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Masked Primes Activate Feature Representations in Reading Aloud

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Theories of reading aloud are silent about the role of subphonemic/subsegmental representations in translating print to sound. However, there is empirical evidence suggesting that feature representations are activated in speech production and visual word recognition. In the present study, we sought to determine whether masked primes activate feature representations in reading aloud using a variation of the masked onset priming effect (MOPE). We found that target nonwords (e.g., BAF) were read aloud faster when preceded by masked nonword primes that shared their initial phoneme with the target (e.g., *bez*), or primes whose initial phoneme shared all features except voicing with the first phoneme of the target (e.g., *piz*), compared with unrelated primes (e.g., *suz*). We obtained the same result in 2 experiments that used different participants and prime durations (around 60 ms in Experiment 1 and 50 ms in Experiment 2). The significant masked feature priming effect that was observed in both experiments converges with the empirical evidence in the speech production and visual word recognition domains indicating a functional role for features in reading aloud. Our findings motivate the further development of current theories of reading aloud and have important implications for extant theories of speech production.

Keywords: reading aloud, speech production, feature representations, masked priming

The idea that individual speech sounds (phonemes) are composite entities made up of features was first advanced by Alexander Melville Bell in 1867. In his book *Visible Speech*, Bell introduced a phonetic alphabet wherein the symbols corresponding to speech sounds graphically represented the activities of the articulatory organs involved in speech production. The role of features in speech production has since been evidenced primarily by analyses of speech errors (e.g., Dell, 1986; Fromkin, 1971; Levitt & Healy, 1985): in "glear plue sky" for "clear blue sky," for example, the voicing feature of /k/ (i.e., [−voice]) and /b/ (i.e., [+voice]) are reversed. Further, some experimental studies have supported the idea that features influence speech production using a variety of paradigms and measures (McMillan & Corley, 2010; Meyer & Gordon, 1985; Rogers & Storkel, 1998; Roon & Gafos, 2014). For example, using a combination of acoustic and articulatory measures in a tongue-twister paradigm, McMillan and Corley (2010) observed that competing phonemes that differed by a single feature, either voicing (e.g., *kef gef gef kef*) or place of articulation (e.g., *kef tef tef kef*), yielded more articulatory variability than control sequences (e.g., *kef kef kef kef*). Such variability was not observed when the competing phonemes differed by more than one feature (e.g., *kef def def kef*). Additionally, Roon and Gafos (2014) found that speakers were faster in producing syllables that shared all features except voicing with an auditory distractor (e.g., *pa-ba*) than when the syllable to be produced and the distractor differed by two features (e.g., *pa-da*). These results suggest that feature representations must be activated during the speech planning process. However, some researchers claim that unambiguous single-feature speech errors occur rarely (see Shattuck–Hufnagel & Klatt, 1979; Stemberger, 1991). Further, in a picture-naming task that used the form-preparation paradigm, Roelofs (1999) found no influence of features on the preparation of a speech response: when the names of pictures in a block of trials shared their initial phoneme (e.g., *book*, *bear*), participants named the pictures faster relative to blocks of trials where the picture names had unrelated initial phonemes (e.g., *file*, *kite*). Yet, a naming advantage was not observed when the picture names in a block consisted of initial phonemes that

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shared features (e.g., *book*, *pear*).[1] These results are inconsistent with the idea that feature representations are activated during speech planning. Accordingly, while some theories of speech production assign a critical role to features (e.g., Dell, 1986; Dell, Juliano, & Govindjee, 1993), others posit that features are "chunked" into segments and therefore cannot be independently manipulated during the planning of an utterance (e.g., Levelt, Roelofs, & Meyer, 1999; Roelofs, 1997, 1999).

Some empirical evidence for independent activation of feature representations has also been obtained in the domain of visual word recognition (Ashby, Sanders, & Kingston, 2009; Lukatela, Eaton, Lee, & Turvey, 2001; Lukatela, Eaton, Sabadini, & Turvey, 2004). Using a masked priming paradigm in a lexical-decision task, Lukatela et al. (2001) found that target words such as *sea*, *film*, and *basic* were responded to faster when preceded by masked nonword primes that shared all features except voicing with their targets in initial position (ZEA, VILM, PASIC), compared with control masked nonword primes (VEA, JILM, SASIC). Additionally, in a series of lexical decision experiments, Lukatela et al. (2004) observed that target words with voiced final consonants, such as *plead*, were responded to more slowly than matched words with voiceless final consonants, such as *pleat* (see also Abramson & Goldinger, 1997). When spoken, words with voiced final consonants have a longer vowel and are overall longer in duration than words with voiceless final consonants. Thus, the explanation that Lukatela et al. (2004) offered for their finding was that feature representations must be accessed during lexical access, and as a result, they influence visual word recognition.[2] Furthermore, using a masked priming paradigm in silent reading, Ashby et al. (2009) found that early in processing, the brain potentials of skilled readers were more negative when the target word *fat* was preceded by a nonword prime whose last phoneme differed in voicing from the last phoneme of the target (e.g., *faz*), compared with when prime and target consisted of a last phoneme with similar voicing (e.g., *fak*–*fat*). The early onset of this effect led the authors to conclude that skilled readers must activate feature representations. Models of visual word recognition that do not assume representations for features (e.g., Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001) cannot accommodate these findings.

If feature representations influence speech production and visual word recognition we would also expect that they influence reading aloud. In the present study we investigated this issue using a variation of the masked onset priming effect (MOPE). The MOPE refers to the finding that target reading aloud is faster when targets (e.g., BAF) are preceded by briefly presented onset-related masked primes (e.g., ***b**ez*), compared to unrelated masked primes (e.g., ***s**uz*). This empirical phenomenon is thought to occur because unconscious processing of the first phoneme (at least) of the prime exerts 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 (e.g., Forster & Davis, 1991; Mousikou, Coltheart, Finkbeiner, & Saunders, 2010a). Accordingly, we hypothesized that if feature representations are activated in reading aloud, prime-target pairs that share all of their features except voicing in the onset (e.g., *piz*–BAF) should yield faster target reading aloud latencies than unrelated prime-target pairs (e.g., *suz*–BAF).

In the present article, we use the term *features* to refer to mental representations with articulatory and/or acoustic correlates that distinguish allophones of one phoneme (e.g., /b/) from allophones of another (e.g., /p/). The relevant correlates of the voicing feature, for example, include voice–onset time (VOT), extent of first-formant transitions, magnitude of aspiration, and so forth, which characterize voiced and voiceless consonants in initial syllable position in English (Lisker & Abramson, 1964; Stevens & Klatt, 1974). Although several types of subphonemic/subsegmental representations have been proposed in the literature (e.g., *distinctive features* as described by Chomsky & Halle, 1968, or *articulatory gestures* as described by Browman & Goldstein, 1989), our study does not allow us to adjudicate between the alternative possibilities.

Yet, our study has important implications for extant theories of reading aloud (e.g., Coltheart et al., 2001; Perry, Ziegler, & Zorzi, 2007, 2010; Plaut, McClelland, Seidenberg, & Patterson, 1996) insofar as none of them postulates any type of subphonemic/subsegmental representations in the process of translating print to sound. Furthermore, our study provides converging empirical evidence from a reading-aloud task for the role of features in speech production. Although reading aloud and speech production have been traditionally treated as separate disciplines, the process of initiating a verbal response is common to both. Hence, if the activation of feature representations influences the initiation of articulation in reading aloud, it must also influence the same process in speech production. Given the inconsistency of the findings in the speech-production domain (see Roelofs, 1999), this additional empirical evidence from the closely related area of reading aloud is critical for determining whether feature representations are activated during speech planning.

Finally, it is worth noting that most theories of speech production and reading aloud assume that there are separate levels for phonemic and articulatory processing. As such, an ongoing debate in the literature concerns the nature of information flow between these two levels. According to the staged approach (e.g., Levelt et al., 1999), a unique phonological code must be selected before articulation can begin. According to the cascaded approach (e.g., Kello & Plaut, 2000), articulatory processes can be initiated on the basis of a partially activated phonological code. The present study sheds light on this debate: if masked primes activate feature representations in reading aloud, our result would be consistent with the cascaded view.

[1] Although this experiment was carried out in Dutch, the English words provided as examples here are equivalent to the Dutch words used in the experiment. Damian and Bowers (2003) found that the naming advantage in the form–preparation paradigm is disrupted by orthographic dissimilarities between the items (e.g., *camel* and *kidney* showed no naming advantage despite of sharing their initial phoneme). Thus, the absence of a naming advantage for pictures whose names consist of initial phonemes with shared features (e.g., *book* and *pear*) could be due to conflicting orthographic representations, not to the absence of a feature similarity effect.

