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Reading skill and exposure to orthography influence speech production

MEREDITH SALETTA
University of Iowa

LISA GOFFMAN
Purdue University

DIANE BRENTARI
University of Chicago

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ADDRESS FOR CORRESPONDENCE
Meredith Saletta, Department of Communication Sciences and Disorders, University of Iowa, Wendell Johnson Speech and Hearing Center, Iowa City, IA 52242. E-mail: meredith-saletta@uiowa.edu

ABSTRACT
Orthographic experience during the acquisition of novel words may influence production processing in proficient readers. Previous work indicates interactivity among lexical, phonological, and articulatory processing; we hypothesized that experience with orthography can also influence phonological processing. Phonetic accuracy and articulatory stability were measured as adult, proficient readers repeated and read aloud nonwords, presented in auditory or written modalities and with variations in orthographic neighborhood density. Accuracy increased when participants had read the nonwords earlier in the session, but not when they had only heard them. Articulatory stability increased with practice, regardless of whether nonwords were read or heard. Word attack skills, but not reading comprehension, predicted articulatory stability. Findings indicate that kinematic and phonetic accuracy analyses provide insight into how orthography influences implicit language processing.

It is well documented that the characteristics of a word's phonology, including its phonotactic frequency and phonological neighborhood density, influence the perception and production of that word. What is less obvious is that the characteristics of a word's orthography, including its grapheme–phoneme correspondences and orthographic neighborhood density, also influence its perception and production (Alario, Perre, Castel, & Ziegler, 2007; Ventura, Morais, Pattamadilok, & Kolinsky, 2004; Ziegler & Ferrand, 1998; Ziegler, Ferrand, & Montant, 2004; Ziegler, Jacobs, & Klueppel, 2001; Ziegler, Van Orden, & Jacobs, 1997). Perceiving a word auditorily will activate its orthographic representation even when the listener is not performing a spelling task (Miller & Swick, 2003). The degree of spelling–sound consistency of novel words may influence speech in tasks such as picture naming and auditory lexical decision making, further suggesting that orthographic factors are involved even when the individual is not actually reading (Rastle, McCormick, Bayliss, & Davis, 2011). This effect is known as *orthographic interference*; that is, facilitation or disruption may occur as the result of phonological–orthographic correspondence or incongruency (Burgos, Cucchiarini, van Hout, & Strik, 2014; Weber-Fox, Spencer, Cuadrado, & Smith, 2003).

Interactive models of reading capture the relationship between a word's phonology and orthography by positing a bidirectional flow of information: orthographic representations activate phonological representations, but the reverse occurs as well (Jacobs & Grainger, 1994). Morton's classic model (1969) describes three types of information included in the representation of a word in the mental lexicon. Spelling, sound, and meaning are available when a word is recognized, regardless of the modality in which the word was received (Miller & Swick, 2003). Furthermore, interactive models define the relationship among semantic, syntactic, phonological, and orthographic information as "nodes" that are triggered in sequence or simultaneously (Rapp & Goldrick, 2000); these nodes can activate and mutually influence one another (Alario et al., 2007). Knowledge of orthography changes an individual's perception of the spoken word (Pattamadilok, Perre, Dufau, & Ziegler, 2009; Ventura, Morais, & Kolinsky, 2007). Similarly, the association of novel words with consistent or inconsistent representations of spelling and sound may create an immediate effect on participants' picture naming (Rastle et al., 2011), providing evidence for the interaction between orthography and spoken language processing. These studies lead to the conclusion that experience with reading changes how words are produced. It is the goal of the current study to determine how manipulations of the modality of presentation of nonword stimuli (i.e., auditory or written) influence speech production.

Specific characteristics of a word's orthography can influence its processing. These factors include *neighborhood density*, *consistency*, and *transparency/opacity* effects. Neighborhood density effects involve the number of words that are orthographically or phonologically similar to a given sequence (Coltheart, Davelaar, Jonasson, & Besner, 1977; Storkel, 2013). Consistency effects involve the degree of grapheme–phoneme correspondence in the word's spelling (Bolger, Hornickel, Cone, Burman, & Booth, 2008). English includes many inconsistent mappings and, consequently, is on the opaque end of the continuum (Frost, Katz, & Bentin, 1987; Ziegler & Goswami, 2005). For instance, in English, the sequence /ɝ/ can be spelled in several ways, including *birch*, *lurch*, *perch*, and *search* (Ventura et al., 2007). These three factors (density, consistency, and transparency) interact differently in various languages based on the languages' orthography. For instance, the psycholinguistic grain size theory (Ziegler & Goswami, 2005) predicts that readers of English need to use both "small unit" and "large unit" recoding strategies (Brown & Deavers, 1999). This happens because the inconsistency, or opaque characteristics, of smaller units (such as graphemes) is much higher than that of larger units (such as rimes). Languages that contain more transparent characteristics do not have this dual focus. This is important for the current study because our procedures involve the manipulation of these smaller units. The nonword stimuli in this study will be presented with either transparent or opaque spellings; the influence of these manipulations on speech production accuracy and stability will be assessed.

In spoken language, frequency effects such as neighborhood density influence production processes, as indexed by measures such as reaction time and phonetic accuracy (e.g., Rastle et al., 2011; Vitevitch, 2002). The influence of orthographic neighborhood factors on production processes has been minimally explored, though there is substantial evidence that orthographic factors influence phonological organization. Frequency and transparency effects likely overlap (e.g., the English homophones *peek* and *pique* differ in regard to both of these factors; the former spelling has a greater number of orthographic neighbors and is also more transparent). Neighborhood density influences spoken language processing; however, little is known about how orthographic factors, including orthographic density, may analogously influence language production. Therefore, we have chosen to manipulate orthographic neighborhood density in order to explore one way in which orthography influences processing.

ORTHOGRAPHY INFLUENCES EXPLICIT AND METALINGUISTIC PROCESSING

Influences of orthography on language processing have predominantly been investigated using metalinguistic measures. These methods target an *explicit* level of processing; that is, participants are asked to attend to the sound structure of the spoken or written stimuli and then to make mindful decisions (Snow, Burns, & Griffin, 1998). Examples of such tasks include monitoring lists for rhyming words (Seidenberg & Tannenhaus, 1979; Zecker, 1991), counting phonemes (Ehri & Wilce, 1980) or syllables (Ventura, Kolinsky, Brito-Mendes, & Morais, 2001), or training on homonym definition and ambiguous sentence detection in order to improve reading comprehension (Zipke, Ehri, & Smith Cairns, 2009).

