
CRANNY	‘kr{nI	85	86	84	87	85	87
FRESCO	‘frEsk5	92	94	92	94	91	93
FROLIC	‘frQlIk	85	87	84	87	84	87
GOGGLE	‘gQg@l	86	88	86	88	86	88
FACILE	‘f{s2l	81	83	81	84	81	84
SKILLET	‘skIlIt	95	97	95	98	95	97
PILLAGE	‘pIlI_	87	89	87	90	87	89
GLIMMER	‘glIm@	81	84	81	84	82	84
PUDGY	‘pV_I	79	81	79	81	79	81
COMBO	‘kQmb5	85	86	84	89	84	86
MUSSEL	‘mVs@l	85	87	85	86	85	86
SMUGGLE	‘smVg@l	87	88	87	89	87	89
PERISH	‘pErIS	76	79	77	79	76	79
MANGO	‘m{Ng5	79	81	79	81	79	81
DINGO	‘dINg5	82	85	82	85	82	85
FEEBLE	‘fib@l	75	78	75	77	75	77
CRETIN	‘krEtIn	87	88	87	88	87	89
STINGY	‘stIn_I	90	92	90	92	90	93
HICCUP	‘hIkVp	84	86	84	86	84	86
PEDDLE	‘pEd@l	80	83	80	83	80	91
MUZZLE	‘mVz@l	80	83	80	82	80	82
STUTTER	‘stVt@	83	85	83	85	83	85
FRITTER	‘frIt@	87	90	87	89	87	89
STAMMER	‘st{m@	82	84	82	84	82	84
CODDLE	‘kQd@l	89	91	89	90	89	90
LIMBER	‘lImb@	82	84	82	88	82	85
GOBBLE	‘gQb@l	84	86	83	85	83	85
GARISH	‘g8rIS	83	85	84	85	83	86
NIFTY	‘nIftI	111	112	111	111	112	111
TEPID	‘tEpId	73	75	73	75	73	75
TALON	‘t{l@n	85	88	85	87	84	88
MANGLE	‘m{Ng@l	85	85	83	85	83	85
SORDID	‘s$dId	79	81	79	81	79	81

RODENT	‘r5d@nt	84	89	84	86	84	86
PIDGIN	‘pI_In	86	88	86	89	86	91