Journal of Experimental Psychology:
Human Perception and Performance
2000, Vol. 26, No. 3, 1178–1191

0096-1523/00/$5.00 DOI: 10.1037//0096-1523.26.3.1178

Reading Aloud Begins When the Computation of Phonology Is Complete

Kathleen Rastle
Macquarie University and University of Cambridge

Jonathan Harrington, Max Coltheart, and
Sallyanne Palethorpe
Macquarie University

Naming latency experiments in which monosyllabic items are read aloud are based on the assumption that the vocal response is not initiated until the phonology of the entire syllable has been computed. Recently, this assumption has been challenged by A. H. Kawamoto, C. T. Kello, R. Jones, and K. Bame (1998), who argued instead that the reading-aloud response begins as soon as the initial phoneme is computed. This view would be refuted by evidence of anticipatory coarticulation effects on the initial phoneme due to the nature of the following vowel in the speeded reading-aloud task. The authors provide such evidence.

The 1960s saw a resurgence of interest in the processes that underlie visual word recognition and reading aloud, encouraging a proliferation of empirical work designed to build a theoretical account of these cognitive skills. The body of empirical findings generated from this research over the past 40 years consists largely of data collected from the lexical decision and reading-aloud tasks. It is the latter of these tasks with which we are concerned.

The reading-aloud task measures the time between the onset of a visually presented letter string and the onset of a vocal response. The reading-aloud response is generally considered to involve the completion of a number of cognitive events, some of which include visual feature analysis, abstract letter identification, computation of a phonological code from orthography, generation of an articulatory program from this phonological code, and execution of this articulatory program (see, e.g., Balota & Chumbley, 1984; Coltheart, 1978; Henderson, 1982; Monsell, 1990). In this work, we wish to examine whether the reading-aloud task does indeed reflect one of these cognitive events, that of the *complete* generation of a phonological code from orthography.

There are two general positions regarding this issue, at least where monosyllables are concerned, contained in the literature. According to the first position, which we refer to as the *initial-phoneme criterion* for the initiation of articulation, articulation begins when a phonological code for the first phoneme in the letter string is generated. According to the other position, which we refer to as the *whole-word criterion* for the initiation of articulation, articulation begins only when the entire letter string has been translated to a phonological code.

Investigating this issue is critical for two reasons. First, theories and models of reading aloud are largely oversimplified regarding processes that occur subsequent to the generation of phonology, such as those involved in articulation; the resolution of this issue will determine when, in a model of reading, the reading-aloud response should be deemed to have occurred. Second, the reading-aloud task has almost exclusively informed our understanding of the processes by which people translate the printed word to speech. Only by resolving this issue can we interpret correctly the entire body of empirical data collected using this task.

Four computational models of reading aloud are currently being studied: the dual-route cascaded (DRC) model (Coltheart, Curtis, Atkins, & Haller, 1993; Coltheart & Rastle, 1994; Rastle & Coltheart, 1998; Rastle & Coltheart, 1999a, 1999b), the multiple-levels model (Norris, 1994), the connectionist dual-process model (Zorzi, Houghton, & Butterworth, 1998), and the parallel-distributed processing (PDP) implementations by Plaut, McClelland, Seidenberg, and Patterson (1996). Although the generation and execution of the motor program for articulation is beyond the scope of each of these models, they all make the fundamental assumption that the reading-aloud response occurs only when the orthography–phonology conversion is complete—when all of the phonemes in the syllable have "become known." These phonemes are considered to have become known if, for example, they reach a predetermined activation criterion (as in the DRC model) or have settled such that the average change within a phoneme unit across successive time slices falls below a predetermined value (as in the attractor network of Plaut et al., 1996). Of course, the means by which the orthography–phonology conversion occurs differs in each model; what is relevant here is that not one of them makes the assumption that a reading-aloud response can begin before the orthography–phonology conversion is complete.

Kathleen Rastle, Macquarie Centre for Cognitive Science and Speech, Hearing, and Language Research Centre, Macquarie University, Sydney, Australia and Department of Experimental Psychology, University of Cambridge, Cambridge, United Kingdom; Jonathan Harrington, Max Coltheart, and Sallyanne Palethorpe, Macquarie Centre for Cognitive Science and Speech, Hearing, and Language Research Centre, Macquarie University, Sydney, Australia.

This research was supported by an ARC Special Investigator Grant and by a Macquarie University Research Grant. We are grateful to Chris Callaghan for his technical assistance, to Jo Ziegler for helpful discussion, and to Alan Kawamoto, Dennis Norris, Arthur Samuel, and an anonymous reviewer for thoughtful comments on an earlier version of this article.

Correspondence concerning this article should be addressed to Kathleen Rastle, Macquarie Centre for Cognitive Science, Macquarie University, Sydney, NSW 2109, Australia. Electronic mail may be sent to kathy@maccs.mq.edu.au.

This is not to say, however, that the former position—the initial-phoneme criterion for the initiation of articulation—has not made its occasional appearance in the literature (see, e.g., Frederiksen & Kroll, 1976; Treiman, Mullennix, Bijeljac-Babic, & Richmond-Welty, 1995; MacKay, 1987). It is illustrated well in the following statements:

> Since the length of a consonant cluster has an effect on naming latency when the cluster is in the initial position, and since we know on linguistic grounds that the rules for the assignment of phonemic correspondents are more complex for long consonant clusters than for short ones (Hansen & Rogers, 1968), we are led to conclude that a translation of the right-hand portion of the array takes place only after articulation has been initiated. We thus are led to reject a theory of naming that postulates the creation of an abstract and complete phonological representation prior to articulation, which can be directly and serially interpreted by the articulatory system. (Frederiksen & Kroll, 1976, p. 368)

> Articulation begins as soon as the initial element in the array has been translated. (Frederiksen & Kroll, 1976, p. 376)

> The initial phoneme had a much larger effect in the McGill study, where it explained 22.8% of the unique variance in RT [reaction time], than in the Wayne State study, where it accounted for 5.2% of the unique variance. This difference may reflect the fact that the McGill students responded more quickly than the Wayne State students or were more likely to begin vocalizing the word before they had fully processed it. (Treiman et al., 1995, p. 119)

Initially rejected by authors such as Henderson (1982), the initial-phoneme account has made another appearance recently in important work carried out by Kawamoto, Kello, Jones, and Bame (1998), who investigated the issue regarding the criterion for the initiation of articulation in much greater depth than has been done previously. They approached this issue by developing and testing the predictions of each account as they relate to the regularity effect, the finding that exception words (e.g., *pint*) are read aloud more slowly than are regular words (e.g., *mint;* Coltheart & Rastle, 1994; Paap & Noel, 1991; Seidenberg, Waters, Barnes, & Tanenhaus, 1984). Although every computational model of reading aloud posits that this effect occurs because exceptional or inconsistent phonemes take longer to become known than do regular or consistent phonemes, Kawamoto et al. suggested that a finer analysis of the regularity effect in human readers may reveal information critical to resolving the issue of articulation initiation.

Kawamoto et al. (1998) began with the observation that naming latency is a measurement whose meaning differs for stimuli beginning with plosive (oral stop consonants /p b t g d k/) and nonplosive phonemes. For nonplosives, they argued that the naming-latency measurement corresponds to the initiation of articulation. For plosives, naming latency corresponds to the release of the plosive closure, an event that cannot occur until the phoneme following the plosive becomes known; naming latency in this case is thus a measurement of the initiation of articulation plus the duration of the initial phoneme (which, in this case, is silent).

Given this distinction, Kawamoto et al. (1998) then suggested that if articulation begins as soon as the initial phoneme becomes known, then a regularity effect should be observed only for items with plosive initial phonemes. Consider CVC (C = consonant; V = vowel) words with an irregular vowel. In cases in which the first phoneme is nonplosive such as *sew,* articulation—and thus the generation of acoustic energy—will begin when the initial phoneme is known; computation of the irregular vowel can then occur *during* the articulation of the initial nonplosive phoneme. Thus, no regularity effect will be observed, since acoustic energy will have been generated and a voice key triggered before difficulties in translating the irregular-vowel phoneme arise. In cases in which the first phoneme is a plosive such as *pint,* however, acoustic energy will not be generated until the release of the plosive, and this release occurs only when the irregular-vowel phoneme becomes known. Here, the irregular-vowel phoneme will affect naming latency and an irregularity cost will emerge.

The alternative position—that articulation begins only when the orthography–phonology conversion has been completed—predicts that irregular words with nonplosive initial phonemes and irregular words with plosive initial phonemes should suffer an irregularity cost equal in magnitude. By this account, articulation cannot begin until the irregular vowel—and indeed the entire syllable—becomes known, regardless of the phonetic class of the onset.

Consider now these accounts of the reading-aloud task in relation to the words *cooks* and *looks,* both of which contain irregular grapheme–phoneme correspondences in the vowel. If the whole-word position is correct, then these words will display a cost of irregularity equal in magnitude (all relevant variables being equal), because the initiation of articulation will not begin until all phonemes become known. If the initial-phoneme position is correct, however, then only *cooks* will show an irregularity cost. Because the initial phoneme in *looks* is nonplosive, articulation of that item—and thus the triggering of the voice key—begins before the irregular-vowel phoneme is computed; so *looks* will not suffer by being irregular. In the item *cooks,* however, while articulation can begin as soon as the initial phoneme has been computed, since the initial phoneme is plosive and therefore silent, the generation of acoustic energy (and hence the triggering of the voice key) will not occur until the irregular-vowel phoneme is computed and the plosive closure is released; so *cooks* will suffer by being irregular.