[2] It is worth pointing out that Lukatela et al. (2004) carried out the same experiment using a reading-aloud task. However, the effect in reading aloud was much weaker than in lexical decision. The authors suggested that this could be because, in contrast to the lexical decision task, the reading-aloud task does not require access to the lexical representation of the target word in order to read it aloud. Hence, if the vowel-length effect originates at the level of lexical representations, and reading aloud engages these representations to a lesser degree than lexical decision, then the effect in reading aloud should be less pronounced than in lexical decision.

The MOPE (*bez*–BAF < *suz*–BAF) has been typically reported in the literature at prime durations of around 50 ms (e.g., Kinoshita, 2003; Mousikou, Coltheart, Saunders, & Yen, 2010c; Schiller, 2004). To maximize our chances of obtaining the more subtle feature priming effect (*piz*–BAF < *suz*–BAF), in Experiment 1 we used a prime duration of around 60 ms, which according to the orthographic masked priming literature is the longest prime duration that can be used before participants become aware of the presence of the primes (Forster & Davis, 1984; Forster, Davis, Schoknecht, & Carter, 1987).

Experiment 1

Method

Participants. Twenty-four undergraduate students from Royal Holloway, University of London were paid £5 to participate in the study. Participants were monolingual native speakers of southern British English and reported no visual, reading, or language difficulties.

Materials. Seventy-eight nonwords with a consonant–vowel–consonant (CVC) graphemic and phonological structure served as target items. Another 234 nonwords with the same characteristics served as onset related, feature related, and unrelated primes. All items were extracted from the ARC Nonword Database (Rastle, Harrington, & Coltheart, 2002) and consisted of three letters and three phonemes each. The three types of primes were matched on a number of psycholinguistic variables that are listed in Table 1.

Three groups of 78 prime–target pairs were formed, with each group corresponding to a different experimental condition: onset related, feature related, and unrelated. The targets remained the same in all three conditions. In the onset-related condition, primes and targets shared only their first letter and phoneme (e.g., *bez*–BAF). In the feature-related condition, primes and targets had no letters or phonemes in common but consisted of initial phonemes that shared all of their features except voicing (e.g., *piz*–BAF). In the unrelated condition, primes and targets shared no letters/phonemes in the same position. Also, their initial phonemes did not share any of the features manipulated in our study (e.g., *suz*–BAF). In order to further match the three types of primes on orthographic and phonological dimensions, all prime trios that corresponded to a target shared their last letter/phoneme (*bez*/*piz*/*suz*–BAF). Furthermore, we quantified the relative phonological similarity among the three types of primes and their corresponding targets by calculating phoneme similarity scores. The procedure that we followed to calculate these scores, a matrix that contains them, and the experimental stimuli that we used are provided in the Appendix. The average similarity scores (see Table 2 and Appendix) indicated that the three types of primes were phonologically similar in all phoneme positions but the first, which forms the experimental manipulation of interest in our experiment ($p < .001$ for first position and $p > .05$ for second and third positions). In addition to the 234 prime–target pairs that formed the experimental stimuli, six pairs of primes and targets that matched the experimental stimuli on the same criteria were selected as practice items.

The subtlety of feature similarity relations requires the use of a significant number of items to increase experimental power. Because of the constraints we had in matching the three types of primes on a number of psycholinguistic variables that are known to affect reading aloud latencies and to avoid the influence of lexical variables on the subtle effects under investigation, we opted for using nonwords in our experiment. We considered this choice to be optimal as the analysis of nonword reading performance has significantly increased our understanding of the processes underlying word reading (Andrews & Scarratt, 1998; Besner, Twilley, McCann, & Seergobin, 1990; Pritchard, Coltheart, Palethorpe, & Castles, 2012). Furthermore, nonwords do not have lexical representations. On the assumption that the orthographic characteristics of letter strings that do not have lexical representations are less prominent than those that do (i.e., words), it is less likely that the orthographic dissimilarities between feature-related nonword primes and nonword targets would attenuate any feature similarity effects (as it was suggested to be the case in the Roelofs' 1999 study).

Design. Each experimental condition consisted of 78 prime–target pairs for a total of 234 trials per participant in a fully counterbalanced design. This meant that every participant saw the 78 targets three times, each time preceded by a different type of prime. The 234 trials were divided into three blocks so that the

Table 1
Mean Values of Psycholinguistic Variables for Each Prime Type and Statistics for the ANOVAs of Prime Type Comparisons for Each Variable

	Prime types				
Psycholinguistic variables	Onset related	Feature related	Unrelated	*F*	*p*
NN	8.97	10.01	9.00	1.233	.293
SFN	1148.77	1459.45	1723.80	0.866	.422
NBN	5.77	7.74	6.44	1.745	.177
SFBN	1797.24	2778.38	1618.40	1.056	.349
NBF	5.21	6.99	5.97	1.324	.268
NBE	0.56	0.76	0.46	1.012	.365
SFBF	573.94	965.92	889.60	1.199	.303
SFBE	1223.31	1812.46	728.79	0.923	.399
NON	473.31	463.82	348.97	2.575	.078
SFON	27236.27	26634.32	25587.55	0.041	.960
NPN	18.29	18.74	20.06	1.069	.345
SFPN	2810.00	2595.45	3813.18	2.305	.102
BFNC	167.37	163.35	209.18	1.213	.299
BFNT	135437.18	160984.60	218006.05	2.269	.106
TFNC	1.99	1.56	4.27	1.289	.278
TFNT	493.37	1032.13	1256.15	1.219	.298
BFSC	8.05	9.35	8.08	2.445	.089
BFST	20205.05	25749.35	25732.45	0.362	.697
TFSC	0	0	0		
TFST	0	0	0		

Note. ANOVAs = analyses of variance; NN = no. of neighbors (*N*); SFN = summed frequency of neighbors; NBN =no. of body neighbors; SFBN = summed frequency of body neighbors; NBF = no. of body friends; NBE = No. of body enemies; SFBF = summed frequency of body friends; SFBE = summed frequency of body enemies; NON = no. of onset neighbors; SFON = summed frequency of onset neighbors; NPN = no. of phonological neighbors; SFPN = summed frequency of phonological neighbors; BFNC = bigram frequency (position nonspecific)–type; BFNT = bigram frequency (position nonspecific)–token; TFNC = trigram frequency (position nonspecific)–type; TFNT = trigram frequency (position nonspecific)–token; BFSC = bigram frequency (position specific)–type; BFST = bigram frequency (position specific)–token; TFSC = trigram frequency (position specific)–type; TFST = trigram frequency (position specific)–token.

Table 2
Average Phoneme Similarity Scores for Experimental Prime–Target Pairs

Prime type	Prime–target phoneme similarity by position			Similarity prime 1st phoneme with target 3rd phoneme	Overall prime–target similarity by position	Overall prime–target similarity independent of position
	1st	2nd	3rd			
Onset related	1.00	0.54	0.28	0.35	0.60	0.54
Feature related	0.67	0.46	0.28	0.35	0.47	0.44
Unrelated	0.00	0.51	0.28	0.33	0.26	0.28

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 52 trials intervened before the same target could reappear. Three lists (A, B, C) were constructed to counterbalance the order of block presentation, so if *bez*–BAF appeared in the first block in List A, it would appear in the second block in List B and in the third block in List C. An equal number of participants ($N = 8$) were tested on each list.

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 nonwords presented in uppercase letters and that they had to read aloud the nonwords as quickly 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 500.6 ms. The prime was then presented in lowercase letters for 58.8 ms (five ticks based on the monitor's refresh rate of 11.76 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 2,000 ms or until participants responded, whichever happened first. 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). Any phoneme mispronunciations (4.1% of the data) were treated as errors and discarded. To control for temporal dependencies between successive trials (Taylor & Lupker, 2001), we took reaction time (RT) of the previous trial and trial order into account in the analyses, so trials whose previous trial corresponded to an error and participants' first trial in each block (5.2% of the data) were excluded from the analyses. Extreme outliers were also identified for each participant and removed (16 observations).

The RT analyses were performed using linear mixed effects modeling (Baayen, 2008; Baayen, Davidson, & Bates, 2008). A linear mixed-effects model using the lme4 Version 1.0–5 (Bates, Maechler, Bolker, & Walker, 2013) and languageR packages (Baayen, 2008) implemented in R Version 3.0.2—"Frisbee sailing" (R Core Team, 2013) was created using a backward stepwise model selection procedure. Model comparison was performed using chi-square log-likelihood ratio tests with maximum likelihood.