However, metalinguistic judgments represent only some aspects of linguistic processing, and these results come with important caveats. The types of studies mentioned above involve analyzing language at a high (i.e., explicit) level of awareness and consciousness, which is not a requirement for speaking and may not be present in all adult talkers. For example, competent speakers who are not literate in an alphabetic system may experience difficulty in some metalinguistic tasks, such as sound segmentation (Morais, Cary, Algria, & Bertelson, 1979; Read, Zhang, Nie, & Ding, 1986). Drawing conclusions based exclusively on metalinguistic judgments presents an incomplete picture, because these same individuals would likely be proficient in tasks involving more implicit components of linguistic processing. Orthographic factors may have a deeper effect on speakers and readers: one that is apparent in their implicit linguistic processing and accessible via the methods we will employ in this study.

DOES ORTHOGRAPHY INFLUENCE IMPLICIT LINGUISTIC PROCESSING?

A different aspect of learning involves *implicit* processing, in which the aspects of language usage are not available for conscious access (Poldrack, Prabhakaran, Seger, & Gabrieli, 1999). Implicit learning can be described as unintentional, or outside of the awareness that learning has occurred; it occurs over an extended period; it involves the knowledge of rules or procedures rather than facts (Thomas et al., 2004); it requires no mindful judgments (Hoff, 2011); and it may not be available for introspective report (Berry & Broadbent, 1984). Behavioral outcomes also differ based on the type of learning that has occurred. For instance, participants can perform differently on a task depending upon whether or not they are given explicit instructions (Gebauer & Mackintosh, 2007); thus, the implicit/explicit difference goes beyond introspective report or description (Xie, Gao, & King, 2013).

Researchers have used several different methodologies, ranging from phonetic accuracy measures to reaction time to fine-grained acoustic and kinematic analyses, to quantify implicit processing and provide evidence for interactions among lexical, phonological, and phonetic levels of processing in spoken language (e.g., Pierrehumbert, 2002). For example, studies of speech production reveal that there are interactions between lower levels of speech output and higher levels of language processing. Slips of the tongue often have a lexical bias; that is, erroneous phoneme substitution is likely to lead to the production of real words. This indicates that slips of the tongue do not simply reflect problems in motor programming, but suggest that the planning of lexical components of speech production is implicated at this level (Goldrick, Baker, Murphy, & Baese-Berk, 2011; McMillan, Corley, & Lickley, 2009). Thus, overt and covert errors that occur at lower levels of speech production may reveal interactivity with higher level aspects of language processing.

Beyond these interactions in spoken language, some studies demonstrate that orthographic factors also influence implicit processing. Furthermore, orthography interacts with both higher level linguistic processes and lower level speech output. This occurs even in tasks that do not directly involve reading, including auditory shadowing tasks (Rastle et al., 2011; Ventura et al., 2007), auditory lexical decision tasks (Dich, 2011; Zeguers et al., 2011), and semantic category judgment (Assink, van Bergen, van Teeseling, & Knuijt, 2004; Booth, Bebko, Burman, & Bitan, 2007). These effects may be modified by the specific orthographic characteristics of the study's stimuli (e.g., consistent vs. inconsistent spellings) and/or participants' reading skill. For instance, while phonological neighborhood density effects are present in all speakers, orthographic neighborhood effects emerge only in proficient readers (Ziegler, Muneaux, & Grainger, 2003).

The measures described above, such as phonetic accuracy and lexical decision and shadowing, may be used to quantify implicit processing because they do not require participants to make conscious judgments about the stimuli that they hear or read. Unlike what is assessed by metalinguistic tasks, many components of speaking and reading do not require conscious awareness, and thus may be viewed as automatic. This automaticity becomes established throughout the development of children's reading skills, which proceeds from a visual/logographic stage, to more segmental analysis, to the identification of written words by sight (Ehri, 1991; Kamhi & Catts, 2012; Masonheimer, Drum, & Ehri, 1984; Ventura et al., 2007). Readers at this mature level bypass phonological conversion by applying regularly occurring patterns such as morphemes and shared letter sequences (Kamhi & Catts, 2012). These implicit components of the effects of reading on global language processing are the focus of the present investigation. Specifically, little is known regarding changes in participants' ability to speak or read aloud that occur as a function of exposure to the written word. Measuring speech production can circumvent the limitations inherent in studies of exclusively metalinguistic tasks, in that it addresses a different level of processing that is present in all speakers, not just those who are literate. Therefore, in the present work, we will evaluate whether exposure to orthographic cues during learning interacts with speech production processes in adult learners. Specifically, we will assess participants' production accuracy and speech movement stability as they learn nonwords that vary in modality of presentation (auditory or written) or in orthographic transparency (transparent or opaque spelling). We will also explore whether these factors are modulated by individual differences in reading proficiency.

IMPLICIT PROCESSING AS MEASURED BY ARTICULATORY KINEMATICS AND NONWORD REPETITION

A primary methodology that has been used and will be a focus here is phonetic accuracy, or the assessment of errors that talkers include in their productions of novel word forms. An additional promising methodology, which has the potential to quantify implicit learning and which also targets the interaction between speech motor output and language processing, involves speech kinematics (Goffman, Gerken, & Lucchesi, 2007; Heisler, Goffman, & Younger, 2010; McMillan et al., 2009; Smith & Goffman, 1998). Analyses of speech kinematics necessitate only that the speaker produce target words or sentences, not make metalinguistic decisions. Measuring articulatory stability provides a direct analysis of the influences of lexical, grammatical, and phonological factors on speech production. For example, Saletta et al. (in preparation) discovered that adults' speech movement stability changes according to the syntactic complexity of a given sentence. In addition, children acquiring a novel word form showed increased speech movement stability when that form was paired with a meaningful referent, but not when it was simply heard and produced as a meaningless nonword (Gladfelter & Goffman, 2013; Heisler et al., 2010). Articulatory movement analysis has the potential to reveal how readers' experience with orthography may reorganize their phonological processing.