In accordance with the initial-phoneme position, Kawamoto et al. (1998) reported an interaction between regularity and plosivity in two experiments, such that irregular items with plosive initial phonemes were subject to an irregularity cost while irregular items with nonplosive initial phonemes were not. They further reported a post hoc analysis of data reported by Rastle and Coltheart (1999b) that showed a similar interaction between regularity and plosivity, an interaction not predicted by or consistent with a whole-word position. The finding of an interaction between plosivity and regularity is important because it is an effect that cannot be explained by any of the current computational models of reading.

Coarticulatory Effects in Reading Aloud

Despite growing empirical support for an initial-phoneme account of the initiation of articulation (see, e.g., Bachoud-Lévi, Dupoux, Cohen, & Mehler, 1998; Cortese, 1998; Cortese & Zevin, 1998), it is an account inconsistent with a large body of literature on speech production. If an initial-phoneme account is correct, then in the speeded reading-aloud task, articulation of an initial phoneme should not be influenced by the nature of the following vowel (since the vowel is not known when articulation of the initial phoneme is initiated); the position of the articulatory apparatus (e.g., the lips, tongue, and jaw) should be the same at plosive closure for the item *gawk* as for the item *geek*, for example. It is well known in other speech-production situations, however, that the articulation of such initial phonemes *is* influenced by the nature of the following vowel.

Although it is indisputable that languages build words from a set of finite, phoneme-sized units, phoneticians and phonologists have recognized for well over 100 years that in the production of speech, sounds overlap with each other in time: That is, they are *coproduced* or *coarticulated.* Coarticulation can be both anticipatory (e.g., the lips are rounded in the production of /s/ of *soon* in anticipation of the following rounded /u/ vowel) and perseverative (the rounding from /u/ persists to the following /n/). Vowels can be substantially affected by the coarticulatory influences of consonants (Lindblom, 1963; Recasens, 1990; Stevens & House, 1963) particularly if they occur in unstressed syllables (Bell-Berti & Harris, 1979; Browman & Goldstein, 1990; Fowler, 1981). Likewise, consonants can be affected by the coarticulatory influences of vowels (Bell-Berti & Harris, 1979, 1981; Daniloff & Moll, 1968; Lubker, 1981), and there is a large body of experimental data that has demonstrated vowel-to-vowel coarticulatory effects in VCV sequences (Alfonso & Baer, 1982; Butcher & Weiher, 1976; Carré & Chennoukh, 1995; Farnetani, 1990; Manuel, 1990; Öhman, 1966, 1967; Perkell, 1969; Recasens, Pallarès, & Fontdevila, 1997), demonstrating that coarticulatory influences need not be restricted to abutting segments (Huffman, 1986; Magen, 1989; Recasens, 1989).

Coarticulation, it has been argued, may be *necessary* (Fowler & Rosenblum, 1989; Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967; Liberman & Mattingly, 1985) because it allows phonemes to be communicated in parallel and therefore transmitted to the listener far more rapidly than if speech production were a serial production of nonoverlapping phoneme-size gestures. In fact, it is probably never possible to produce natural, spontaneous uncoarticulated speech, though it is clear that the extent to which speech is coarticulated can be controlled by the talker to communicate the clarity with which a particular syllable is produced. Speech-production gestures tend to be hyperarticulated, implying less coarticulation, when the listener-oriented communicative situation requires a particularly clear speech-production style (de Jong, 1995; Keating, Lindblom, Lubker, & Kreiman, 1994). On the other hand, hypoarticulation, in which speech-production gestures are undershot and blended (i.e., strongly coarticulated) can occur to the extent that the listener's understanding of the intended speech communication is not compromised.

Kawamoto et al. (1998) proposed to reconcile the initial-phoneme account with the apparent ubiquity of coarticulation by raising the possibility that coarticulation might not occur in all speech-production situations. They argued, "Although we agree that coarticulatory effects in typical speech production experiments should be found, we do not believe that this argument applies to speeded word naming" (p. 878).

They went on to discuss an experiment devised by Whalen (1990), which showed that coarticulation could be artificially blocked in the laboratory under some circumstances. In Whalen's (1990) study, participants were instructed to produce various kinds of VCV sequences. In some trials, talkers were presented with the orthography for the vowels, but not for the medial consonant (e.g., participants might be presented with A_I); as soon as voicing for the first vowel was detected, the missing consonant letter was supplied and participants produced the entire sequence. Other trials were conducted in the same way but with a missing second vowel (e.g., participants were initially provided with AB_). Whalen (1990) found evidence for anticipatory coarticulation of the second vowel on the first in the trials like A_I in which both vowels were known, but not in trials like AB_ in which the second vowel was known only after phonation for the first vowel had begun. Because anticipatory coarticulation was clearly present only when the segments were known prior to articulation, Whalen (1990) concluded that coarticulation must be planned rather than automatically produced and, furthermore, that it should not be present under conditions in which there is insufficient time for such planning.[1]

Like in the AB_ type trials of Whalen's (1990) experiment, Kawamoto et al. (1998) claimed that the vowel is "unknown" in the speeded reading-aloud task (assuming CVC sequences) at the onset of articulation. Thus, the vowel cannot exert the anticipatory coarticulatory influences that are normally found in speech production. They wrote,

> Imagine having to say as quickly as possible either "sip" or "soup." However, unlike the standard naming task, the letters of the body are presented 1 s after the initial consonant is presented. Clearly, articulation of the initial /s/ can be initiated without knowledge of the vowel. Only after the vowel becomes known will coarticulatory effects of the vowel on the consonant be manifested—roughly a second after the /s/ has been initiated. We argue that in the speeded naming task a similar situation arises, but on the order of tens of milliseconds. (p. 878)

Thus, Kawamoto et al. (1998), while not ruling out coarticulatory effects on the initial phoneme entirely, explicitly committed themselves to the prediction that such effects will not be manifested during the initial period of articulation—that there will be a frame of "tens of milliseconds" in which there will be no influence of the vowel on the preceding initial phoneme. If coarticulatory effects occur in the speeded reading-aloud task, and they are present during these initial periods of articulation, then the initial phoneme theory advanced by Kawamoto et al. (1998) cannot be correct.

Let us consider more specifically what time frame might constitute these initial periods of articulation. Kawamoto et al. (1998) wrote,

> No regularity effect would be expected for nonplosives because the initial consonant can be produced without knowledge of the vowel,

[1] Kawamoto et al. (1998) cited Whalen (1990) in support of their argument that coarticulation effects should not be found in the speeded reading-aloud task. However, the link between the speeded reading-aloud task and the experimental situation described by Whalen (1990) was not clearly demonstrated by Kawamoto et al. (1998). In Whalen (1990), participants were required to begin articulation of a stimulus (e.g., AB__) before a second vowel phoneme was presented; in this situation, there could be no coarticulation of the initial phoneme based on the nature of the unpresented vowel since participants did not know the second vowel and hence could not prepare for its production. The experimental situation in the speeded reading-aloud task is quite different, since participants are presented with the entire letter string. Here, there is the possibility for participants to precompute what the state of the vocal tract must be for production of the letter string; this possibility was absent in Whalen's (1990) task.

> but the typical regularity advantage would be expected for plosives because the release of air-pressure cannot occur until the pronunciation of the irregular vowel is determined. (p. 866)

Here, it seems clear that Kawamoto et al. (1998) wished to propose that for items with nonplosive and plosive initial phonemes, articulation can and does begin without knowledge of the vowel. Coarticulatory effects on the initial nonplosive phoneme observed at the onset of acoustic energy, however, would imply that the vowel *is* known at this point in time. For syllables that begin with plosive phonemes, Kawamoto et al. argued that "the release of air-pressure cannot occur until the pronunciation of the irregular vowel is determined" (p. 866). The statement that plosive closure is released when the vowel is determined also, of course, implies that the vowel is not known during any part of the closure that precedes the release. Thus, if coarticulatory effects due to the nature of the vowel on initial plosive phonemes are observed at the onset of plosive closure, then the theory that the reading-aloud response begins before the computation of phonology is complete is false.

The Experiment

The experimental work presented here was designed to investigate whether in the speeded reading-aloud task, the oral response is initiated as soon as the initial phoneme becomes known in monosyllabic words. Specifically, we sought to investigate whether there is any evidence for the view that anticipatory coarticulation effects are absent in the production of some parts of the initial consonant in the reading-aloud task, for both plosive and nonplosive initial phonemes.

We compared the anticipatory coarticulatory influences of Australian English vowels which varied maximally in their placement—/i:/ (as in *heed*) and /o:/ (as in *hoard*)—when these vowels followed three sets of consonants: (a) the oral plosives /k/ and /g/; (b) the glottal fricative (nonplosive) /h/; and (c) the labial-velar approximant (nonplosive) /w/. We chose the vowels /i:/ and /o:/ because they are phonetically divergent on two parameters that distinguish vowel quality: /i:/ is a phonetically front vowel in which the main constriction location is between the tongue dorsum and the hard palate, whereas /o:/ is a phonetically back vowel in Australian English and has its constriction location in the upper pharynx; second, /i:/ is phonetically unrounded and is produced with the lips in a spread position, whereas /o:/ is a rounded vowel and is produced with protruded lips. We chose a range of initial-phoneme consonants with different manners of articulation, some of which are generally thought to be prone to coarticulatory influences in unspeeded speech-production situations. It is very well known that the place of articulation of the velars /k/ and /g/ varies extensively with the backness of the following vowel (e.g., Potter, Kopp, & Green, 1947) and that the glottal fricative /h/ is highly susceptible to coarticulatory influences of the following vowel (Lehiste, 1964).