The logarithmic transformation proved to be optimal according to the Box–Cox procedure; hence, the model we report included logRT as the dependent variable, and prime type (onset related vs. feature related vs. unrelated), 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 type to remove the assumption that all participants showed the same amount of priming: logRT $\sim$ prime type $+$ PrevRT $+$ trial order $+$ (1 $+$ prime type$|$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). Target reading-aloud latencies were significantly faster in the onset-related condition than in the unrelated condition, $t = -8.409$, $p < .001$, indicating a MOPE. Target reading-aloud latencies were also faster in the feature-related condition than in the unrelated condition, $t = -3.671$, $p = .001$, indicating a masked feature priming effect. To determine whether the difference between the onset-related and feature-related conditions was significant, we retested the model with the prime type factor re-leveled to have the feature-related condition as the reference. The results indicated faster reading-aloud latencies in the onset-related condition than in the feature-related condition, $t = -8.684$, $p < .001$.

The error analysis was performed using a logit mixed model (Jaeger, 2008) with prime type as a fixed effect and intercepts for subjects and items as random effects. Both the feature and the unrelated conditions yielded significantly more errors than the onset-related condition ($z = 3.851$, $p < .001$ and $z = 3.340$, $p < .001$, respectively). Mean RTs for each condition (calculated from a total of 4,981 observations), and percentage of errors (based on the total number of trials in each condition), are presented in Table 3. The output of the main model (RT data) with the unrelated condition as the reference is shown in Table 4.[3]

Discussion

To maximize our chances of obtaining a masked feature priming effect in Experiment 1, we used a prime duration of around 60 ms. According to the literature in the orthographic masked priming domain, this is the longest prime duration that can be used before participants become aware of the presence of the primes. We found

[3] To estimate denominator degrees of freedom and *p* values of the fixed effects we used Satterthwaite's approximation, implemented in the R package lmerTest (Kuznetsova, Brockhoff, & Christensen, 2013).

Table 3
Mean Reading-Aloud Latencies (and SDs) and Percentage of Error Rates in Experiments 1 and 2

Condition	Experiment 1 RTs	(*SD*s)	%E	Experiment 2 RTs	(*SD*s)	%E	Examples
Onset related	482	(74)	2.6	458	(58)	1.7	*bez*–BAF
Feature related	500	(75)	5.0	474	(59)	2.7	*piz*–BAF
Unrelated	509	(68)	4.6	484	(60)	2.7	*suz*–BAF
Onset effect	27			26			
Feature effect	9			10			

Note. Reaction times (RTs) are in milliseconds. Prime duration for Experiment 1 = 58.8 ms; prime duration for Experiment 2 = 50 ms. %E = percentage of error rates.

a robust MOPE of 27 ms and a significant masked feature priming effect of 9 ms, which indicates that features must play a functional role in reading aloud. Thus, our results are consistent with the empirical evidence obtained in the speech production and visual word recognition domains. In Experiment 2, we sought to replicate the results from Experiment 1 using a prime duration that is most typically used in the masked onset priming literature, namely, 50 ms.

Experiment 2

Method

Participants. Twenty-four new participants recruited from the same population and with the same characteristics as those in Experiment 1 participated in Experiment 2.

Materials and design. The same materials and design as in Experiment 1 were used.

Apparatus and procedure. The same apparatus and procedure as in Experiment 1 were used; however, the primes in Experiment 2 were presented for 50 ms (three ticks based on the monitor's refresh rate of 16.67 ms). Each trial started with the presentation of a forward mask (###) that remained on the screen for 500 ms, followed by the prime presented in lowercase letters for 50 ms, followed by the target presented in uppercase letters for 2,000 ms or until participants responded, whichever happened first.

Results

The analyses in Experiment 2 were performed similarly as in Experiment 1. Participants' responses were hand marked using CheckVocal (Protopapas, 2007). Any phoneme mispronunciations (2.3% of the data) were treated as errors and discarded. Trials whose previous trial corresponded to an error and participants' first trial in each block (3.6% of the data) were excluded from the analyses. Extreme outliers were also identified for each participant and removed (11 observations).

The logarithmic transformation proved to be optimal according to the Box–Cox procedure; hence, the model we report included logRT as the dependent variable, and prime type (onset related vs. feature related vs. unrelated), 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 type: logRT $\sim$ prime type + PrevRT + trial order + (1 + prime type$|$subject) + (1$|$target). Outliers with a standardized residual greater than 2.5 standard deviations from zero were removed from the fitted model (2.2% of the data). The results mimicked those in Experiment 1 such that reading-aloud latencies were significantly faster in the onset-related condition than in the unrelated condition, $t = -15.327$, $p < .001$, indicating a MOPE. Similarly, reading-aloud latencies were significantly faster in the feature-related condition than in the unrelated condition, $t = -6.029$, $p < .001$, indicating a masked feature priming effect. To determine whether the difference between the onset-related and feature-related conditions was significant, we retested the model with the prime type factor re-leveled to have the feature-related condition as the reference. Target reading-aloud latencies were significantly faster in the onset-related condition than in the feature-related condition, $t = -6.503$, $p < .05$.

The error analysis was performed in the same way as in Experiment 1, with prime type as a fixed effect and intercepts for subjects and items as random effects. Both the feature and the unrelated conditions yielded significantly more errors than the onset-related condition ($z = 2.122$, $p = .034$ in both cases). Mean RTs for each condition (calculated from a total of 5,161 observations) and percentage of errors (based on the total number of trials in each condition), are presented in Table 3. The output of the main model (RT data) with the unrelated condition as the reference is shown in Table 4.

Discussion

Experiment 2 replicated Experiment 1: we obtained a robust MOPE of 26 ms and a significant MOPE of 10 ms. These results further establish that masked primes activate feature representations in reading aloud.

General Discussion

Two masked priming experiments using different prime durations were carried out to investigate the role of feature representations in reading aloud. We found faster target reading-aloud

Table 4
Models' Output for Experiments 1 and 2

Fixed effects	Estimate	*SE*	*df*	*t* value	*p* value
Experiment 1					
(Intercept)	6.041	0.018	107	344.872	$<0.001^{***}$
Onset related	−0.054	0.006	23	−8.409	$<0.001^{***}$
Feature related	−0.018	0.005	27	−3.671	0.001^{**}
PrevRT	<0.001	<0.001	4872	20.414	$<0.001^{***}$
Trial order	<−0.001	<0.001	4901	−14.116	$<0.001^{***}$
Experiment 2					
(Intercept)	5.968	0.016	121	374.901	$<0.001^{***}$
Onset related	−0.057	0.004	25	−15.327	$<0.001^{***}$
Feature related	−0.022	0.004	24	−6.029	$<0.001^{***}$
PrevRT	<0.001	<0.001	5064	20.664	$<0.001^{***}$
Trial order	<−0.001	<0.001	5054	−2.205	0.028^{*}

Note. *p* value; PrevRT = RT of previous trial.
Significance codes: * *p*-value between 0.01 and 0.05. ** *p*-value between 0.001 and 0.01. *** *p*-value between 0 and 0.001.

latencies when targets were preceded by masked primes with shared features in initial position (*piz*–BAF), compared with when primes and targets were unrelated to each other (*suz*–BAF), indicating a masked feature priming effect. These findings are consistent with the empirical evidence in the closely related areas of speech production and visual word recognition, indicating that feature representations are activated in the process of translating print to sound. As we noted in the introduction, several types of subphonemic/subsegmental representations have been proposed in the literature (e.g., distinctive features, articulatory gestures). Our data do not speak to the nature of these representations, so in principle, they are compatible with all alternative possibilities, yet their implications for theories of reading aloud and speech production are important, irrespective of the type of subphonemic/subsegmental representations assumed.

In the reading-aloud domain, for example, some of the most prominent theories (e.g., Coltheart et al., 2001; Perry, Ziegler, & Zorzi, 2007, 2010; Plaut, McClelland, Seidenberg, & Patterson, 1996) do not assume subphonemic/subsegmental representations. How could these theories be modified to explain the present findings? The dual route cascaded (DRC) model, for example, a computational implementation of the dual route theory of reading (Coltheart et al., 2001), is the only model that has offered an explicit account of a whole range of empirical phenomena around the MOPE (see Mousikou, Coltheart, & Saunders, 2010b). According to this model, the MOPE is due to the activation of the first phoneme of the prime during prime presentation, which exerts an influence (facilitatory or inhibitory) on the first phoneme of the target (see Mousikou, Coltheart, Finkbeiner, & Saunders, 2010a). On the basis of the present findings, this model would need to be further developed to include feature representations. One possibility is that when the prime is *piz*, its first phoneme (/p/) is activated at the phoneme level, which then activates its corresponding features at a subsequent level that includes feature representations. If the target starts with a phoneme that shares features with the first phoneme of the prime (e.g., BAF), savings in target processing lead to faster target reading-aloud latencies, compared with an unrelated condition where prime and target have no features in common in the first position (*suz*–BAF). In this explanation, the masked feature priming effect is assumed to be facilitatory. However, it could also be that when primes and targets have no features in common in the initial position (e.g., *suz*–BAF), competition between the incongruent features inhibit target reading aloud compared with that in a feature-congruent condition (*piz*–BAF). This explanation assumes that the masked feature priming effect is inhibitory. The effect could also be due to both facilitatory and inhibitory processes taking place (cf. Roon & Gafos, 2013). All three explanations are compatible with our findings.