In these sorts of studies, it is essential that nonwords be used as stimuli. It is evident that speech production is highly sensitive to experience, and only the use of nonwords can control an individual's prior knowledge. Furthermore, a task involving nonwords may be useful in differentiating individuals with varying levels of reading proficiency. Whereas high- and low-proficiency readers have similar word repetition skills, they differ in their nonword repetition skills (Castro-Caldas, Petersson, Reis, Stone-Elander, & Ingvar, 1998). When repeating auditory material, speakers may use any of three strategies or processing pathways. Word repetition predominantly engages semantic or lexical pathways, whereas nonword repetition predominantly engages the phonological pathway (Castro-Caldas et al., 1998). Thus, nonword production tasks enable assessment of the relationship between language skills and speech motor output. More specifically, manipulating the orthographic frequency of the nonword stimuli may provide further insight into the nature of the interaction between orthography and speech production.

OBJECTIVES

To explore the influence of orthography on the production of spoken language, we created nonwords, which were presented with systematic variations in modality (i.e., auditory or visual) and orthographic frequency (i.e., relatively frequent or infrequent spelling). We then measured proficient adult readers' phonetic accuracy and their articulatory movement stability before and after they either heard and repeated (auditory exposure) or read and repeated (orthographic exposure) the nonwords. The overarching goal was to evaluate whether experience reading as opposed to only hearing these nonword forms would influence speech production.

Specifically, we asked three questions:

1. Does exposure to a written word influence the phonetic accuracy and the articulatory movement stability of an adult talker's production of this new word form?
2. Do specific orthographic characteristics of this nonword, including orthographic transparency and opacity (defined as high and low orthographic neighborhood density) influence phonetic accuracy or articulatory movement stability?
3. Even within a relatively homogeneous group of proficient adult readers, do those individuals who demonstrate better reading skills also produce nonwords with greater articulatory stability?

METHODS

Participants

Participants included 18 adults (10 females) between the ages of 19 years, 3 months (19;3) and 64;3 ($M = 28;8$; $SD = 13$). Participants had between 13 and 18 years of education; all were at least college freshmen. All participants were native speakers of English; they reported no history of speech, language, hearing, or reading problems, neurological disease, or learning delay/disability; and they passed a hearing screening. Approval for this study was granted by the Purdue University Institutional Review Board.

Equipment

High-quality audio and video recordings were obtained for the analysis of phonetic accuracy. Simultaneously, three-dimensional kinematic data were collected at 250 samples/second using a three-camera Optotrak 3020 motion capture system or 3D Investigator motion capture system (both Northern Digital, Inc., Waterloo, ON, Canada). Small (6 mm) infrared light emitting diodes (IREDs) were attached with antiallergenic medical adhesive to each participant's upper lip, lower lip, and a lightweight splint under the chin at midline to approximate jaw movement. Five

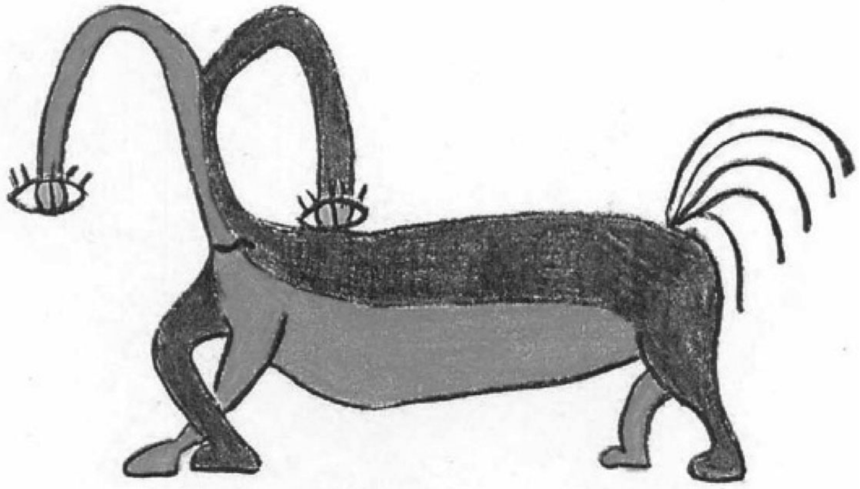

Figure 1. An example of an illustration of a novel character (Ohala, 1996). While viewing this picture, participants heard the word /mʌnfik/ and then said, “Bob saw a /mʌnfik/ before.”

additional IREDs were used to create a three-dimensional head coordinate system in order to subtract head motion artifact (Smith, Johnson, McGillem, & Goffman, 2000). A time-locked acoustic signal was collected at 16,000 samples/second to confirm that movement records aligned with target nonword productions.

Procedures and session structure

Each individual participated in one session, which was approximately 90 min long and included behavioral testing and the collection of acoustic and kinematic data. In the experimental component of the session, participants heard nonwords, which were described as the names of types of make-believe aliens and were each associated with a specific illustration of a novel character (Ohala, 1996; Figure 1). **Figure 1** Participants were instructed to listen to each character’s name and then say its name in the sentence “Bob saw a (insert name) before.” This carrier sentence was used to increase complexity and provide linguistic context, and because it contains several labial consonants, to facilitate articulatory kinematic analysis.

There were a total of three experimental blocks. Each block was associated with a single presentation condition: high orthographic density (corresponding with transparent) orthography, low orthographic density (corresponding with opaque) orthography, and auditory-only presentation. Each experimental block contained 2 target nonwords and 10 fillers (i.e., nonwords that had phonetic characteristics similar to the target words and were included to increase the difficulty of the task. Participants did not know which stimuli were fillers, and fillers were not analyzed). Each condition was further divided into three phases: pretest, learning, and

Table 1. *Session structure: three phases (pretest, learning, and posttest) within three conditions (auditory only, low density orthography, and high density orthography).*

	Auditory	Low Density	High Density
Pretest	Hear/repeat	Hear/repeat	Hear/repeat
Learning	Hear/repeat	Read/repeat	Read/repeat
Posttest	Hear/repeat	Hear/repeat	Hear/repeat

posttest. During the pretest phase, participants heard each nonword presented 10 times and then, after each presentation, repeated it in the carrier sentence. During the learning phase, participants either read each nonword aloud 10 times (in the high-density orthography and low-density orthography conditions) or heard and repeated each nonword 10 times (in the auditory-only condition). The posttest phase was identical to the pretest phase. This arrangement allowed us to determine whether participants' productions of the nonwords changed as a result of experience with reading aloud or listening to the stimuli, and whether participants' productions of the nonwords were influenced by the degree of orthographic neighborhood density to which they were exposed.