Coarticulatory effects were measured using acoustic, kinematic, and electropalatographic (EPG) data. These techniques enable us to observe horizontal and vertical movement of the lips and the contact of the tongue with the palate during the period between the presentation of the target and the initiation of the naming response. Our conclusions regarding coarticulatory effects in the speeded reading-aloud task will be determined by the extent to which these measurements of the articulation of the initial phoneme differ for each vowel type.

If the initial-phoneme account advanced by Kawamoto et al. (1998) is correct, then there should be no evidence of coarticulation at the onset of acoustic energy for items beginning with nonplosive consonant phonemes; for plosive initial phonemes, there should be no evidence of coarticulation at the point of maximum closure (by which we mean the time at which the closure, as judged from EPG contacts, attains its maximum value). In both cases, the nature of the vowel should not affect articulation of the initial phoneme.

Method

Participants. Four female talkers of Australian English with no known speech or hearing deficiencies participated in the experiment. The talkers' accents were intermediate between Cultivated Australian, which bears the greatest resemblance to British English Received Pronunciation, and General Australian, which is spoken by the majority of the population. (See Bernard, 1970; Cox, 1996; and Harrington, Cox, & Evans, 1997, for further details on an analysis of Australian English vowels, and Harrington & Cassidy, 1994, for an acoustic comparison between Australian and Southern British English Received Pronunciation vowels.)

Stimuli. Twenty-three test stimuli that were varied on initial consonant phoneme (/g/, /k/, /h/, /w/) and vowel (/i:/ or /o:/) were selected. In each of the eight cells of test stimuli, there were three items, with the exception of the /gi:/ cell, which contained only two items (for the reason that there are only two monosyllabic words that begin /gi:/). All target words were monosyllabic, were monomorphemic, and had a phonological CVC structure. They are shown in Table 1.

Targets were presented 10 times to each participant, over 10 blocks of trials, for speeded reading aloud. Because target words were presented 10 times to each participant, we included additional filler items and catch trials in each trial block. Thirteen filler items that began with one of the four target initial phonemes but had a different vowel than those used in the target items were included so that coarticulatory effects would not be exaggerated by participants producing only two vowels through the entire experiment. Catch trials were also included that differed for each trial block, contained different vowels to the target items, and numbered roughly 10% of the stimulus list (four items). The catch trials resembled the

Table 1
The Test Items Categorized According to the Initial Consonant and Vowel Phonemes That Were Analyzed for Coarticulatory Effects

	Vowel	
Consonant	i:	o:
k	keen	cord
	keel	cork
	keep	corn
g	geek	gaul
	geese	gauze
		gawk
h	heap	hall
	heat	hawk
	heed	hoard
w	wean	ward
	weep	warp
	weed	worn

Table 2
The Number of Tokens of the Consonant–Vowel Phoneme Combinations Produced by the 4 Participants That Were Analyzed for Coarticulatory Effects

	Consonant–vowel phoneme							
	k		g		h		w	
Participant	ko:	ki:	go:	gi:	ho:	hi:	wo:	wi:
FC	29	30	29	19	29	27	27	29
MT	30	30	29	18	29	30	26	29
SP	30	29	30	18	30	27	27	30
ZE	30	30	30	20	30	29	30	30

target items such that each catch-trial item began with one of the test initial phonemes, had a phonological CVC structure, and was monosyllabic and monomorphemic.

To ensure that participants were carrying out the reading-aloud task in the orthodox way, we included in the first trial block the 20 items with irregularities in the first position (e.g., *chef*) and their 20 regular matched controls (e.g., *shed*) from Rastle and Coltheart (1999b). Rastle and Coltheart (1999b) reported a robust effect of regularity for these items, which we also expected to find here. In total, participants read aloud 40 items (23 targets, 13 fillers, 4 catch trials) in each of 10 trial blocks, except for the first trial block, which included 80 items (because it included those irregular and regular items from Rastle and Coltheart, 1999b).

Apparatus. Participants were recorded in a sound-treated room in the Speech, Hearing, and Language Research Centre, Macquarie University, using the MOVETRACK magnetometer system (Branderud, 1985) and the EPG3+ Reading electropalatograph.

The operation of the MOVETRACK magnetometer system is as follows: transmitter coils fixed to a helmet fitted to each participant generate unique electromagnetic fields, each of which induces an alternating signal in receiver coils attached to articulatory landmarks (such as the lips and chin); the distance between receiver and transmitter coils can be determined from the strength of the signal in the receiver coils; continuous sampling of the strength of this signal provides a displacement signal over time. For each participant, the x (horizontal) helmet coordinate was placed in line extending from the angle of the mandible to the upper front teeth, and the y (vertical) helmet coordinate was at right angles to the x coordinate at the

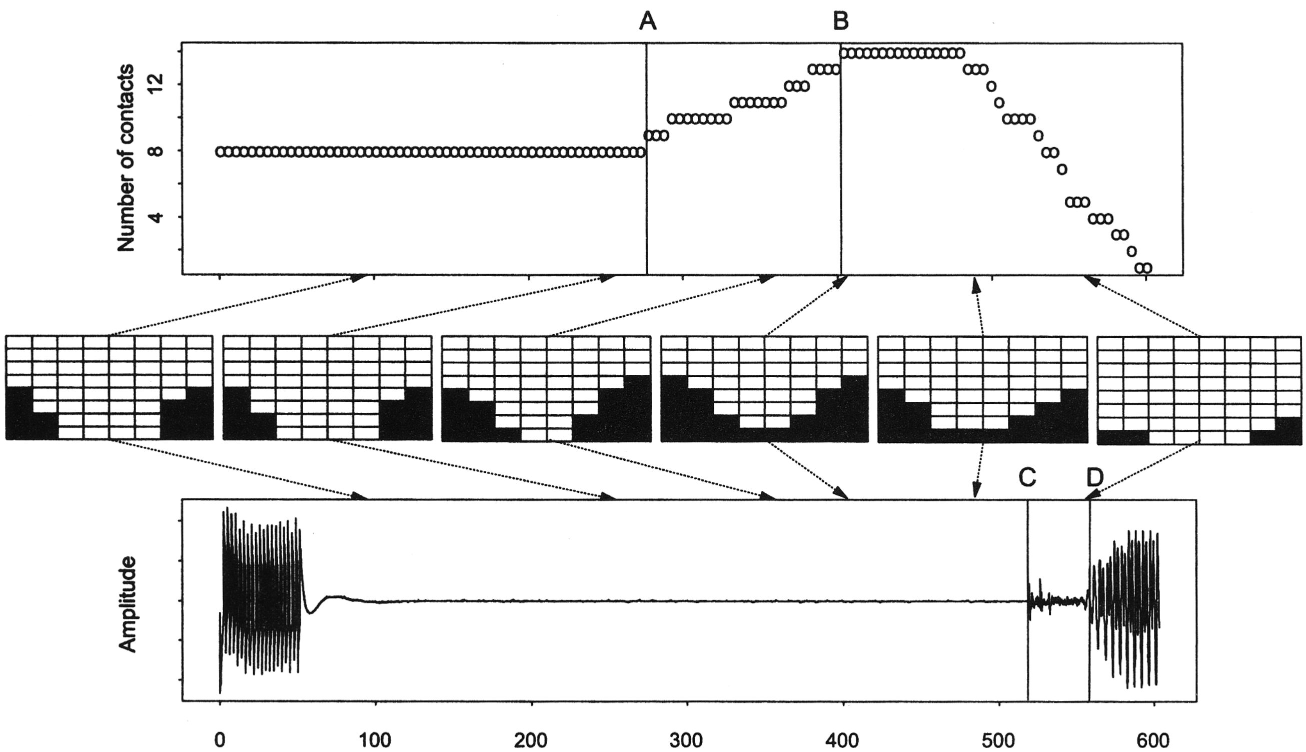

Figure 1. Electropalatographic and acoustic displays of the production of /ko:/ by Participant FC. The bottom panel shows the acoustic signal (in ms) including the target-onset tone (between 0 and 80 ms), *acoustic silence, acoustic frication,* and the *acoustic vowel onglide.* Points C and D on this display mark the *onset of frication* and the *onset of periodicity,* respectively. The top panel is the total number of contacts in rows 7–8 in the palatograms as a function of time and synchronized with the acoustic signal. The interval between Points A and B is the *approach to the closure* and Point B is the *onset of maximum articulatory closure.* The middle panel shows various palatograms sampled at the times marked by the arrows on the display (the top and bottom of each palatogram are contacts at the front and back of the mouth, respectively). The two leftmost palatograms are taken before the approach to the closure and show no change in the contact pattern although they are more than 100 ms apart. The third palatogram from the left is taken in the approach to the closure and shows an incomplete back row of contacts. The fourth palatogram from the left marks the onset of articulatory closure at which the contacts are first at their maximum value. The fifth palatogram is taken toward the end of the articulatory closure, and the final palatogram, taken at the onset of periodicity of the back vowel, shows only a very small number of contacts.

line of the upper teeth. Receiver coils were attached to three articulatory landmarks to record three sets of vertical and horizontal positions: These were the midpoint of the upper and lower lips on the vermillion border and on the chin (to register jaw position). The *x*- and *y*-axis values of the receiver coils were measured relative to fixed transmitter coils mounted on the helmet behind and above the head.