Another possibility is that features are represented in the absence of phoneme representations. For example, it could be that the feature-related prime *piz* activates the features of [+stop], [+labial], and [−voice] (or the articulatory gestures of bilabial constriction and devoicing if our data allowed us to identify features with linguistically significant actions of the vocal tract) without activating the phonemic representation of /p/ (see Dell et al., 1993; Mowrey & MacKay, 1990). When the target BAF is presented, it has more features in common with the feature-related prime (e.g., [+stop], [+labial]) than with an unrelated prime (*suz*), and so BAF is read aloud faster in the feature-related condition than in the unrelated condition. Accordingly, if the effect is inhibitory, as explained earlier, the unrelated prime *suz* would activate the features [+coronal], [+fricative], and [−voice], which would compete with the features [+stop], [+labial], and [+voice] when the target BAF is presented, thus slowing down target reading aloud in the unrelated condition. Therefore, irrespective of the type of subphonemic/subsegmental representations assumed, extant theories of reading aloud would need to be modified to accommodate the present findings.

Similarly, speech production theories according to which features form properties of selected segments that cannot be independently activated during the planning of an utterance (e.g., Levelt et al., 1999; Roelofs, 1997) or theories that treat segments as the basic units in the absence of sufficient empirical evidence for a role of features in speech production (e.g., Bohland, Bullock, & Guenther, 2010) cannot accommodate the present findings. It is worth noting that our study involved nonword reading aloud, which is beyond the scope of these theories, yet initiating a verbal motor response is necessarily involved in producing speech. For this reason, we believe that our data are relevant to theories of speech production, supporting the idea that features play an independent role in the speech-planning process.

Finally, as we mentioned in the introduction, the vast majority of theories of speech production and reading aloud postulate that there are separate levels for phonemic and articulatory processing. On the basis of this assumption, there is an ongoing debate in the literature on the nature of information flow between these two levels. Some theories assume that information flows in a staged manner (e.g., Levelt et al., 1999), so that the preparation of a verbal motor response does not begin until a phonological code of a certain grain size has been selected for articulation. Yet, converging empirical evidence from reading-aloud and speech-production tasks (e.g., Goldrick & Blumstein, 2006; Kello & Plaut, 2000; Kello, Plaut, & MacWhinney, 2000) suggests that speech motor processes begin as soon as a phonological code has been partially activated, indicating that information between phonemic and articulatory levels of processing must flow in a cascaded manner. Our data showed that unselected letter strings (masked primes) influenced the preparation of a verbal motor response, thus contradicting the staged view in theories that assume separate levels for phonemic and articulatory processing in the speech-production and reading-aloud systems.

To summarize, although further work is required to determine whether our results generalize to features other than place and manner of articulation, the present findings converge with empirical evidence in the closely related domains of speech production and visual word recognition showing that some features at least are activated in reading aloud. Furthermore, on the assumption that there are separate levels for phonemic and articulatory processing, as most theories of speech production and reading aloud postulate, our data contribute to the debate on the nature of the relationship between these two levels supporting the idea that it is cascaded.

References

Abramson, M., & Goldinger, S. D. (1997). What the reader's eye tells the mind's ear: Silent reading activates inner speech. *Perception & Psychophysics, 59,* 1059–1068. http://dx.doi.org/10.3758/BF03205520

Andrews, S., & Scarratt, D. R. (1998). Rule and analogy mechanisms in reading nonwords: Hough dou peapel rede gnew wirds? *Journal of*

Experimental Psychology: Human Perception and Performance, 24, 1052–1086. http://dx.doi.org/10.1037/0096-1523.24.4.1052

Ashby, J., Sanders, L. D., & Kingston, J. (2009). Skilled readers begin processing sub-phonemic features by 80 msec during visual word recognition: Evidence from ERPs. *Biological Psychology, 80,* 84–94. http://dx.doi.org/10.1016/j.biopsycho.2008.03.009

Baayen, R. H. (2008). *Analyzing linguistic data: A practical introduction to statistics using R*. New York, NY: Cambridge University Press. http://dx.doi.org/10.1017/CBO9780511801686

Baayen, R. H., Davidson, D. J., & Bates, D. M. (2008). Mixed-effects modeling with crossed random effects for subjects and items. *Journal of Memory and Language, 59,* 390–412. http://dx.doi.org/10.1016/j.jml.2007.12.005

Bates, D., Maechler, M., Bolker, B., & Walker, S. (2013). lme4: Linear mixed–effects models using Eigen and S4. R package Version 1.0–5 [Computer software]. Retrieved from http://CRAN.R-project.org/package=lme4

Bell, A. M. (1867). *Visible speech: The science of universal alphabetics*. London, England: Simkin, Marshall, & Co.

Besner, D., Twilley, L., McCann, R. S., & Seergobin, K. (1990). On the association between connectionism and data: Are a few words necessary? *Psychological Review, 97,* 432–446. http://dx.doi.org/10.1037/0033-295X.97.3.432

Bohland, J. W., Bullock, D., & Guenther, F. H. (2010). Neural representations and mechanisms for the performance of simple speech sequences. *Journal of Cognitive Neuroscience, 22,* 1504–1529. http://dx.doi.org/10.1162/jocn.2009.21306

Browman, C. P., & Goldstein, L. M. (1989). Articulatory gestures as phonological units. *Phonology, 6,* 201–251. http://dx.doi.org/10.1017/S0952675700001019

Chomsky, N., & Halle, M. (1968). *The sound pattern of English*. New York, NY: Harper & Row.

Coltheart, M., Rastle, K., Perry, C., Langdon, R., & Ziegler, J. (2001). DRC: A dual route cascaded model of visual word recognition and reading aloud. *Psychological Review, 108,* 204–256. http://dx.doi.org/10.1037/0033-295X.108.1.204

Damian, M. F., & Bowers, J. S. (2003). Effects of orthography on speech production in a form–preparation paradigm. *Journal of Memory and Language, 49,* 119–132. http://dx.doi.org/10.1016/S0749-596X(03)00008-1

Dell, G. S. (1986). A spreading-activation theory of retrieval in sentence production. *Psychological Review, 93,* 283–321. http://dx.doi.org/10.1037/0033-295X.93.3.283

Dell, G. S., Juliano, C., & Govindjee, A. (1993). Structure and content in language production: A theory of frame constraints in phonological speech errors. *Cognitive Science, 17,* 149–195. http://dx.doi.org/10.1207/s15516709cog1702_1

Forster, K. I., & Davis, C. (1984). Repetition priming and frequency attenuation in lexical access. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 10,* 680–698. http://dx.doi.org/10.1037/0278-7393.10.4.680

Forster, K. I., & Davis, C. (1991). The density constraint on form–priming in the naming task: Interference effects from a masked prime. *Journal of Memory and Language, 30,* 1–25. http://dx.doi.org/10.1016/0749-596X(91)90008-8

Forster, K. I., Davis, C., Schoknecht, C., & Carter, R. (1987). Masked priming with graphemically related forms: Repetition or partial activation? *Quarterly Journal of Experimental Psychology, 39,* 211–251. http://dx.doi.org/10.1080/14640748708401785

Forster, K. I., & Forster, J. C. (2003). DMDX: A windows display program with millisecond accuracy. *Behavior Research Methods, Instruments, & Computers, 35,* 116–124. http://dx.doi.org/10.3758/BF03195503

Fromkin, V. A. (1971). The non-anomalous nature of anomalous utterances. *Language, 47,* 27–52. http://dx.doi.org/10.2307/412187

Goldrick, M., & Blumstein, S. E. (2006). Cascading activation from phonological planning to articulatory processes: Evidence from tongue twisters. *Language and Cognitive Processes, 21,* 649–683. http://dx.doi.org/10.1080/01690960500181332

International Phonetic Association. (1999). *Handbook of the International Phonetic Association: A guide to the use of the International Phonetic Alphabet*. New York, NY: Cambridge University Press.

Jaeger, T. F. (2008). Categorical data analysis: Away from ANOVAs (transformation or not) and toward logit mixed models. *Journal of Memory and Language, 59,* 434–446. http://dx.doi.org/10.1016/j.jml.2007.11.007

Kello, C. T., & Plaut, D. C. (2000). Strategic control in word reading: Evidence from speeded responding in the tempo-naming task. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 26,* 719–750. http://dx.doi.org/10.1037/0278-7393.26.3.719

Kello, C. T., Plaut, D. C., & MacWhinney, B. (2000). The task dependence of staged versus cascaded processing: An empirical and computational study of Stroop interference in speech production. *Journal of Experimental Psychology: General, 129,* 340–360. http://dx.doi.org/10.1037/0096-3445.129.3.340.