In the pretest and posttest phases, each target nonword was presented 10 times and each filler was presented 1 time; thus, there were a total of 30 nonwords presented in the pretest and posttest phases. In the learning phase, each target nonword was presented 10 times, but fillers were not presented (because the fillers were not designed to address the experimental questions, but only to increase the complexity of the task); thus, there were a total of 20 nonwords presented in the learning phase. Participants produced this number of repetitions in order to facilitate the capture of changes in articulatory variability across the course of the experiment (Smith et al., 2000).

The order of the conditions, as well as which condition contained which nonwords, were fully counterbalanced (i.e., blocked) across participants. Six participants viewed each version of the three counterbalancing schemes, thus controlling for item effects. Within each condition, stimuli were presented in a quasi-random order, with no more than two of the same nonwords occurring consecutively. See Table 1 for a summary of the session structure. See Appendix A for an example of one block of stimuli. **Table 1**

Stimuli

Each target nonword began with a labial consonant to facilitate kinematic analysis. Each word was disyllabic and trochaic, and each syllable followed a consonant–vowel–consonant pattern. We chose to construct disyllabic stimuli because unpublished pilot work suggested that a task consisting of exclusively monosyllabic nonwords would not be sufficiently challenging for adults and may be insensitive to differences in the learning phase of the study. Thus, the first syllable in each nonword was present only in order to increase its complexity, and was drawn from the list of 120 high-probability nonsense syllables presented by Vitevitch, Luce, Charles-Luce, and Kemmerer (1997). These syllables were defined as having segments with high positional probabilities and frequent biphone probabilities. The second syllable in each nonword was subjected to the relevant manipulations. Each nonword's second syllable was constructed based on a pair of homophones with the initial consonant changed. For example, the homophone /pik/ ("peek/pique") was changed to /fik/ ("feek/fique"); this syllable made up the second syllable of the nonword stimulus /mʌnfik/. The syllable's more frequent or transparent spelling (e.g., "munfeek") was used in the high-density condition, and its more infrequent or opaque spelling (e.g., "munfique") was used in the low-density condition.

The degree of orthographic frequency was determined based on the number of orthographic neighbors of each spelling (Table 2). The spelling of the nonword /fik/ as "feek" has six orthographic neighbors, while the spelling "fique" has one orthographic neighbor; thus, "feek" has higher type frequency than "fique." This manipulation was similar to that of Rastle et al. (2011), who created nonword stimuli that could be spelled in a regular or irregular manner (according to English grapheme–phoneme correspondence) and that were matched according to orthographic neighborhood density. Finally, the second syllables in the nonwords were balanced for phonological neighborhood density and phonotactic frequency (positional segment frequency and biphone probability). These characteristics were calculated using the online Speech and Hearing Lab Neighborhood Database of Washington University in St. Louis (Sommers, 2002). The nonword stimuli used for fillers were either one or three syllables in length, and were created from the list of high-probability syllables in Vitevitch et al. (1997; Appendix B).

Table 2

Data processing

Data were processed in Matlab (Mathworks, 2009). The sentences were segmented out of each trial and were then sorted by condition and phase in preparation for measurement. Because effects often appear in multimovement contexts for the kinematic analysis, we chose to analyze the whole sentence in which the target word was embedded. Phonetic accuracy was measured only in the target word.

Q1

The lip aperture variability (LA) index is a composite measure of spatial and temporal variability that quantifies the movement of three effectors (upper lip, lower lip, and jaw) as they interact during speech to control oral opening and closing (Smith & Zelaznik, 2004; Walsh & Smith, 2002). The LA index is derived by subtracting upper lip from lower lip movement, resulting in a measure of lip aperture. This measure quantifies articulatory stability.

To calculate the LA index, the onsets and offsets of each sentence were selected based on peak velocity of lower lip and jaw movement. Head movement was corrected, and the data were then low-pass filtered (10 Hz cutoff). Movement onsets and offsets were selected by visually inspecting the displacement record for local

Table 2. *Characteristics of target nonwords*

Homophone Pairs (2nd Syllable)	Transcription	High Density Spelling	Low Density Spelling	No. of Phonological Neighbors	No. of Orthographic Neighbors For High Density Spelling	No. of Orthographic Neighbors For Low Density Spelling	Positional Segment Frequency	Biphone Probability of Medial Consonants
“strait/straight”	/fispet/	“feespait”	“feespaight”	34	15	1	0.1796	.0081
“peek/pique”	/mΛnfik/	“munfeek”	“munfique”	20	6	1	0.1318	.0022
“ate/eight”	/bɑɪnvet/	“binevate”	“bineveight”	19	12	1	0.1176	.0113
“loot/lute”	/pΛlvut/	“pulvoot”	“pulvute”	26	18	9	0.1305	.0015
“cash/cache”	/fΛlvæʃ/	“fulvash”	“fulvache”	15	12	2	0.1096	.0015
“side/sighed”	/bispɑɪd/	“beespide”	“beespighed”	5	13	0	0.1566	.0081