EPG recordings, which register the dynamic change in the contact of the tongue against the roof of the mouth, were obtained from an artificial acrylic palate worn by the participant that forms part of the Reading EPG3+ electropalatograph system (Arnfield, 1997). The artificial palate is made from a plaster cast impression of the mouth for each participant, and electrodes are embedded in the palate in eight evenly spaced rows from the front to the back of the palate. These electrodes are used to register tongue–palate contact from behind the upper front teeth to the junction between the hard and soft palate. The 62 wires that are connected to the electrodes are fed out in two thin tubes from the corners of the mouth and connected to the EPG3+ control box. When an electrode on the palate is contacted by the surface of the tongue, an electrical circuit, set up using a small current passed through an electrode held in the participant's hand, is completed and contact is registered. Tongue–palate registration is always binary in this system (i.e., an electrode is either contacted by the tongue or not).

Stimulus recording and data collection were controlled by the DMASTR software (Forster & Forster, 1990). Response latencies were collected using a small microphone approximately 5 mm in diameter that was clipped to the helmet and was placed approximately 1 in. from the mouth. Acoustic data were collected using a second microphone placed approximately 8 in. from the mouth. Stimulus presentation was integrated with acoustic data collection such that a marker was placed on the acoustic data at the onset of each target stimulus. This marker took the form of an acoustic tone that could not be heard by the participant.

Procedure. Participants were seated approximately 24 in. from the computer monitor. They were fitted with the magnetometer and EPG system apparatus, including the helmet, artificial palate, and sensors, which were calibrated appropriately.

After the apparatus was fitted properly, the acoustic and physiological recording equipment was checked by having participants repeat the words *beeb* and *barb* three times each. They then were asked to practice speaking the words "Mama moved to Melbourne" to ensure that the vertical jaw height and lip aperture differences were being appropriately recorded.

Participants were then told that they would be seeing a series of words that they were to read aloud as quickly and as accurately as possible. Each participant was given 10 practice items to read aloud so that the voice-key sensitivity could be adjusted to each individual participant.

Each experimental trial proceeded in the following way: a READY? prompt appeared in the center of the screen and was replaced with an asterisk (*) for 550 ms when participants indicated that they were ready by pressing a button. The target word replaced the asterisk and remained on the screen until the participant responded. It was then replaced by the READY? prompt. The stimulus presentation procedure followed as closely as possible that used by Kawamoto et al. (1998).

Participants were given a rest period between each of the 10 trial blocks. The first block of trials consisted of 80 items, since the first-position irregular words and their matched regular controls from Rastle and Coltheart (1999b) were presented along with the 40 target items; the remaining nine blocks of trials consisted of only 40 items each. A different random order of the stimulus items was used for each participant and for each trial block. Errors were recorded by the experimenter and were verified later in the acoustic data.

Data Preparation

Digitization, segmentation, and acoustic labeling. We excluded a small number of tokens produced by each participant from the analyses, as they were judged to have been mispronounced. The number of tokens that were used in the analysis is shown in Table 2.

The acoustic, kinematic, and electropalatographic data were digitized directly to a SUN workstation at 20 kHz, 500 Hz, and 200 Hz, respectively. The ESPS/Waves+ system was used for acoustic segmentation and labeling and to compute the fundamental frequency, root-mean-square amplitude, and formant frequencies. The first four formant center frequencies and their bandwidths were automatically tracked using the default settings (12th order linear-predictive-coding analysis, cosine window, 49-ms frame size, and 39-ms frame shift. See, e.g., Clark & Yallop, 1995; Harrington & Cassidy, 1999; Kent & Read, 1992, for a discussion of these techniques in speech signal processing). The automatically tracked formants were checked for accuracy, and hand corrections were made. Figure 1 shows an example of the EPG and acoustic displays of the production of /ko:/ by 1 participant.

Various acoustic boundaries were marked using the waveform and spectrographic data. For words with initial consonants /k/ or /g/, there are three acoustic phonetic segments: (a) *acoustic silence,* corresponding to the occluded phase of the vocal tract in which air pressure is built up behind the point of maximum constriction; (b) *acoustic frication,* that is the result of a turbulent airstream produced when air is forced through the narrow constriction between the tongue dorsum and the palate and between the (approximated, but not vibrating) vocal folds; and (c) the *acoustic vowel onglide* at which the vocal folds begin to vibrate and during which the vocal tract usually becomes progressively less constricted until it reaches the acoustic vowel target. We marked the two boundaries between these three acoustic phonetic segments (Figure 1): (a) the *onset of frication* (the boundary between acoustic silence and acoustic frication corresponding to the release of the stop), which was clearly visible as an increase in amplitude on the waveform and the onset of mid–high frequency energy in a spectrogram; and (b) the *onset of periodicity* (the boundary between acoustic frication and the acoustic vowel onglide), which was marked at the onset of the first glottal pulse on the waveform (first vertical striation on the wideband spectrogram).

For /h/-initial words, there are two acoustic phonetic segments: (a) *acoustic frication* that is caused primarily by a turbulent airstream at the glottis in the production of /h/, and (b) the *acoustic vowel onglide* defined above. We marked the *onset of frication* and *onset of periodicity* using very similar kinds of information as for oral stops. The mean durations in ms of the fricated section of /h/, calculated as the mean difference between these two time points, were as follows for /hi:/ and /ho:/, respectively: for FC, 75.9 and 82.1; for MT, 78.8 and 77.4; for SP, 79.0 and 77.5; for ZE, 78.7 and 79.5.

For /w/-initial words, in which there is no obvious acoustic discontinuity with the following vowel, we marked a single acoustic boundary at the acoustic onset of periodicity, which can be interpreted as the acoustic onset of /w/. Finally, for all syllables, we marked on the acoustic data the time point at which each target appeared.

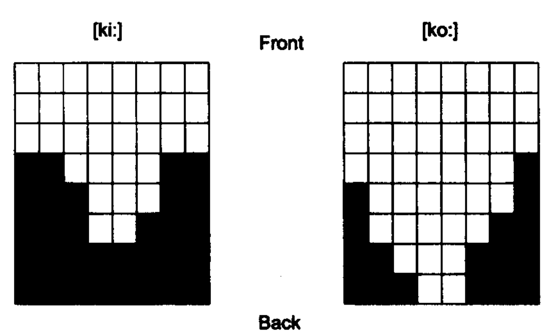

Figure 2. Palatograms sampled at the onset of articulatory closure for a single token of /ki:/ and /ko:/ produced by Participant FC. The black squares indicate a tongue–palate contact and "front" and "back" indicate nearest the front and back of the mouth, respectively.

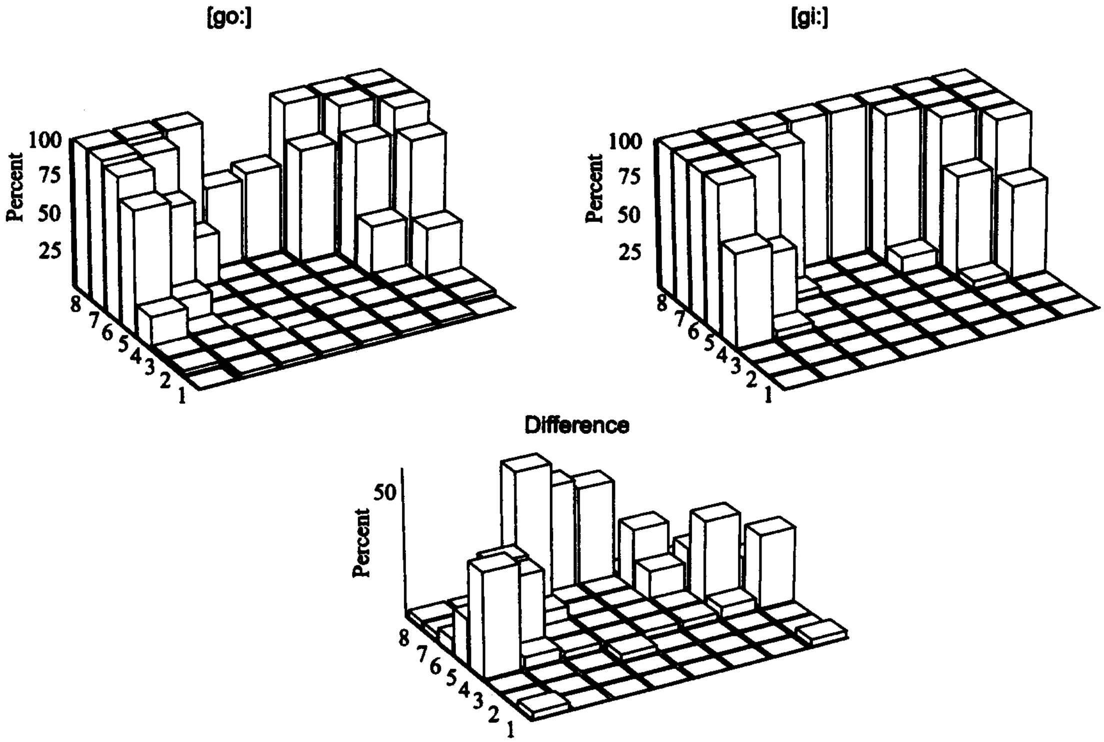

Figure 3. Three-dimensional bar charts showing the percentage of contacts in the 62 cells of /go:/ and /gi:/ tokens produced by Participant FC, as well as the percentage difference between these. Row 8 is the back of the palate.