Kinoshita, S. (2003). The nature of masked onset priming effects in naming: A review. In S. Kinoshita & S. J. Lupker (Eds.), *Masked priming. The state of the art* (pp. 223–238). Hove, England: Psychology Press.

Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2013). lmerTest: Tests for random and fixed effects for linear mixed effect models (lmer objects of lme4 package). R package Version 2.0–3 [Computer software]. Retrieved from http://CRAN.R-project.org/package=lmerTest

Ladefoged, P., & Johnson, K. (2011). *A course in phonetics* (6th ed.). Boston, MA: Wadsworth Cengage Learning.

Levelt, W. J. M., Roelofs, A., & Meyer, A. S. (1999). A theory of lexical access in speech production. *Behavioral and Brain Sciences, 22,* 1–38. http://dx.doi.org/10.1017/S0140525X99001776

Levitt, A. G., & Healy, A. F. (1985). The roles of phoneme frequency, similarity, and availability in the experimental elicitation of speech errors. *Journal of Memory and Language, 24,* 717–733. http://dx.doi.org/10.1016/0749-596X(85)90055-5

Lisker, L., & Abramson, A. S. (1964). A cross–language study of voicing in initial stops: Acoustical measurements. *Word, 20,* 384–422.

Lukatela, G., Eaton, T., Lee, C., & Turvey, M. T. (2001). Does visual word identification involve a sub-phonemic level? *Cognition, 78,* 41–52. http://dx.doi.org/10.1016/S0010-0277(00)00121-9

Lukatela, G., Eaton, T., Sabadini, L., & Turvey, M. T. (2004). Vowel duration affects visual word identification: Evidence that the mediating phonology is phonetically informed. *Journal of Experimental Psychology: Human Perception and Performance, 30,* 151–162. http://dx.doi.org/10.1037/0096-1523.30.1.151

McMillan, C. T., & Corley, M. (2010). Cascading influences on the production of speech: Evidence from articulation. *Cognition, 117,* 243–260. http://dx.doi.org/10.1016/j.cognition.2010.08.019

Meyer, D. E., & Gordon, P. C. (1985). Speech production: Motor programming of phonetic features. *Journal of Memory and Language, 24,* 3–26. http://dx.doi.org/10.1016/0749-596X(85)90013-0

Mousikou, P., Coltheart, M., Finkbeiner, M., & Saunders, S. (2010a). Can the dual-route cascaded computational model of reading offer a valid account of the masked onset priming effect? *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 63,* 984–1003. http://dx.doi.org/10.1080/17470210903156586.

Mousikou, P., Coltheart, M., & Saunders, S. (2010b). Computational modelling of the masked onset priming effect in reading aloud. *European Journal of Cognitive Psychology, 22*[Special issue], 725–763. http://dx.doi.org/10.1080/09541440903052798

Mousikou, P., Coltheart, M., Saunders, S., & Yen, L. (2010c). Is the orthographic/phonological onset a single unit in reading aloud? *Journal* *of Experimental Psychology: Human Perception and Performance, 36,* 175–194. http://dx.doi.org/10.1037/a0015795

Mowrey, R. A., & MacKay, I. R. A. (1990). Phonological primitives: Electromyographic speech error evidence. *Journal of the Acoustical Society of America, 88,* 1299–1312. http://dx.doi.org/10.1121/1.399706

Perry, C., Ziegler, J. C., & Zorzi, M. (2007). Nested incremental modeling in the development of computational theories: The CDP+ model of reading aloud. *Psychological Review, 114,* 273–315. http://dx.doi.org/10.1037/0033-295X.114.2.273

Perry, C., Ziegler, J. C., & Zorzi, M. (2010). Beyond single syllables: Large-scale modeling of reading aloud with the connectionist dual process (CDP++) model. *Cognitive Psychology, 61,* 106–151. http://dx.doi.org/10.1016/j.cogpsych.2010.04.001

Plaut, D. C., McClelland, J. L., Seidenberg, M. S., & Patterson, K. (1996). Understanding normal and impaired word reading: Computational principles in quasi-regular domains. *Psychological Review, 103,* 56–115. http://dx.doi.org/10.1037/0033-295X.103.1.56

Pritchard, S. C., Coltheart, M., Palethorpe, S., & Castles, A. (2012). Nonword reading: Comparing dual-route cascaded and connectionist dual-process models with human data. *Journal of Experimental Psychology: Human Perception and Performance, 38,* 1268–1288. http://dx.doi.org/10.1037/a0026703

Protopapas, A. (2007). CheckVocal: A program to facilitate checking the accuracy and response time of vocal responses from DMDX. *Behavior Research Methods, 39,* 859–862. http://dx.doi.org/10.3758/BF03192979

Rastle, K., Harrington, J., & Coltheart, M. (2002). 358,534 nonwords: The ARC Nonword Database. *Quarterly Journal of Experimental Psychology, 55,* 1339–1362. http://dx.doi.org/10.1080/02724980244000099.

R Core Team. (2013). *R: A language and environment for statistical computing [Computer software].* Vienna, Austria: R Foundation for Statistical Computing.

Roelofs, A. (1997). The WEAVER model of word-form encoding in speech production. *Cognition, 64,* 249–284. http://dx.doi.org/10.1016/S0010-0277(97)00027-9

Roelofs, A. (1999). Phonological segments and features as planning units in speech production. *Language and Cognitive Processes, 14,* 173–200. http://dx.doi.org/10.1080/016909699386338

Rogers, M. A., & Storkel, H. L. (1998). Reprogramming phonologically similar utterances: The role of phonetic features in pre-motor encoding. *Journal of Speech, Language, and Hearing Research, 41,* 258–274. http://dx.doi.org/10.1044/jslhr.4102.258

Roon, K. D., & Gafos, A. I. (2013). A dynamical model of the speech perception–production link. In M. Knauff, M. Pauen, N. Sebanz, & I. Wachsmuth (Eds.), Proceedings of the 35th annual conference of the Cognitive Science Society (pp. 1241–1246). Austin, TX: Cognitive Science Society.

Roon, K. D., & Gafos, A. I. (2014). Perceptuo-motor effects of response-distractor compatibility in speech: Beyond phonemic identity. *Psychonomic Bulletin & Review,* Advance online publication.

Schiller, N. O. (2004). The onset effect in word naming. *Journal of Memory and Language, 50,* 477–490.

Shattuck-Hufnagel, S., & Klatt, D. H. (1979). The limited use of distinctive features and markedness in speech production: Evidence from speech error data. *Journal of Verbal Learning and Verbal Behavior, 18,* 41–55.

Stemberger, J. P. (1991). Radical underspecification in language production. *Phonology, 8,* 73–112. http://dx.doi.org/10.1017/S0952675700001287

Stevens, K. N., & Klatt, D. H. (1974). Role of formant transitions in the voiced–voiceless distinction for stops. *Journal of the Acoustical Society of America, 55,* 653–659. http://dx.doi.org/10.1121/1.1914578.

Taylor, T. E., & Lupker, S. J. (2001). Sequential effects in naming: A time–criterion account. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 27,* 117–138.

(*Appendix follows*)

Appendix

Procedure for Calculating Phoneme Similarity Scores Between Primes and Targets

Consonants were categorized on three contrastive dimensions: place of articulation (labial, coronal, dorsal, or glottal), manner of articulation (plosive, glide, fricative, lateral, or nasal), and voicing (either voiced or voiceless). Vowels were also categorized according to three contrastive dimensions: height (on a scale from closed to open), backness (either back or not back), and rounding (lips either rounded or unrounded). All features were treated as binary except vowel height, which was treated as a four-level scale, where /ɪ/ = 3, /o/ = 2, /ɛ, ʌ/ = 1, and /æ/ = 0 (International Phonetic Association, 1999; Ladefoged & Johnson, 2011). Thus, two vowels differing in height were rated as more similar if they were closer on the height dimension (e.g., open /æ/ vs. open–mid /ɛ/) than if they were further apart on that dimension (e.g., open /æ/ vs. closed /ɪ/). For each prime–target pair, the similarity between the phonemes in the same position (initial, middle, and final) was calculated by assigning 1 for each binary feature on which they matched and 0 for each binary feature on which they mismatched. For vowel height, the similarity for each pair was calculated as $(3 - [|\text{height}_{v1} - \text{height}_{v2}|])/3$ to ensure a similarity score between 0 and 1. These positional comparison values were summed and then divided by 3 (the number of features). For example, similarity scores for /b/ − /b/ = 1, /b/ − /p/ = 0.67, /b/ − /n/ = 0.33, /b/ − /s/ = 0, /æ/ − /ɪ/ = 0.67, and /o/ − /ɪ/ = 0.22. The similarity score between the first phoneme of the prime and third phoneme of the target was also similarly calculated. Using these phoneme similarity scores, we calculated target–prime positional similarity as the average of the three positional phoneme similarity scores, and overall similarity as the average of the three positional phoneme similarity scores plus the first through third scores.[4]

[4] We classified /w/ as labial even though it is also dorsal. This classification had minimal effect on the similarity scores since /w/ was only contained in the unrelated prime /wɛs/ which was paired up with the coronal–initial target /tɪv/. We opted for the more conservative classification of labial so that the /w/ would be scored as more similar to /v/ in the first through third comparison for this pair than if it had been labelled dorsal. It is also worth pointing out that two target items, BES and PES, were pronounced by our participants with either a /s/ or a /z/ sound in the end. Both pronunciations were treated as correct, and so the similarity scores were calculated by considering the last sound either as voiced or voiceless. This classification had minimal effect on the positional and overall average scores.