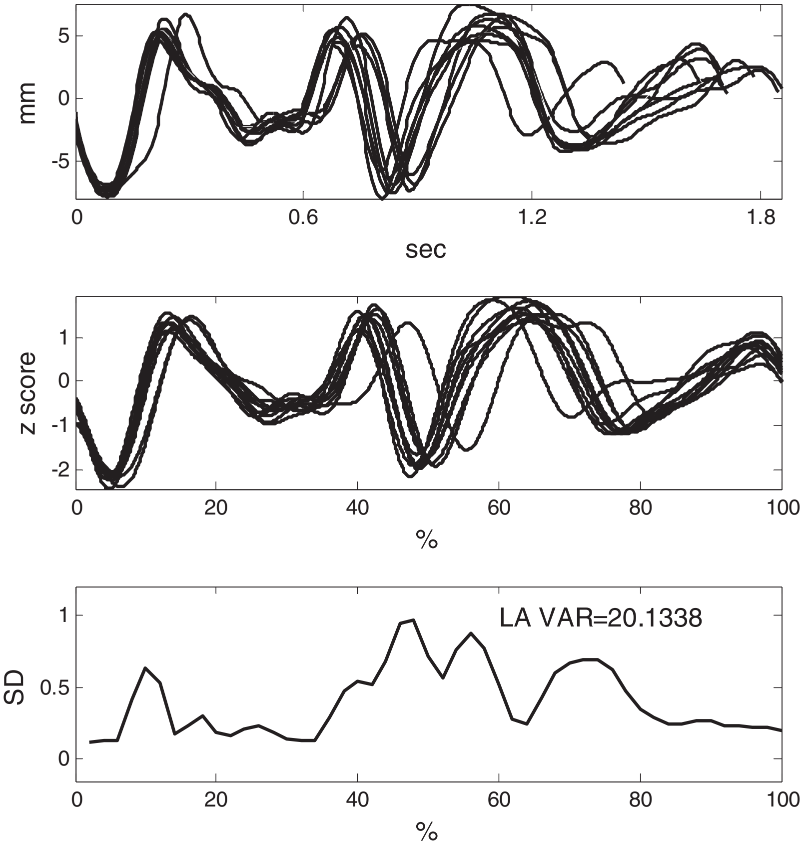

Figure 2. Examples of extracted movement sequences from the utterance “Bob saw a /mΛnfik/ before.” The top panel represents the raw records. The middle panel represents the time- and amplitude-normalized records. The bottom panel represents the standard deviations used to calculate the lip aperture variability index values.

minima. The minimum value was then confirmed by an algorithm, which determined the point at which velocity crossed zero within a 25-point (100-ms) window of the point selected by the experimenter. The movement trajectories were then linearly amplitude and time normalized. Time normalization was accomplished by setting each record to a common time-base of 1,000 points, using a spline function to interpolate between points. Amplitude normalization was completed by setting the mean to 0 and the standard deviation to 1. After normalizing the data, standard deviations were computed at 2% intervals in relative time across the 10 records and then summed. The sum of the 50 *SD* is the LA index; a higher value reflects greater movement variability (Figure 2; see Smith, Goffman, Zelaznik, Ying, & McGillem, 1995; Smith & Zelaznik, 2004).

Figure 2

Outcome variables

Segmental accuracy. The video recordings were used to transcribe each utterance and determine the percentage consonants correct (PCC). The PCC quantifies speech accuracy by measuring the proportion of consonants in each nonword produced accurately. Reliability of phonetic transcription was established by using an independent coder to transcribe 20% of the sessions. The phonetic transcriptions of the first author and the independent coder were in agreement for 98% of the consonants produced by participants (the coding of the first author was used as the default in cases of disagreement). Along with the raw PCC values, pretest/posttest difference scores were calculated as a more direct index of within-individual change.

Speech movement stability. The LA index values were evaluated separately for each phase within each condition. As with the PCC data, pretest/posttest difference scores were calculated along with the raw LA index values.

Reading and oral language skills. To quantify reading proficiency, we administered the Woodcock Reading Mastery Tests—Revised-Normative Update (WRMT$^{\text{TM}}$-R/NU; Woodcock, 2011). The subtests included word identification (participants' standard score range = 87–133, *SD* = 10.16), word attack (standard score range = 79–132, *SD* = 12.61; note that one participant scored more than a standard deviation below the test's mean of 100), word comprehension (antonyms, synonyms, and analogies; standard score range = 87–130; *SD* = 11.57), and passage comprehension (standard score range = 86–143; *SD* = 14.04). In addition, we quantified oral language skills by administering two subtests of the Test of Adolescent and Adult Language, 3rd Edition (Hammill, Brown, Larsen, & Wiederholt, 2011). Because some participants were outside of the standardization group's age range for this test, we report raw scores rather than standard scores. The subtests included listening grammar (raw score range = 8–33 out of 35) and speaking grammar (raw score range = 14–23 out of 30). Although all of our participants had at least some college education, they showed variation in their reading and language scores.

The critical tests for our analyses of individual differences were the word attack and word comprehension subtests of the WRMT$^{\text{TM}}$-R/NU. These were chosen based on the fact that they employ two very similar tasks (i.e., reading single items) to measure two very different aspects of reading skills (i.e., decoding vs. comprehension). The other tests and subtests were used to confirm that participants demonstrated typical reading and language skills, but were not subjected to statistical analyses.

Statistical analyses

All variables were analyzed using a within-participant analysis of variance, with condition (auditory only, high-density orthography, and low-density orthography), phase (pretest and posttest), and nonword (first or second nonword) as the within-participant factors. Simple effect analyses were used for pairwise comparisons when main effects were present. We used an arcsine transform to compensate for the fact that the accuracy data are not normally distributed. The α level was set to 0.05. Linear regression was also used to determine whether a relationship exists between two aspects of reading skill (word attack and word comprehension) and overall LA variability. For the correlations, the α level was changed to 0.025 using a Bonferroni adjustment. This adjustment accounts for the potentially inflated Type I error inherent in conducting multiple correlations on related dependent variables (Tabachnick & Fidell, 2007). We also report effect sizes for all results.

RESULTS

Analytic issues

Approximately 9% of the data were excluded due to disfluencies or other interruptions in the speech signal, such as laughing, coughing, or omitting the article. The productions obtained during the learning phase were not analyzed (these data differed from the pretest and posttest data because, in the high-density and low-density orthography conditions, the nonwords were read aloud instead of repeated). For the kinematic analysis, substitutions of one labial consonant for another, as well as vowel errors, were included; these tokens were considered correct for kinematic analysis. An additional 9% of the data, while amenable to phonetic accuracy analysis, were excluded from the kinematic analysis because the participants did not produce initial, medial, and final labial consonants or because an IRED was missing from the cameras' view. In these cases, articulatory trajectories could not be extracted from the speech stream. We counterbalanced the nonwords across conditions, and found no significant effects of specific nonwords (i.e., that one nonword was associated with different PCC or LA index values than the other five nonwords). Therefore, all statistical analyses were collapsed across the nonwords.