Electropalatographic labeling. In the /k/- and /g/-initial words, there is an uninterrupted interval of acoustic silence between the tone marking the onset of the target stimulus and the acoustic onset of frication, as Figure 1 shows. However, this interval can be subdivided into three intervals based on the time at which the tongue dorsum contacts the palate for the production of the closure phase of the stop (see Figure 1). First, there is an interval of articulatory inactivity following the onset of the target stimulus during which the motor program must be assembled to produce the syllable. In this interval, there is minimal, or no, change in the tongue–palate contact patterns. This period is followed by an interval in which the tongue dorsum moves toward its target position, which is to form a complete airtight seal against the palate (for /k/ and /g/): We call this interval the *approach to the closure,* and it is characterized electropalatographically by a progressive increase in the number of EPG contact patterns. For example, if the configuration of the tongue was close to a "neutral" schwa-like vowel at the onset of the stimulus, then, in this second interval, the tongue dorsum has to be pulled up and back from that neutral position until it forms a seal at the palate. The third interval during the acoustically silent phase is the *articulatory closure* in which the seal between the tongue dorsum and the palate is maintained preventing any air behind the closure from escaping through the oral cavity. In this third interval, the number of EPG contact patterns at the back of the palate (for /k/ and /g/) is expected to reach a maximum, which is often maintained for at least 50 ms, as shown in Figure 1.

For each oral stop, we attempted to mark the onset of the third interval: that is, the *onset of maximum articulatory closure.* We defined this event as the time at which the number of EPG contacts in rows 7–8 of the palate attained a maximum value (Figure 1). There were four /k/ tokens and one /g/ token produced by SP that showed no clear maximum on this parameter. These tokens were excluded from the EPG analysis.

Table 3
Average Number of Contacts in Rows 3–8 of the Palate (see Figure 1) for /k/ and /g/ Extracted at the Onset of Maximum Articulatory Closure in the Two Vowel Contexts

	k				g			
Participant	ko:	ki:	*df*	*F*	go:	gi:	*df*	*F*
FC	15.7	23.6	1, 57	89.7*	18.8	22.6	1, 46	11.1*
MT	7.9	14.8	1, 58	100.1*	10.0	14.5	1, 45	39.0*
SP	12.3	18.8	1, 54	31.6*	13.2	18.8	1, 45	26.1*
ZE	19.3	24.6	1, 58	38.5*	19.8	25.6	1, 48	22.9*

* $p < .01$.

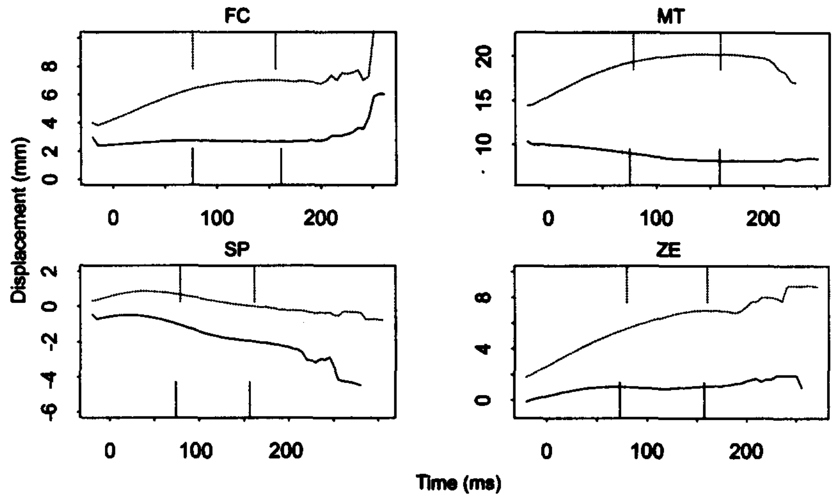

Figure 4. Lower-lip-*x* trajectories synchronized and then averaged at the onset of articulatory closure (t = 0 ms) separately in /ki:/ (dotted lines) and /ko:/ (solid lines) tokens for the 4 participants. The vertical lines are the average times of the onset of frication and the onset of periodicity shown separately for /ki:/ (top, dotted) and /ko:/ (bottom, solid). Lower values imply more extensive lip protrusion.

Data extraction. The EPG contacts and horizontal (x) movement of the lips were found to be the most valuable articulatory parameters for assessing the coarticulatory influence of the vowel on the preceding consonant. The EPG data were used to determine whether consonants followed by /i:/ were more palatalized, as assessed by the extent of lateral and posterior tongue contact against the artificial palate, than the same consonants in the context of the back vowel /o:/.

We used the lower-lip and upper-lip horizontal movement data to analyze whether the consonants were produced with a greater degree of lip protrusion in the context of the rounded /o:/ vowel compared with the unrounded /i:/ vowel: In this case, our expectation was that the extent of lip protrusion should be greater in the rounded than in the unrounded vowel context.

Data regarding movement of the jaw were also collected. However, preliminary analyses of these data showed too much variability across the talkers, or else provided no consistent evidence to show that the consonants were produced differently in the two contexts, and so we considered them no further.

For /w/-initial words, formant frequencies were also extracted because they can provide contributory information about the extent of tongue fronting.

The articulatory and acoustic parameters were extracted at the onset of the maximum articulatory closure in the velar stops /k/ and /g/, at the onset of frication in /h/, and at the onset of periodicity in /w/. We compared the differences separately for each participant on these articulatory and acoustic parameters. The differences were assessed using a two-level ANOVA (analysis of variance) function; when results are reported as significant, the criterion is $p < .01$ in all cases.

Results

RT data. We collected RT data from the first block of trials containing the regular and irregular items from Rastle and Coltheart (1999b). Those latencies for errors and their matched controls and for spoiled trials (because of voice-key failure) were discarded, and the remaining data were winsorized to the second standard-deviation boundary.

We analyzed data both by participants and by items, using an ANOVA that treated regularity as a within-groups variable. The by-participants analysis revealed a significant effect of regularity,

Table 4
Averaged Absolute Values (in Millimeters) Extracted at the Onset of Closure of the Horizontal Position of the Transducer Attached to the Lower Lip and Upper Lip for /k/ in the Two Vowel Contexts

	Lip							
	Lower				Upper			
Participant	ko:	ki:	*df*	*F*	ko:	ki:	*df*	*F*
FC	2.49	4.27	1, 57	6.7	−0.9	−0.5	1, 57	0.5
MT	9.96	15.49	1, 58	141.1*	9.1	10.7	1, 58	35.2*
SP	−0.55	0.60	1, 57	23.9*	−2.7	−2.8	1, 57	1.1
ZE	0.30	2.64	1, 58	83.5*	−2.3	−1.2	1, 58	88.1*

Note. The values are relative to a fixed position behind the head. Lower values imply greater horizontal protrusion of the lower or upper lips.
* $p < .01$.

Table 5
Averaged Absolute Values (in Millimeters) Extracted at the Onset of Closure of the Horizontal Position of the Transducer Attached to the Lower Lip and Upper Lip for /g/ in the Two Vowel Contexts

	Lip							
	Lower				Upper			
Participant	go:	gi:	*df*	*F*	go:	gi:	*df*	*F*
FC	2.66	3.79	1, 46	2.5	−1.1	−0.5	1, 46	1.2
MT	11.09	15.39	1, 45	53.8*	9.2	10.8	1, 45	23.0*
SP	−0.60	0.54	1, 46	13.1*	−2.8	−2.8	1, 46	0.1
ZE	0.43	2.22	1, 48	36.9*	−2.2	−1.3	1, 48	28.6*

Note. The values are relative to a fixed position behind the head. Lower values imply greater horizontal protrusion of the lower or upper lips.
* $p < .01$.

$F(1, 3) = 51.65, p < .01$, as irregular items yielded longer naming latencies (M = 493 ms) than regular items (M = 440 ms). The by-items analysis also revealed a significant effect of regularity, $F(1, 19) = 17.18, p < .001$, with irregular items yielding longer naming latencies (M = 500 ms) than regular items (M = 444 ms).

Physiological data: /k/ and /g/. Figure 2 shows palatograms extracted at the onset of maximum articulatory closure for single /k/ tokens produced by 1 participant, FC, in the contexts of /i:/ and /o:/. The /ki:/ palatogram shows considerably more extensive contact both laterally and in the last row, which corresponds approximately to the hard–soft palate junction. The lateral contact is typical for palatalized consonants (e.g., Recasens, 1990). The more extensive contact in the last row suggests that in this token of /ki:/, the principal constriction was at the boundary between the hard palate and soft palate: The diminished contact in the last row of the palatogram for /ko:/ comes about because the principal constriction is further back toward the soft palate, which is beyond the range of the final row of contacts of the acrylic palate.