Table A1
Consonant and Vowel matrix

Letters	Phonemes	Place	Manner	Voice	Heights	Backness	Rounding
#y	j	dorsal	glide	1			
a	æ				0	0	0
b	b	labial	plosive	1			
c	k	dorsal	plosive	0			
d	d	coronal	plosive	1			
e	ɛ				1	0	0
f	f	labial	fricative	0			
g	g	dorsal	plosive	1			
h	h	glottal	fricative	0			
i	ɪ				3	0	0
k	k	dorsal	plosive	0			
l	l	coronal	lateral	1			
m	m	labial	nasal	1			
n	n	coronal	nasal	1			
o	o				2	1	1
p	p	labial	plosive	0			
s	s	coronal	fricative	0			
t	t	coronal	plosive	0			
u	ʌ				1	1	0
v	v	labial	fricative	1			
w	w	labial	glide	1			
y	ɪ				3	0	0
z	z	coronal	fricative	1			

Note. For binary features, 1 indicates + and 0 indicates −.

(*Appendix continues*)

Table A2
Phoneme Similarity Scores Between Onset-Related Primes and Targets

				Average phoneme similarity scores					
				1.00	**0.54**	**0.28**	**0.35**	**0.60**	**0.54**
				By position					
Targets	IPA	Onset primes	IPA	1st	2nd	3rd	Target 3rd w/ prime 1st	Target–prime by position	Overall
bot	bot	byv	bɪv	1.00	0.22	0.00	0.33	0.41	0.39
baf	bæf	bez	bɛz	1.00	0.89	0.33	0.33	0.74	0.64
bal	bæl	beb	bɛb	1.00	0.89	0.33	0.33	0.74	0.64
bes	bɛs	bub	bʌb	1.00	0.67	0.00	0.00	0.56	0.42
bic	bɪk	buv	bʌv	1.00	0.44	0.00	0.33	0.48	0.44
bim	bɪm	bav	bæv	1.00	0.67	0.67	0.67	0.78	0.75
biv	bɪv	bol	bol	1.00	0.22	0.33	0.67	0.52	0.56
bov	bov	baz	bæz	1.00	0.11	0.67	0.67	0.59	0.61
dag	dæg	doz	doz	1.00	0.11	0.33	0.67	0.48	0.53
dan	dæn	div	dɪv	1.00	0.67	0.33	0.67	0.67	0.67
deg	dɛg	dav	dæv	1.00	0.89	0.33	0.67	0.74	0.72
dep	dɛp	dal	dæl	1.00	0.89	0.00	0.33	0.63	0.56
diz	dɪz	dem	dɛm	1.00	0.78	0.33	0.67	0.70	0.69
dop	dop	des	dɛs	1.00	0.22	0.33	0.33	0.52	0.47
daf	dæf	dyz	dɪz	1.00	0.67	0.33	0.00	0.67	0.50
daz	dæz	dyv	dɪv	1.00	0.67	0.67	0.67	0.78	0.75
fac	fæk	fep	fɛp	1.00	0.89	0.67	0.33	0.85	0.72
fam	fæm	fid	fɪd	1.00	0.67	0.33	0.33	0.67	0.58
fec	fɛk	fon	fon	1.00	0.22	0.00	0.33	0.41	0.39
fek	fɛk	fim	fɪm	1.00	0.78	0.00	0.33	0.59	0.53
fet	fɛt	fap	fæp	1.00	0.89	0.67	0.33	0.85	0.72
fip	fɪp	fal	fæl	1.00	0.67	0.00	0.67	0.56	0.58
faz	fæz	fom	fom	1.00	0.11	0.33	0.33	0.48	0.44
foc	fok	fud	fʌd	1.00	0.56	0.33	0.33	0.63	0.56
fod	fod	fes	fɛs	1.00	0.22	0.33	0.00	0.52	0.39
fot	fot	fup	fʌp	1.00	0.56	0.67	0.33	0.74	0.64
foz	foz	fub	fʌb	1.00	0.56	0.33	0.33	0.63	0.56
gan	gæn	gub	gʌb	1.00	0.56	0.33	0.33	0.63	0.56
gam	gæm	gof	gof	1.00	0.11	0.33	0.33	0.48	0.44
gog	gog	gup	gʌp	1.00	0.56	0.33	1.00	0.63	0.72
gop	gop	gaz	gæz	1.00	0.11	0.00	0.33	0.37	0.36
ked	kɛd	kiv	kɪv	1.00	0.78	0.33	0.33	0.70	0.61
ket	kɛt	kiz	kɪz	1.00	0.78	0.33	0.67	0.70	0.69
kev	kɛv	kim	kɪm	1.00	0.78	0.67	0.00	0.81	0.61
kib	kɪb	kec	kɛk	1.00	0.78	0.33	0.33	0.70	0.61
paz	pæz	pum	pʌm	1.00	0.56	0.33	0.00	0.63	0.47
pem	pɛm	pas	pæs	1.00	0.89	0.00	0.33	0.63	0.56
pes	pɛs	pym	pɪm	1.00	0.78	0.00	0.33	0.59	0.53
pid	pɪd	pef	pɛf	1.00	0.78	0.00	0.33	0.59	0.53
pim	pɪm	pez	pɛz	1.00	0.78	0.33	0.33	0.70	0.61
pov	pov	peb	pɛb	1.00	0.22	0.67	0.33	0.63	0.56
pon	pon	piv	pɪv	1.00	0.22	0.33	0.00	0.52	0.39
poz	poz	pif	pɪf	1.00	0.22	0.33	0.00	0.52	0.39
sam	sæm	ses	s∇s	1.00	0.89	0.00	0.00	0.63	0.47
sav	sæv	soz	soz	1.00	0.11	0.67	0.33	0.59	0.53
seb	sɛb	sus	sʌs	1.00	0.67	0.00	0.00	0.56	0.42
sef	sɛf	sud	sʌd	1.00	0.67	0.00	0.67	0.56	0.58
sem	sɛm	sut	sʌt	1.00	0.67	0.00	0.00	0.56	0.42
sev	sɛv	sos	sos	1.00	0.22	0.33	0.33	0.52	0.47
sig	sɪg	sep	sɛp	1.00	0.78	0.33	0.00	0.70	0.53
sof	sof	sab	sæb	1.00	0.11	0.33	0.67	0.48	0.53
sov	sov	syd	sɪd	1.00	0.22	0.33	0.33	0.52	0.47
tal	tæl	tem	tɛm	1.00	0.89	0.33	0.33	0.74	0.64
tob	tob	tes	tɛs	1.00	0.22	0.00	0.33	0.41	0.39
tav	tæv	tud	tʌd	1.00	0.56	0.33	0.00	0.63	0.47
teb	tɛb	tus	tʌs	1.00	0.67	0.00	0.33	0.56	0.50

(*Appendix continues*)

Table A2 (*continued*)

				Average phoneme similarity scores					
				1.00	**0.54**	**0.28**	**0.35**	**0.60**	**0.54**
				By position					
Targets	IPA	Onset primes	IPA	1st	2nd	3rd	Target 3rd w/ prime 1st	Target–prime by position	Overall
tef	tɛf	toc	tok	1.00	0.22	0.33	0.33	0.52	0.47
tiv	tɪv	tas	tæs	1.00	0.67	0.33	0.00	0.67	0.50
toz	toz	tep	tɛp	1.00	0.22	0.00	0.33	0.41	0.39
taz	tæz	tyb	tɪb	1.00	0.67	0.33	0.33	0.67	0.58
val	væl	vof	vof	1.00	0.11	0.00	0.33	0.37	0.36
veb	vɛb	vos	vos	1.00	0.22	0.00	0.67	0.41	0.47
ven	vɛn	vic	vɪk	1.00	0.78	0.00	0.33	0.59	0.53
vep	vɛp	vil	vɪl	1.00	0.78	0.00	0.33	0.59	0.53
vid	vɪd	vem	vɛm	1.00	0.78	0.33	0.33	0.70	0.61
vig	vɪg	vav	væv	1.00	0.67	0.33	0.33	0.67	0.58
vit	vɪt	vog	vog	1.00	0.22	0.33	0.00	0.52	0.39
vob	vob	vec	vɛk	1.00	0.22	0.33	0.67	0.52	0.56
von	von	vab	væb	1.00	0.11	0.33	0.33	0.48	0.44
zan	zæn	zef	zɛf	1.00	0.89	0.00	0.67	0.63	0.64
zep	zɛp	zag	zæg	1.00	0.89	0.33	0.00	0.74	0.56
zid	zɪd	zam	zæm	1.00	0.67	0.33	0.67	0.67	0.67
zig	zɪg	zev	zɛv	1.00	0.78	0.33	0.33	0.70	0.61
zim	zɪm	zeg	zɛg	1.00	0.78	0.33	0.33	0.70	0.61
zin	zɪn	zug	zʌg	1.00	0.44	0.33	0.67	0.59	0.61
zop	zop	zem	zɛm	1.00	0.22	0.33	0.00	0.52	0.39
zom	zom	zil	zɪl	1.00	0.22	0.33	0.33	0.52	0.47
zog	zog	zud	zʌd	1.00	0.56	0.67	0.33	0.74	0.64

Note. IPA = International Phonetic Alphabet.