Segmental accuracy and speech movement stability

Segmental accuracy. To directly assess participants' learning, pretest/posttest difference scores for segmental accuracy were calculated. We found a main effect of condition, F (2, 16) = 16.70, $p < .001$, $\eta_p^2 = 0.68$ (Figure 3). Simple effect analyses indicated that participants' PCC scores became more accurate from pretest to posttest in the high-density, t (17) = 3.25, $p = .005$, and low-density orthography conditions, t (17) = 3.63, $p = .002$, in comparison to the auditory condition. High- and low-density values did not differ from one another, t (17) = 0.46, $p = .65$.

Figure 3

Along with our analysis of difference scores, we examined the raw PCC data. Because by definition, data expressed as proportions are not normally distributed, to stabilize the variance we transformed these data using an arcsine transform (Rucker, Schwarzer, Carpenter, & Olkin, 2009). Analyses of the transformed PCC data indicated that there was a main effect of phase. Participants were less accurate (i.e., lower PCC) in the pretest, $M = 0.93$, $SE = 0.01$, than in the posttest phase, $M = 0.97$, $SE = 0.01$; F (1, 17) = 34.67, $p < .001$, $\eta_p^2 = 0.67$. As shown in Figure 4,

Figure 4

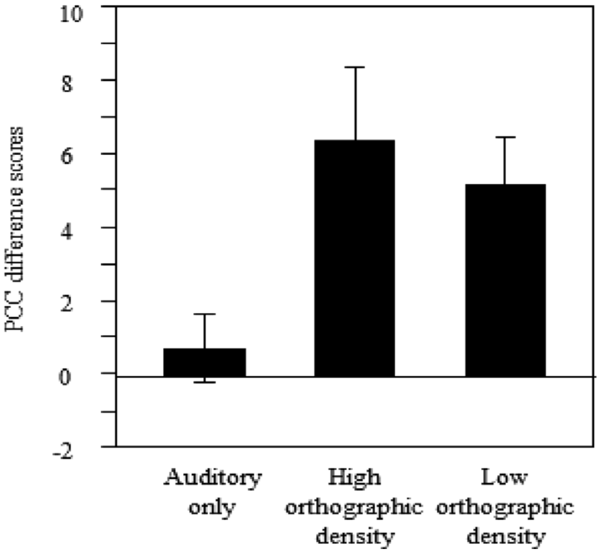

Figure 3. Percentage consonants correct pretest–posttest difference scores (positive scores indicate greater accuracy). Participants became significantly more accurate from pre- to posttest in the two written conditions, but not in the auditory condition. Error bars reflect standard errors.

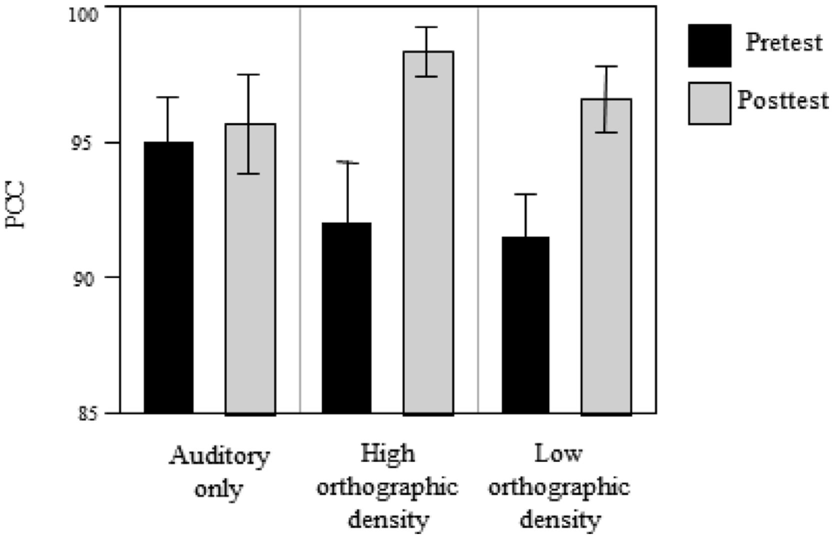

Figure 4. Percentage consonants correct raw scores in each phase within each condition (higher scores indicate greater accuracy). Participants became significantly more accurate from pretest to posttest in the two written conditions, but not in the auditory condition. Error bars reflect standard errors.

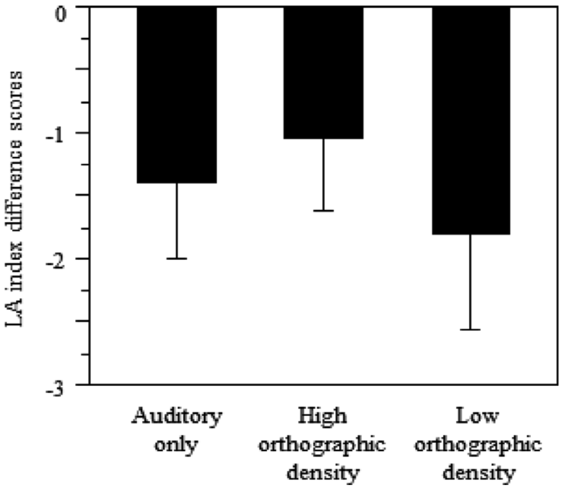

Figure 5. Lip aperture index value pretest–posttest difference scores (negative scores indicate greater articulatory stability). Participants became significantly more stable from pretest to posttest in all three conditions. Error bars reflect standard errors.

condition was not significant, F (2, 16) = 1.12, $p = .35$, $\eta_p{}^2 = 0.12$. There was a significant interaction of phase by condition, F (2, 16) = 10.37, $p = .001$, $\eta_p{}^2 = 0.56$. Simple effect analyses indicated that in all three conditions, participants' PCC increased from pretest to posttest: in the auditory condition, t (17) = 2.30, $p = .03$; in the high orthographic density condition, t (17) = 4.22, $p = .001$; and in the low orthographic density condition, t (17) = 4.17, $p = .001$.