Figure 3 shows three-dimensional barplots of the EPG contacts at the onset of maximum articulatory closure averaged across all of the /gi:/ and /go:/ tokens produced by the same participant. The height of the bar is proportional to the number of times that a tongue–palate contact was made across either the /gi:/ or /go:/ tokens: For example, the maximum height in the back row for /gi:/ means that the tongue contacted the palate at that point in all 19 /gi:/ tokens produced by FC. The lower panel, which is the difference between the barplots for /gi:/ and /go:/, shows more extensive lateral and posterior contact for /gi:/.

Table 6
Average Number of Contacts in Rows 3–8 of the Palate for /h/ Extracted at the Onset of Frication in the Two Vowel Contexts

Participant	ho:	hi:	*df*	*F*
FC	3.7	11.7	1, 54	247.1*
MT	0.8	2.4	1, 57	16.3*
SP	2.5	10.3	1, 55	123.6*
ZE	1.3	10.1	1, 57	331.1*

* $p < .01$.

An examination of similar displays for the other 3 participants showed a similar pattern of contact differences in all cases. In order to quantify these observations, we summed, for each palatogram separately, the number of contacts in rows 3–8 (e.g., in Figure 2, this summation would be 31 and 17—out of a maximum of 40 cells—for the /ki:/ and /ko:/ tokens, respectively). If there is no anticipatory influence of the vowel on the position of the tongue dorsum in the production of velar stops, then the sum of the contacts should be no different in the two vowel contexts. On the other hand, if there is coarticulatory adjustment to the following context, then the sum of the contacts should be greater for /ki:/ and /gi:/ (because of the greater lateral and posterior contact, as shown in Figures 2 and 3) than for /ko:/ and /go:/. Table 3 shows that, for all 4 participants and for both types of velar stops, the number of contacts in rows 3–8 is significantly greater in the context of /i:/ than in the context of /o:/, which confirms that the place of articulation of the velar stops at the point of maximum closure differs in the two vowel contexts in the expected direction.

Figure 4 shows averaged trajectories of the horizontal movement of the lower lip for the 4 participants in producing /ki:/ and /ko:/. The separate kinematic trajectories were time aligned at the onset of maximum articulatory closure and then averaged (without time normalization) separately for each talker and each context. (The averaged trajectories therefore become progressively less reliable for time values distant from t = 0 ms, the time-alignment point.) For all 4 talkers, the trajectories have lower values (a more protruded lower lip) in the context of the back rounded vowel /o:/ compared with /i:/ throughout the entire averaged trajectory. The greater extent of lower-lip protrusion for /k/ in the back-vowel context is clearly apparent at the onset of the maximum closure in all 4 participants, and the difference in the extent of the protrusion becomes progressively greater toward the vowel onset for 3 of the 4 participants. This is precisely the expected pattern if there is anticipatory coarticulation in the closure and release phases of the oral stop: since /o:/ is a rounded vowel that is produced with protruded lips, the lower-lip-x values should be lower for velar stops in this vowel context compared with that of /i:/.

The results of a statistical analysis on lip-x values are shown for /k/ and /g/ in Tables 4 and 5, respectively. The pattern of results is very similar in both /k/ and /g/: lower-lip-x values are significantly lower

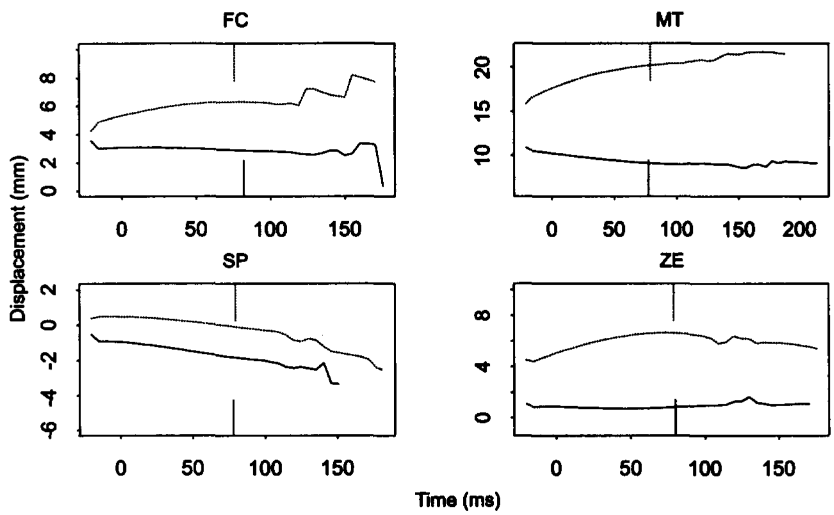

Figure 5. Lower-lip-*x* trajectories synchronized and then averaged at the onset of frication (t = 0 ms) separately in /hi:/ (dotted lines) and /ho:/ (solid lines) tokens for the 4 participants. The vertical lines are the average times of the onset of periodicity for /hi:/ (top, dotted) and /ho:/ (bottom, solid). Lower values imply more extensive lip protrusion.

(therefore more protrusion) for 3 of the 4 participants in the /o:/ compared with the /i:/ context; upper-lip-*x* values are significantly lower for 2 of the 4 participants in the /ko:/ compared with /ki:/ and in the /go:/ compared with /gi:/ contexts. The results therefore do not unequivocally show that /k/ and /g/ are always produced with more lip rounding at the onset of closure. However, taking into account the EPG data, there is strong evidence to support the claim that coarticulatory adjustments of the oral stops to the context of the following vowel are observed in the reading-aloud task.

Physiological data: /h/. Although /h/ is not produced with a closure in the oral cavity, we can nevertheless infer from the EPG contact patterns whether /h/ was more palatalized in /hi:/ than in /ho:/. As discussed earlier, if a consonant is palatalized, then we should expect to see some evidence of lateral and posterior contacts on the artificial palate, although the extent of posterior contact is likely to be less for /hi:/ than /ki:/ (because /k/ is produced with a complete closure). Table 6 shows that the number of contacts in rows 3–8 extracted at the acoustic onset of frication is significantly greater in the /hi:/ than in the /ho:/ context for all 4 participants. These significant differences are consistent with the different coarticulatory adjustments of /h/ to the following-vowel context—specifically that /h/ is more palatalized in /hi:/ than in /ho:/.

Figure 5 shows trajectories of lower-lip-*x* movement time-aligned at the onset of frication (t = 0 ms) and averaged separately for each participant and the two vowel contexts. The pattern of lower-lip movement is very similar to that of the /k/ in the two contexts in Figure 4: the lower-lip values are lower in the back-vowel context at the onset of frication for all 4 participants, suggesting /h/ in the /ho:/ context is produced with greater lower-lip protrusion than in the /hi:/ context. Moreover, these differences between the two vowel contexts at frication onset become progressively more pronounced throughout the frication for 3 of the 4 participants.

A statistical analysis of the position of the lower lip at the onset of frication (Table 7) shows a significant difference ($p < .01$) in

Table 7
Averaged Absolute Values (in Millimeters) Extracted at the Onset of Frication of the Horizontal Position of the Transducer Attached to the Lower Lip and Upper Lip for /h/ in the Two Vowel Contexts

	Lip							
	Lower				Upper			
Participant	ho:	hi:	*df*	*F*	ho:	hi:	*df*	*F*
FC	3.07	5.32	1, 54	12.5*	−1.4	−0.5	1, 54	3.2
MT	10.27	17.63	1, 57	252.6*	8.3	11.5	1, 57	109.5*
SP	−0.96	0.48	1, 55	24.3*	−2.8	−2.7	1, 55	0.9
ZE	0.78	5.08	1, 57	223.3*	−3.2	−0.8	1, 57	355.6*

Note. The values are relative to a fixed position behind the head. Lower values imply greater horizontal protrusion of the lower or upper lips.
* $p < .01$.

Table 8
Average Number of Contacts in Rows 3–8 of the Palate for /w/ Extracted at the Onset of Periodicity in the Two Vowel Contexts

Participant	wo:	wi:	*df*	*F*
FC	3.4	7.2	1, 54	217.7*
MT	0.8	1.1	1, 53	2.3
SP	0.3	4.3	1, 55	238.9*
ZE	4.3	6.0	1, 58	41.3*

*$p < .01$.

the expected direction between the two contexts for all 4 participants. The differences between the two contexts on the horizontal movement of the upper lip are significant in the expected direction for 2 of the 4 participants.

In summary, both the EPG and the kinematic data are strongly indicative of the adjustment of /h/ to the context of the following vowel.

Physiological data: /w/. It is more difficult to assess the extent of anticipatory coarticulation of the vowel on /w/ from the available physiological data for two reasons. First, because /w/ is an approximant, the vocal tract must be sufficiently unconstricted (and certainly less so than for the velar stops) to ensure that the airstream does not become turbulent: Consequently, the extent of lingual–palatal contact is likely to be a good deal less than for the velar stops or /h/. Second, because /w/ is itself specified as a tongue-backed and lip-rounded articulation, and because these are two of the main features that make it distinctive from /j/ (as in *you*), the extent of deflection away from these targets due to the coarticulatory influence of the following vowel may well be a good deal less than in /h/ (which is not in opposition on either of these features to any other phonemes of English); that is, /w/ is likely to be a good deal more *resistant* to coarticulation on these articulatory measures than /h/ (see Farnetani, 1990; Fowler & Saltzman, 1993; and Recasens, 1984, for an analysis and discussion of coarticulatory resistance).