Table A3
Phoneme similarity scores between feature-related primes and targets

				Average phoneme similarity scores					
				0.67	**0.46**	**0.28**	**0.35**	**0.47**	**0.44**
				By position					
Targets	IPA	Feature primes	IPA	1st	2nd	3rd	Target 3rd w/ prime 1st	Target–prime by position	Overall
bot	bot	pav	pæv	0.67	0.11	0.00	0.67	0.26	0.36
baf	bæf	piz	pɪz	0.67	0.67	0.33	0.67	0.56	0.58
bal	bæl	pib	pɪb	0.67	0.67	0.33	0.00	0.56	0.42
bes	bɛs	pob	pob	0.67	0.22	0.00	0.33	0.30	0.31
bic	bɪk	pev	pɛv	0.67	0.78	0.00	0.67	0.48	0.53
bim	bɪm	puv	pʌv	0.67	0.44	0.67	0.33	0.59	0.53
biv	bɪv	pel	pɛl	0.67	0.78	0.33	0.33	0.59	0.53
bov	bov	pyz	pɪz	0.67	0.22	0.67	0.33	0.52	0.47
dag	dæg	tez	tɛz	0.67	0.89	0.33	0.33	0.63	0.56
dan	dæn	tev	tɛv	0.67	0.89	0.33	0.33	0.63	0.56
deg	dɛg	tuv	tʌv	0.67	0.67	0.33	0.33	0.56	0.50
dep	dɛp	tol	tol	0.67	0.22	0.00	0.67	0.30	0.39
diz	dɪz	tum	tʌm	0.67	0.44	0.33	0.33	0.48	0.44
dop	dop	tis	tɪs	0.67	0.22	0.33	0.67	0.41	0.47
daf	dæf	tuz	tʌz	0.67	0.56	0.33	0.33	0.52	0.47
daz	dæz	tov	tov	0.67	0.11	0.67	0.33	0.48	0.44
fac	fæk	vop	vop	0.67	0.11	0.67	0.00	0.48	0.36
fam	fæm	ved	vɛd	0.67	0.89	0.33	0.67	0.63	0.64
fec	fɛk	vun	vʌn	0.67	0.67	0.00	0.00	0.44	0.33
fek	fɛk	vam	væm	0.67	0.89	0.00	0.00	0.52	0.39
fet	fɛt	vip	vɪp	0.67	0.78	0.67	0.00	0.70	0.53
fip	fɪp	vel	vɛl	0.67	0.78	0.00	0.33	0.48	0.44

(*Appendix continues*)

Table A3 (*continued*)

Targets	IPA	Feature primes	IPA	By position 1st (**0.67**)	By position 2nd (**0.46**)	By position 3rd (**0.28**)	Target 3rd w/ prime 1st (**0.35**)	Target–prime by position (**0.47**)	Overall (**0.44**)
				Average phoneme similarity scores					
faz	fæz	vum	vʌm	0.67	0.56	0.33	0.67	0.52	0.56
foc	fok	vad	væd	0.67	0.11	0.33	0.00	0.37	0.28
fod	fod	vas	væs	0.67	0.11	0.33	0.33	0.37	0.36
fot	fot	vap	væp	0.67	0.11	0.67	0.00	0.48	0.36
foz	foz	vib	vɪb	0.67	0.22	0.33	0.67	0.41	0.47
gan	gæn	keb	kɛb	0.67	0.89	0.33	0.00	0.63	0.47
gam	gæm	kif	kɪf	0.67	0.67	0.33	0.00	0.56	0.42
gog	gog	kep	kɛp	0.67	0.22	0.33	0.67	0.41	0.47
gop	gop	kyz	kɪz	0.67	0.22	0.00	0.67	0.30	0.39
ked	kɛd	gav	gæv	0.67	0.89	0.33	0.67	0.63	0.64
ket	kɛt	goz	goz	0.67	0.22	0.33	0.33	0.41	0.39
kev	kɛv	gom	gom	0.67	0.22	0.67	0.33	0.52	0.47
kib	kɪb	goc	gok	0.67	0.22	0.33	0.67	0.41	0.47
paz	pæz	bym	bɪm	0.67	0.67	0.33	0.33	0.56	0.50
pem	pɛm	bis	bɪs	0.67	0.78	0.00	0.67	0.48	0.53
pes	pɛs	bam	bæm	0.67	0.89	0.00	0.00	0.52	0.39
pid	pɪd	bof	bof	0.67	0.22	0.00	0.67	0.30	0.39
pim	pɪm	boz	boz	0.67	0.22	0.33	0.67	0.41	0.47
pov	pov	bab	bæb	0.67	0.11	0.67	0.67	0.48	0.53
pon	pon	bev	bɛv	0.67	0.22	0.33	0.33	0.41	0.39
poz	poz	bef	bɛf	0.67	0.22	0.33	0.33	0.41	0.39
sam	sæm	zus	zʌs	0.67	0.56	0.00	0.33	0.41	0.39
sav	sæv	zez	zɛz	0.67	0.89	0.67	0.67	0.74	0.72
seb	sɛb	zos	zos	0.67	0.22	0.00	0.33	0.30	0.31
sef	sɛf	zod	zod	0.67	0.22	0.00	0.33	0.30	0.31
sem	sɛm	zit	zɪt	0.67	0.78	0.00	0.33	0.48	0.44
sev	sɛv	zas	zæs	0.67	0.89	0.33	0.67	0.63	0.64
sig	sɪg	zup	zʌp	0.67	0.44	0.33	0.33	0.48	0.44
sof	sof	zib	zɪb	0.67	0.22	0.33	0.33	0.41	0.39
sov	sov	zad	zæd	0.67	0.11	0.33	0.67	0.37	0.44
tal	tæl	dom	dom	0.67	0.11	0.33	0.67	0.37	0.44
tob	tob	dis	dɪs	0.67	0.22	0.00	0.67	0.30	0.39
tav	tæv	dod	dod	0.67	0.11	0.33	0.33	0.37	0.36
teb	tɛb	das	dæs	0.67	0.89	0.00	0.67	0.52	0.56
tef	tɛf	dac	dæk	0.67	0.89	0.33	0.00	0.63	0.47
tiv	tɪv	dus	dʌs	0.67	0.44	0.33	0.33	0.48	0.44
toz	toz	dap	dæp	0.67	0.11	0.00	0.67	0.26	0.36
taz	tæz	dob	dob	0.67	0.11	0.33	0.67	0.37	0.44
val	væl	fif	fɪf	0.67	0.67	0.00	0.00	0.44	0.33
veb	vɛb	fis	fɪs	0.67	0.78	0.00	0.33	0.48	0.44
ven	vɛn	fak	fæk	0.67	0.89	0.00	0.00	0.52	0.39
vep	vɛp	fol	fol	0.67	0.22	0.00	0.67	0.30	0.39
vid	vɪd	fum	fʌm	0.67	0.44	0.33	0.00	0.48	0.36
vig	vɪg	fev	fɛv	0.67	0.78	0.33	0.00	0.59	0.44
vit	vɪt	feg	fɛg	0.67	0.78	0.33	0.33	0.59	0.53
vob	vob	fic	fɪk	0.67	0.22	0.33	0.33	0.41	0.39
von	von	feb	fɪb	0.67	0.22	0.33	0.00	0.41	0.31
zan	zæn	sif	sɪf	0.67	0.67	0.00	0.33	0.44	0.42
zep	zɛp	sug	sʌg	0.67	0.67	0.33	0.33	0.56	0.50
zid	zɪd	som	som	0.67	0.22	0.33	0.33	0.41	0.39
zig	zɪg	suv	sʌv	0.67	0.44	0.33	0.00	0.48	0.36
zim	zɪm	sog	sog	0.67	0.22	0.33	0.00	0.41	0.31
zin	zɪn	seg	sɛg	0.67	0.78	0.33	0.33	0.59	0.53
zop	zop	sim	sɪm	0.67	0.22	0.33	0.33	0.41	0.39
zom	zom	sal	sæl	0.67	0.11	0.33	0.00	0.37	0.28
zog	zog	sid	sɪd	0.67	0.22	0.67	0.00	0.52	0.39

Note. IPA = International Phonetic Alphabet.