Speech movement stability. To directly assess participants' learning, pretest/posttest difference scores for LA index values were calculated. While difference scores were less than zero (reflecting a move toward greater stability; Figure 5), there were no significant condition effect for LA index difference scores, F (2, 16) = 0.26, $p = .77$, $\eta_p{}^2 = .03$. Along with our analysis of difference scores, we examined the raw LA index data. There was a significant main effect of phase. Participants had significantly higher (i.e., more variable) LA index values in the pretest ($M = 20.14$, $SE = 0.62$) than in the posttest phase ($M = 18.44$, $SE = 0.62$), F (1, 17) = 5.37, $p = .03$, $\eta_p{}^2 = 0.24$. The main effect of condition was not significant, F (2, 16) = 1.07, $p = .37$, $\eta_p{}^2 = 0.12$, and there was no significant interaction, F (2, 16) = 0.25, $p = .78$, $\eta_p{}^2 = 0.03$ (Figure 6).

Figure 5

Figure 6

Relationship between reading skills and LA variability. The results of a linear regression indicated that word attack raw scores predicted LA variability, F (1, 17) = 7.34, $p = .02$, $R^2 = .31$ (Figure 7a). Given the p value of .025 based on the Bonferroni type adjustment, this result was significant. In contrast, the

Figure 7

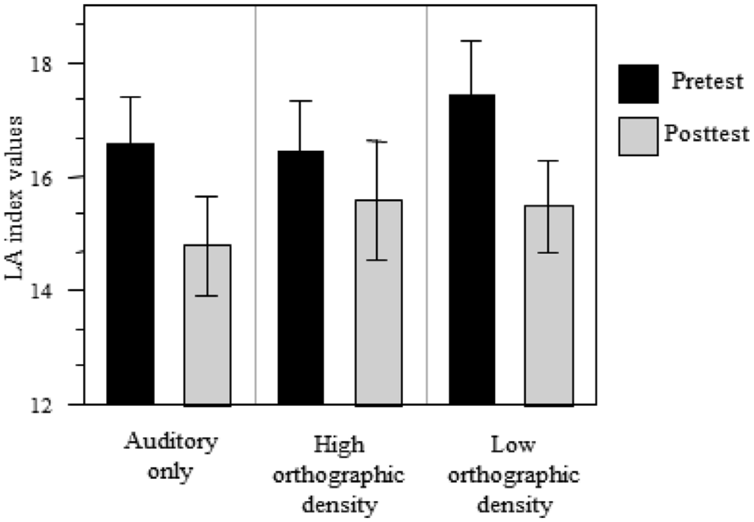

Figure 6. Lip aperture index values (lower scores indicate greater articulatory stability). Participants became significantly more stable from pretest to posttest in all three conditions. Error bars reflect standard errors.

results of a second linear regression indicated that word comprehension *w* scores (a measure applied to the WRMT^{TM}-R/NU, consisting of an equal-interval scale that represents both a person's ability level and the difficulty level of the items; Jaffe, 2009; Woodcock, 2011) did not predict LA variability, $F(1, 17) = 1.80$, $p = .20$, $R^2 = .10$ (Figure 7b).

DISCUSSION

We inquired whether manipulations of nonword presentation modality and orthography impact how proficient readers produce language. In addition, we asked if individual differences in reading facility, even in these proficient adult readers, influence orthographic effects on word production. To address these questions, we created a nonword production task in which we systematically manipulated the modality of the presentation (auditory or written) and the degree of neighborhood density (transparent or opaque spellings) of the nonword stimuli.

Our data lead to several key findings. We might expect that manipulating modality and orthographic density would influence participants' phonetic accuracy and articulatory stability. Our findings supported the first component of this prediction, that modality influences production. Participants produced nonwords more accurately (i.e., higher PCC in post- compared with pretest) after reading them, but not after just hearing them, even with the same degree of exposure. It is crucial that viewing the written cue enabled participants to produce the nonword with greater accuracy in the posttest phase (i.e., even when they were no longer able to read it).

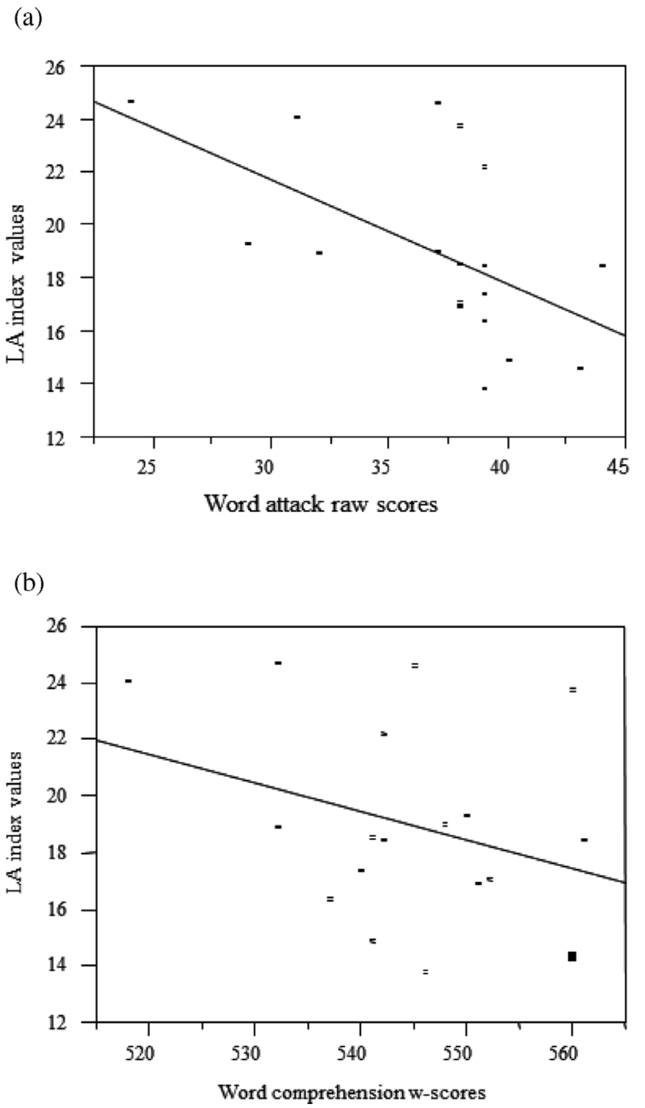

Figure 7. (a) Regression line representing the correlation between Woodcock Reading Mastery Tests—Revised-Normative Update word attack raw scores and overall lip aperture variability. (b) Regression line representing the correlation between Woodcock Reading Mastery Tests—Revised-Normative Update word comprehension *w* scores and overall lip aperture variability.