Nevertheless, although the number of contacts in rows 3–8 is considerably less than for either the velar stops or /h/, Table 8 shows that for 3 of the participants, there is a significantly greater number of contacts at the onset of periodicity of /wi:/ compared with /wo:/.

However, as shown in Table 9, there is less evidence than for the other two consonant categories to show a greater extent of lower- or upper-lip protrusion at the onset of periodicity of /w/ in the /wo:/ compared with the /wi:/ contexts: the lower-lip-x and upper-lip-x values are significantly lower for 2 of the 4 and 1 of the 4 participants, respectively, at the onset of periodicity in the /wo:/ compared with the /wi:/ contexts.

We also examined second formant frequencies in our analysis of /w/. Our expectation was that if the tongue dorsum was further forward and the lips less protruded at the periodic onset of /wi:/ compared with /wo:/, then the second formant frequency should be raised at this point: The greater tongue-dorsum fronting and lip spreading at the target of /i:/ compared with the target of /o:/ both contribute to its substantially raised F2 value (e.g., Fant, 1960).

The averaged F2 trajectories time-aligned at the onset of periodicity for these two contexts in Figure 6 show that F2 at the onset of periodicity is raised in /wi:/ compared with /wo:/, and these differences are significant for 3 of the 4 participants as is shown in Table 10.

Discussion

The data presented are clear. Coarticulatory effects are observed in the reading-aloud task for each type of word onset that we studied. Coarticulatory effects were most evident for those items beginning with the plosive phonemes /g/ and /k/: all 4 of the participants showed significantly greater tongue–palate contact in the context of the /i:/ vowel phoneme than /o:/. Moreover, 3 of the 4 participants showed significantly greater lower-lip protrusion for those items beginning /ko:/ and /go:/ than /ki:/ and /gi:/; 2 of the 4 participants showed significantly greater upper-lip protrusion for those items beginning /ko:/ and /go:/ than /ki:/ and /gi:/.

Coarticulatory effects were also observed for those items beginning with the nonplosive phoneme /h/. For these items, significantly more tongue–palate contact was observed in the context of the /i:/ vowel phoneme than the /o:/ vowel phoneme for all 4 participants. Furthermore, all 4 of the participants showed significantly greater lower-lip protrusion at the onset of frication of /h/

Table 9
Averaged Absolute Values (in Millimeters) Extracted at the Onset of Periodicity of the Horizontal Position of the Transducer Attached to the Lower Lip and Upper Lip for /w/ in the Two Vowel Contexts

	Lip							
	Lower				Upper			
Participant	wo:	wi:	*df*	*F*	wo:	wi:	*df*	*F*
FC	1.6	1.9	1, 54	0.3	−3.1	−3.1	1, 54	0.0
MT	6.9	7.0	1, 53	0.0	6.1	6.5	1, 53	4.3
SP	−2.6	−1.6	1, 55	19.4*	−4.0	−3.6	1, 55	5.8
ZE	−1.1	0.3	1, 58	76.5*	−5.2	−4.5	1, 58	13.7*

Note. The values are relative to a fixed position behind the head. Lower values imply greater horizontal protrusion of the lower or upper lips.
*$p < .01$.

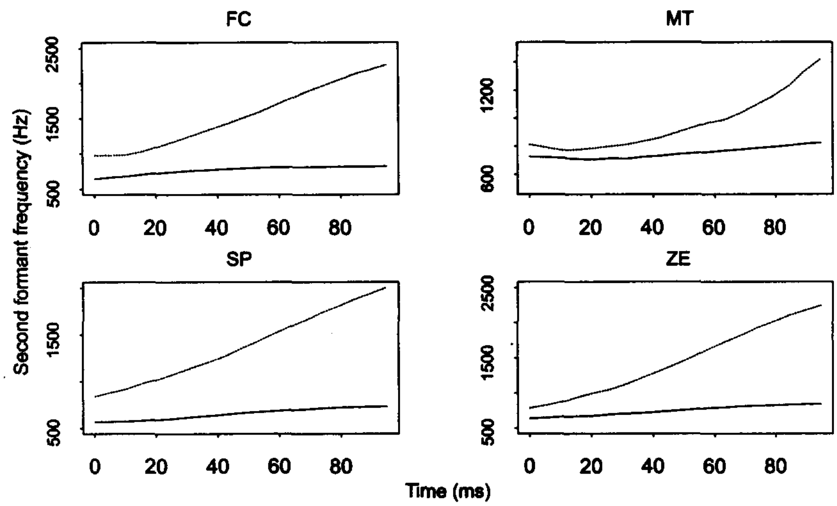

Figure 6. Second formant frequency trajectories synchronized and then averaged at the onset of periodicity (t = 0 ms) separately in /wi:/ (dotted lines) and /wo:/ (solid lines) tokens for the 4 participants.

in the context of /o:/ than in the context of /i:/; 2 of the 4 participants showed significantly greater upper-lip protrusion for /h/ in the context of /o:/ than in the context of /i:/.

Coarticulatory effects were least pronounced for items beginning with the phoneme /w/. Nevertheless, 3 of the 4 participants showed significantly greater total tongue–palate contact for /w/ in the context of /i:/ than in the context of /o:/. Greater lower-lip protrusion and greater upper-lip protrusion was evident for /w/ in the context of /o:/ than in the context of /i:/ for 2 of the 4 participants and 1 of the 4 participants, respectively.

In summary, the EPG and lip-protrusion data indicate that coarticulatory effects are observed in the single-word reading-aloud task, for items beginning both with plosive and with nonplosive phonemes. These effects are observed in the presence of reaction-time data that clearly replicate what has been reported already by Rastle and Coltheart (1999b) regarding the regularity effect in the reading-aloud task. Taken together, these data suggest strongly that the abundance of findings regarding anticipatory coarticulatory effects in other speech-production situations also apply to single-word speeded reading aloud.[2]

The presence of anticipatory coarticulatory effects in the production of certain parts of the initial-consonant phoneme in the speeded reading-aloud task refutes a theory of the initiation of articulation based on knowledge of the initial phoneme. If articulation were initiated without taking into account the influence of the subsequent vowel phoneme, then anticipatory coarticulatory effects would not have been observed during the articulation of the initial phoneme.

Some ambiguity remains, however, as to what exactly is known before articulation is initiated in reading aloud. Although we have unambiguously refuted an initial-phoneme account of the initiation of articulation, we have not shown unambiguously that the development of a complete phonological representation is required before articulation is initiated in reading aloud. Further research investigating the effects of final parts of the syllable on the articulation of the initial phoneme would be required to show categorically that the computation of phonology is complete before articulation is initiated in reading aloud. Additional possibilities include (a) using polysyllabic items to differentiate between whole-word and whole-syllable criteria for the initiation of articulation and (b) investigating whether coarticulatory effects occur to the same degree in regular words (such as those used here) and in items in which the generation of phonology is slow (e.g., nonwords and irregular words).

Table 10
Averaged Second Formant Frequencies (Hz) Extracted at the Onset of Periodicity for /w/ in the Two Vowel Contexts

Participant	wi:	wo:	*df*	*F*
FC	977	644	1, 54	24.2*
MT	813	726	1, 53	2.1
SP	840	568	1, 55	15.6*
ZE	784	638	1, 58	13.9*

* $p < .01$.

[2] These results represent average coarticulatory effects over multiple presentations of the stimulus set, as is typical in speech physiology research. It could be argued that the robust coarticulatory effects that we observed were due to or heightened by these multiple presentations, and so may not reflect processes that occur in the standard naming task. In order to investigate this possibility we conducted all of the analyses that appear in the Results section again, using data collected during the first trial block only. Because the number of tokens was small (on average one tenth of the number shown in Table 2), we did not necessarily expect to find statistical significance; rather, we sought to determine whether the same trends would be evident in the first trial block as were observed over the 10 trial blocks. The results of the analyses from the Block 1 data were extremely similar to the analyses reported in the Results section, and in many cases reached statistical significance. We are therefore confident that the coarticulatory effects we observed were not restricted to only some of the trial blocks or due to the repetition of the stimulus items.

Quite apart from these possibilities, we have shown that robust coarticulatory effects are observed in the reading-aloud task: Articulation of the initial phoneme, plosive or nonplosive, is affected by the nature of the following vowel. It therefore cannot be the case that in speeded reading-aloud experiments, initial phonemes are produced (and, in the case of initial nonplosive phonemes, the voice key is triggered) without knowledge of subsequent phonemes. How these facts can be reconciled with the intriguing findings of Kawamoto et al. (1998) regarding the interaction between regularity and plosivity on naming latency is a matter for further empirical and theoretical consideration.

References

Alfonso, P., & Baer, T. (1982). Dynamics of vowel articulation. *Language and Speech, 25,* 151–173.

Arnfield, S. (1997) *EPG3+ documentation.* Unpublished manuscript, Department of Linguistic Science, University of Reading. Available on-line at http://www.linguistics.reading.ac.uk/research/speechlab/epg/.

Bachoud-Lévi, A. -C., Dupoux, E., Cohen, L., & Mehler, J. (1998). Where is the length effect? A cross-linguistic study of speech production. *Journal of Memory and Language, 39,* 331–346.