(*Appendix continues*)

Table A4
Phoneme Similarity Scores Between Unrelated Primes and Targets

				Average phoneme similarity scores					
				0.00	**0.51**	**0.28**	**0.33**	**0.26**	**0.28**
				By position					
Targets	IPA	Unrelated primes	IPA	1st	2nd	3rd	Target 3rd w/ prime 1st	Target–prime by position	Overall
bot	bot	hiv	hɪv	0.00	0.22	0.00	0.33	0.07	0.14
baf	bæf	suz	sʌz	0.00	0.56	0.33	0.67	0.30	0.39
bal	bæl	heb	hɛb	0.00	0.89	0.33	0.00	0.41	0.31
bes	bɛs	hab	hæb	0.00	0.89	0.00	0.67	0.30	0.39
bic	bɪk	huv	hʌv	0.00	0.44	0.00	0.33	0.15	0.19
bim	bɪm	hev	hɛv	0.00	0.78	0.67	0.00	0.48	0.36
biv	bɪv	sul	sʌl	0.00	0.44	0.33	0.33	0.26	0.28
bov	bov	siz	sɪz	0.00	0.22	0.67	0.33	0.30	0.31
dag	dæg	hiz	hɪz	0.00	0.67	0.33	0.00	0.33	0.25
dan	dæn	fuv	fʌv	0.00	0.56	0.33	0.00	0.30	0.22
deg	dɛg	fiv	fɪv	0.00	0.78	0.33	0.00	0.37	0.28
dep	dɛp	hol	hol	0.00	0.22	0.00	0.33	0.07	0.14
diz	dɪz	hom	hom	0.00	0.22	0.33	0.33	0.19	0.22
dop	dop	hus	hʌs	0.00	0.56	0.33	0.33	0.30	0.31
daf	dæf	hez	hɛz	0.00	0.89	0.33	0.67	0.41	0.47
daz	dæz	fov	fov	0.00	0.11	0.67	0.33	0.26	0.28
fac	fæk	nup	nʌp	0.00	0.56	0.67	0.00	0.41	0.31
fam	fæm	lod	lod	0.00	0.11	0.33	0.33	0.15	0.19
fec	fɛk	lun	lʌn	0.00	0.67	0.00	0.00	0.22	0.17
fek	fɛk	lum	lʌm	0.00	0.67	0.00	0.00	0.22	0.17
fet	fɛt	lup	lʌp	0.00	0.67	0.67	0.33	0.44	0.42
fip	fɪp	gol	gol	0.00	0.22	0.00	0.33	0.07	0.14
faz	fæz	lem	lɛm	0.00	0.89	0.33	0.67	0.41	0.47
foc	fok	nid	nɪd	0.00	0.22	0.33	0.00	0.19	0.14
fod	fod	lis	lɪs	0.00	0.22	0.33	0.67	0.19	0.31
fot	fot	dup	dʌp	0.00	0.56	0.67	0.67	0.41	0.47
foz	foz	leb	lɛb	0.00	0.22	0.33	0.67	0.19	0.31
gan	gæn	hib	hɪb	0.00	0.67	0.33	0.00	0.33	0.25
gam	gæm	syf	sɪf	0.00	0.67	0.33	0.00	0.33	0.25
gog	gog	hup	hʌp	0.00	0.56	0.33	0.00	0.30	0.22
gop	gop	sez	sɛz	0.00	0.22	0.00	0.33	0.07	0.14
ked	kɛd	zuv	zʌv	0.00	0.67	0.33	0.67	0.33	0.42
ket	kɛt	loz	loz	0.00	0.22	0.33	0.33	0.19	0.22
kev	kɛv	zum	zʌm	0.00	0.67	0.67	0.67	0.44	0.50
kib	kɪb	zec	zɛk	0.00	0.78	0.33	0.33	0.37	0.36
paz	pæz	lom	lom	0.00	0.11	0.33	0.67	0.15	0.28
pem	pɛm	lus	lʌs	0.00	0.67	0.00	0.33	0.22	0.25
pes	pɛs	yom	jom	0.00	0.22	0.00	0.33	0.07	0.14
pid	pɪd	lef	lɛf	0.00	0.78	0.00	0.67	0.26	0.36
pim	pɪm	laz	læz	0.00	0.67	0.33	0.33	0.33	0.33
pov	pov	lub	lʌb	0.00	0.56	0.67	0.33	0.41	0.39
pon	pon	lev	lɛv	0.00	0.22	0.33	0.67	0.19	0.31
poz	poz	lif	lɪf	0.00	0.22	0.33	0.67	0.19	0.31
sam	sæm	gos	gos	0.00	0.11	0.00	0.33	0.04	0.11
sav	sæv	guz	gʌz	0.00	0.56	0.67	0.33	0.41	0.39
seb	sɛb	yis	jɪs	0.00	0.78	0.00	0.00	0.26	0.19
sef	sɛf	yad	jæd	0.00	0.89	0.00	0.33	0.30	0.31
sem	sɛm	yit	jɪt	0.00	0.78	0.00	0.00	0.26	0.19
sev	sɛv	bys	bɪs	0.00	0.78	0.33	0.67	0.37	0.44
sig	sɪg	yop	jop	0.00	0.22	0.33	0.00	0.19	0.14
sof	sof	yeb	jɛb	0.00	0.22	0.33	0.33	0.19	0.22
sov	sov	gud	gʌd	0.00	0.56	0.33	0.33	0.30	0.31
tal	tæl	yim	jɪm	0.00	0.67	0.33	0.00	0.33	0.25
tob	tob	vus	vʌs	0.00	0.56	0.00	0.67	0.19	0.31

(*Appendix continues*)

Table A4 (*continued*)

				Average phoneme similarity scores					
				0.00	**0.51**	**0.28**	**0.33**	**0.26**	**0.28**
				By position					
Targets	IPA	Unrelated primes	IPA	1st	2nd	3rd	Target 3rd w/ prime 1st	Target–prime by position	Overall
tav	tæv	yed	jɛd	0.00	0.89	0.33	0.00	0.41	0.31
teb	tɛb	yos	jos	0.00	0.22	0.00	0.00	0.07	0.06
tef	tɛf	yic	jɪk	0.00	0.78	0.33	0.33	0.37	0.36
tiv	tɪv	wes	wɛs	0.00	0.78	0.33	0.67	0.37	0.44
toz	toz	yup	jʌp	0.00	0.56	0.00	0.00	0.19	0.14
taz	tæz	yub	jʌb	0.00	0.56	0.33	0.00	0.30	0.22
val	væl	kef	kɛf	0.00	0.89	0.00	0.00	0.30	0.22
veb	vɛb	tys	tɪs	0.00	0.78	0.00	0.33	0.26	0.28
ven	vɛn	tok	tok	0.00	0.22	0.00	0.33	0.07	0.14
vep	vɛp	tul	tʌl	0.00	0.67	0.00	0.67	0.22	0.33
vid	vɪd	tam	tæm	0.00	0.67	0.33	0.67	0.33	0.42
vig	vɪg	kuv	kʌv	0.00	0.44	0.33	0.67	0.26	0.36
vit	vɪt	kag	kæg	0.00	0.67	0.33	0.67	0.33	0.42
vob	vob	kac	kæk	0.00	0.11	0.33	0.33	0.15	0.19
von	von	tib	tɪb	0.00	0.22	0.33	0.33	0.19	0.22
zan	zæn	pof	pof	0.00	0.11	0.00	0.00	0.04	0.03
zep	zɛp	kig	kɪg	0.00	0.78	0.33	0.67	0.37	0.44
zid	zɪd	kem	kɛm	0.00	0.78	0.33	0.33	0.37	0.36
zig	zɪg	kav	kæv	0.00	0.67	0.33	0.67	0.33	0.42
zim	zɪm	pag	pæg	0.00	0.67	0.33	0.33	0.33	0.33
zin	zɪn	pog	pog	0.00	0.22	0.33	0.00	0.19	0.14
zop	zop	kym	kɪm	0.00	0.22	0.33	0.67	0.19	0.31
zom	zom	pul	pʌl	0.00	0.56	0.33	0.33	0.30	0.31
zog	zog	ped	pɛd	0.00	0.22	0.67	0.33	0.30	0.31

Note. IPA = International Phonetic Alphabet.

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