These data suggest that participants were able to integrate the nonword's orthography into their lexical representations. That this occurred only when participants were able to read the nonwords, and not when they received the same amount of exposure in the auditory modality alone, indicates that the reading process contributed to this integration. These adult participants demonstrated high segmental accuracy even in the pretest phase (PCC average = 92%–95%). However, these are not simply ceiling effects, because participants showed systemic improvement in production accuracy when exposed to written but not spoken words during the learning phases.

Highly proficient adult readers were not influenced by neighborhood density in their speech production processes. This was somewhat counter to expectations, because it may be predicted that mature talkers would be sensitive to neighborhood effects. While this frequency measure had no influence, speech movement stability did increase with learning or practice (e.g., Heisler et al., 2010; Walsh, Smith, & Weber-Fox, 2006). However, this effect occurred regardless of whether participants heard or read the stimuli. While measures of production accuracy showed sensitivity to exposure to written versus auditory input, measures of articulatory stability revealed only more global practice effects.

These findings are not fully consistent with those from other researchers, who have used different methodologies to assess how orthography influences speech production. For instance, Damian and Bowers (2003) found that orthographic congruency influences the facilitative effects of priming; however, Alario et al. (2007) did not replicate this result. Miller and Swick (2003), Ziegler and Muneaux (2007), and Rastle et al. (2011) showed that orthographic factors such as neighborhood density and spelling–sound consistency influence priming effects, spoken word production and recognition, and novel picture naming. As a whole, these studies suggest that orthographic representations exert a powerful influence on speech processing and production.

However, kinematic analyses did reveal that individual differences in reading proficiency interact with articulatory stability. Even among this group of adult, proficient readers, individuals with stronger word attack and word identification skills also presented with greater overall speech movement stability in their nonword repetition. Previous work also supports the use of nonword repetition as an index of reading skill. As noted above, poorer readers often demonstrate weaker nonword repetition skills, due to their poor development of phonological awareness (Castro-Caldas & Reis, 2003), lack of focus on sublexical units (Share, 2004; Ventura et al., 2007), and inability to access the phonological pathway strategically (Castro-Caldas et al., 1998). However, it is a new finding that even typical adult readers show differential performance in articulatory stability as a function of their decoding proficiency. This new measure provides an implicit index of the influences of experience and reading skill on speech production.

The above conclusions provide an affirmative answer to our question regarding the relationship between reading skills and articulatory stability. Furthermore, our results indicate that our experimental design using kinematic analysis was an effective tool for assessing the effect of orthography on phonological representations. Aspects of our findings are consistent with those previously obtained using metalinguistic tasks. Specifically, our results follow naturally from the perspective established by earlier works, indicating that reading is an interactive process (Jacobs & Grainger, 1994); that perceiving a word in any modality activates its orthographic representation (Miller & Swick, 2003); that manipulating a word's spelling can impact its processing by listeners and readers (Damian & Bowers, 2003; Fiez, Balota, Raichle, & Petersen, 1999; Rastle et al., 2011); and that orthography is a factor included in a word's representation in the mental lexicon (Morton, 1969). However, our experiment goes beyond these preceding studies, in that we measured speech production as an index of implicit processing and found that this type of processing is influenced by access to orthography. Kinematic analyses enable us to obtain fine-grained quantitative measures of implicit processing and learning.

Future studies need to assess individuals with varying levels of reading skill. Perhaps adult proficient readers rely on automatic and rapid processing when accessing new words regardless of whether they are orthographically high or low density. This may not be true of less proficient readers, who may show more sensitivity to these orthographic distinctions. We predict that individuals who demonstrate reduced reading proficiency, and whose reading skills are less automatic, will be influenced to a greater extent by factors such as orthographic density. It seems likely that orthographic characteristics, such as neighborhood density or transparency, will have increased impact during earlier phases of learning to read, when automaticity is still emerging. One expectation based on previous literature is that of Lavidor, Johnston, and Snowling (2006), who predict that individuals with reading impairment may experience difficulty creating fine-grained grapheme–phoneme mappings. Consequently, they may use a relatively global or coarse coding that creates greater reliance on the visual or orthographic properties of words than on their phonological decoding. In contrast, it is possible that individuals with poorer reading skills may benefit less from orthographic cues than more proficient readers, because poorer readers may be relatively insensitive to this type of manipulation. It is therefore important to pursue this investigation in children who are just developing reading skills and in children and adults who demonstrate reading difficulties.

Conclusion

This kinematic study provides an emerging picture of the relationships among modality, orthographic density (which corresponds to transparency), and language production that confirms and extends previous works. Our findings indicate that modality and reading proficiency impact participants' speech accuracy and efficiency in a nonword production task. Specifically, reading a nonword enables speakers to access its orthography, which facilitates their ability to produce it. Thus, we can conclude that experience with orthography may alter readers' phonological representations of new word forms. In addition, our data indicate that higher reading proficiency is associated with greater articulatory stability of nonword production. Collectively, these findings help us to understand how, in addition to the way in which orthography influences perceptual/explicit processing and speech perception, orthography also influences implicit processing and speech production. We conclude that quantifying speech accuracy and conducting fine-grained kinematic analyses provide insight into the influence of orthography on language processing.

APPENDIX A

A Sample order of a pretest phase

1. wase
2. reeglesape
3. binevate
4. binevate
5. munfeek
6. binevate
7. munfeek
8. lale
9. munfeek
10. binevate
11. huspevate
12. sush
13. munfeek
14. rame
15. binevate
16. gastejun
17. munfeek
18. chun
19. munfeek
10. binevate
21. binevate
22. munfeek
23. binevate
24. binevate
25. munfeek
26. theen
27. munfeek
28. binevate
29. cucklefees
30. munfeek

Note: In the study, the nonwords associated with each condition were counterbalanced across participants.

APPENDIX B

Nonword filler stimuli

Nonword Transcription
/tʃΛn/
/sΛʃ/
/θin/
/lel/
/wes/
/rem/
/hΛspəvet/
/gestədʒən/
/kΛkləfis/
/rigləsep/

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