Balota, D. A., & Chumbley, J. I. (1984). Are lexical decisions a good measure of lexical access? The role of word frequency in the neglected decision stage. *Journal of Experimental Psychology: Human Perception and Performance, 10,* 340–357.

Bell-Berti, F., & Harris, K. (1979). Anticipatory coarticulation: Some implications from a study of lip rounding. *Journal of the Acoustical Society of America, 65,* 1268–1270.

Bell-Berti, F., & Harris, K. S. (1981). A temporal model of speech production. *Phonetica, 38,* 9–20.

Bernard, J. R. L. (1970). Toward the acoustic specification of Australian English, *Zeitschrift für Phonetik, 23,* 113–128.

Branderud, P. (1985). Movetrack—a movement tracking system. *Perilus, IV,* 20–29.

Browman, C. P., & Goldstein, L. (1990). Targetless schwa: An articulatory analysis. *Haskins Laboratories Status Report on Speech Research, SR-101/102,* 194–219.

Butcher, A., & Weiher, E. (1976). An electropalatographic investigation of coarticulation in VCV sequences. *Journal of Phonetics, 4,* 59–74.

Carré, R., & Chennoukh, S. (1995). Vowel-consonant-vowel modeling by superposition of consonant closure on vowel-to-vowel gestures. *Journal of Phonetics, 23,* 231–241.

Clark, J., & Yallop, C. (1995). *Phonetics and phonology* (2nd ed.). Oxford, England: Blackwell.

Coltheart, M. (1978). Lexical access in simple reading tasks. In G. Underwood (Ed.), *Strategies of information processing* (pp. 151–216). London: Academic Press.

Coltheart, M., Curtis, B., Atkins, P., & Haller, H. (1993). Models of reading aloud: Dual-route and parallel-distributed-processing approaches. *Psychological Review, 100,* 589–608.

Coltheart, M., & Rastle, K. (1994). Serial processing in reading aloud: Evidence for dual-route models of reading. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 1197–1211.

Cortese, M. J. (1998). Revisiting serial position effects in reading. *Journal of Memory and Language, 39,* 652–665.

Cortese, M. J., & Zevin, J. D. (1998, November). *Lexicality effects in naming: Where in the word are they?* Poster presented at the 39th annual meeting of the Psychonomic Society, Dallas, TX.

Cox, F. M. (1996). *An acoustic study of vowel variation in Australian English.* Unpublished doctoral dissertation, Macquarie University, Sydney, Australia.

Daniloff, R., & Moll, K. (1968). Coarticulation of the lip rounding system. *Journal of Speech and Hearing Research, 11,* 707–721.

de Jong, K. (1995). The supraglottal articulation of prominence in English: Linguistic stress as localized hyperarticulation. *Journal of the Acoustical Society of America, 97,* 491–504.

Fant, G. (1960). *The acoustic theory of speech production.* The Hague, The Netherlands: Mouton.

Farnetani, E. (1990). V-C-V lingual coarticulation and its spatiotemporal domain. In W. J. Hardcastle & A. Marchal (Eds.), *Speech production and speech modelling* (pp. 93–130). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Forster, K. I., & Forster, J. C. (1990). *User's guide to the DMASTR display system: Laboratory software for mental chronometry.* Unpublished document.

Fowler, C. A. (1981). Production and perception of coarticulation among stressed and unstressed vowels. *Journal of Speech and Hearing Research, 24,* 127–139.

Fowler, C. A., & Rosenblum, L. D. (1989). The perception of phonetic gestures. *Haskins Laboratories Status Report on Speech Research, SR-99/100,* 102–117.

Fowler, C. A., & Saltzman, E. (1993). Coordination and coarticulation in speech production. *Language and Speech, 36,* 171–195.

Frederiksen, J. R., & Kroll, J. F. (1976). Spelling and sound: Approaches to the internal lexicon. *Journal of Experimental Psychology: Human Perception and Performance, 2,* 361–379.

Harrington, J., & Cassidy, S. (1994). Dynamic and target theories of vowel classification: Evidence from monophthongs and diphthongs in Australian English. *Language and Speech, 37,* 357–373.

Harrington, J., & Cassidy, S. (1999). *Techniques in speech acoustics.* Dordrecht, The Netherlands: Kluwer.

Harrington, J., Cox, F., & Evans, Z. (1997). An acoustic phonetic study of broad, general, and cultivated vowels. *Australian Journal of Linguistics, 17,* 155–184.

Henderson, L. (1982). *Orthography and word recognition in reading.* London: Academic Press.

Huffman, M. (1986). Patterns of coarticulation in English. *UCLA Working Papers in Phonetics, 63,* 26–47.

Kawamoto, A. H., Kello, C. T., Jones, R., & Bame, K. (1998). Initial phoneme versus whole word criterion to initiate pronunciation: Evidence based on response latency and initial phoneme duration. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 24,* 862–885.

Keating, P. A., Lindblom, B., Lubker, J., & Kreiman, J. (1994). Variability in jaw height for segments in English and Swedish VCVs. *Journal of Phonetics, 22,* 407–422.

Kent, R., & Read, C. (1992). *The acoustic analysis of speech.* San Diego, CA: Singular Press.

Lehiste, I. (1964). *Acoustical characteristics of selected English consonants.* Bloomington: Indiana University Press.

Liberman, A., Cooper, F., Shankweiler, D., & Studdert-Kennedy, M. (1967). Perception of the speech code. *Psychological Review, 74,* 431–461.

Liberman, A., & Mattingly, I. (1985). The motor theory of speech perception revised. *Cognition, 21,* 1–36.

Lindblom, B. (1963). Spectrographic study of vowel reduction. *Journal of the Acoustical Society of America, 35,* 1773–1781.

Lubker, J. (1981). Temporal aspects of speech production: Anticipatory labial coarticulation. *Journal of Phonetica, 38,* 51–65.

MacKay, D. G. (1987). *The organization of perception and action: A theory for language and other cognitive skills.* New York: Springer Verlag.

Magen, H. (1989). *An acoustic study of V-to-V coarticulation in English.* Unpublished doctoral dissertation, Yale University.

Manuel, S. (1990). The role of contrast in limiting vowel-to-vowel coarticulation in different languages. *Journal of the Acoustical Society of America, 88,* 1286–1298.

Monsell, S. (1990). Frequency effects in lexical tasks: Reply to Balota and Chumbley. *Journal of Experimental Psychology: General, 119,* 335–339.

Norris, D. (1994). A quantitative multiple-levels model of reading aloud. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 1212–1232.

Öhman, S. E. G. (1966). Coarticulation in VCV utterances: Spectrographic measurements. *Journal of the Acoustical Society of America, 39,* 151–168.

Öhman, S. E. G. (1967). Numerical model of coarticulation. *Journal of the Acoustical Society of America, 41,* 310–320.

Paap, K. R., & Noel, R. W. (1991). Dual-route models of print to sound: Still a good horse race. *Psychological Research, 53,* 13–24.

Perkell, J. (1969). *Physiology of speech production: Results and implications of a quantitative cineradiographic study.* Cambridge, MA: MIT Press.

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.

Potter, R., Kopp, G., & Green, H. (1947). *Visible speech.* New York: Van Nostrand.

Rastle, K., & Coltheart, M. (1998). Whammies and double whammies: The effect of length on nonword reading. *Psychonomic Bulletin and Review, 5,* 277–282.

Rastle, K., & Coltheart, M. (1999a). Lexical and nonlexical phonological priming in reading aloud. *Journal of Experimental Psychology: Human Perception and Performance, 25,* 461–481.

Rastle, K., & Coltheart, M. (1999b). Serial and strategic effects in reading aloud. *Journal of Experimental Psychology: Human Perception and Performance, 25,* 482–503.

Recasens, D. (1984). V-to-C coarticulation in Catalan VCV sequences: An articulatory and acoustical study. *Journal of Phonetics, 12,* 61–73.

Recasens, D. (1989). Long range coarticulatory effects for tongue dorsum contact in VCVCV sequences. *Haskins Laboratories Status Reports on Speech Research, SR-99/100,* 19–37.

Recasens, D. (1990). An electropalatographic and acoustic study of consonant-to-vowel coarticulation. *Haskins Laboratories Status Reports on Speech Research, SR-101/102,* 130–148.

Recasens, D., Pallarès, M., & Fontdevila, J. (1997). A model of lingual coarticulation based on articulatory constraints. *Journal of the Acoustical Society of America, 102,* 544–561.

Seidenberg, M. S., Waters, G. S., Barnes, M. A., & Tanenhaus, M. K. (1984). When does irregular spelling or pronunciation influence word recognition? *Journal of Verbal Learning and Verbal Behavior, 23,* 383–404.

Stevens, K. N., & House, A. S. (1963). Perturbation of vowel articulations by consonantal context: An acoustical study. *Journal of Speech and Hearing Research, 6,* 111–127.

Treiman, R., Mullennix, J., Bijeljac-Babic, R., & Richmond-Welty, E. D. (1995). The special role of rimes in the description, use, and acquisition of English orthography. *Journal of Experimental Psychology: General, 124,* 107–136.

Whalen, D. (1990). Coarticulation is largely planned. *Journal of Phonetics, 18,* 3–35.

Zorzi, M., Houghton, G., & Butterworth, B. (1998). Two routes or one in reading aloud? A connectionist dual-process model. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 1131–1161.

Received October 5, 1998
Revision received April 27, 1999
Accepted July 2, 1999 ■