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Research Article

Orthography and Modality Influence Speech Production in Adults and Children

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Purpose: The acquisition of literacy skills influences the perception and production of spoken language. We examined if orthography influences implicit processing in speech production in child readers and in adult readers with low and high reading proficiency.
Method: Children (n = 17), adults with typical reading skills (n = 17), and adults demonstrating low reading proficiency (n = 18) repeated or read aloud nonwords varying in orthographic transparency. Analyses of implicit linguistic processing (segmental accuracy and speech movement stability) were conducted. The accuracy and articulatory stability of productions of the nonwords were assessed before and after repetition or reading.
Results: Segmental accuracy results indicate that all 3 groups demonstrated greater learning when they were able to read, rather than just hear, the nonwords. Speech movement results indicate that, for adults with poor reading skills, exposure to the nonwords in a transparent spelling reduces the articulatory variability of speech production. Reading skill was correlated with speech movement stability in the groups of adults.
Conclusions: In children and adults, orthography interacts with speech production; all participants integrate orthography into their lexical representations. Adults with poor reading skills do not use the same reading or speaking strategies as children with typical reading skills.

Speakers and listeners are affected by the phonological characteristics of the words they produce and hear. Speakers who are literate are additionally influenced by the orthographic characteristics of those words. Although an individual is acquiring the skills necessary to analyze written words, his or her perception and production of the spoken word also becomes transformed. This orthographic interference occurs whether or not reading or spelling is a part of any given task. Therefore, even tasks that do not directly involve the printed word but are completed exclusively by listening or speaking may show evidence of the influence of the orthographic characteristics of the stimuli (e.g., Frith, 1998; Rastle, McCormick, Bayliss, & Davis, 2011). Orthographic knowledge involves rules for how a letter represents a speech sound, rules regarding permissible combinations of letters, and rules regarding positional and contextual letter constraints (Apel, 2011).

Orthographic Interference in Readers of Varying Skill

In the literature on orthographic interference, there is a dearth of evidence regarding the processing of orthography by individuals with reading difficulties or young children who are developing reading skills. When reading skills develop atypically, this processing may be altered as is apparent from both behavioral differences, such as difficulties in nonword repetition (e.g., Castro-Caldas & Reis, 2003; Ziegler, Muneaux, & Grainger, 2003), and cascading effects on neural organization, such as overlap in cortical responses to the speech and print systems (e.g., Shankweiler et al., 2008). Therefore, the objective of the current study was to explore the influence of orthography on speech production in individuals with varying levels of reading proficiency. We examine this question from the developmental perspective (children vs. adults with typical or atypical reading skill; this comparison allows us to inquire whether poor adult readers do or do not reflect typical developmental phenomena) as well as from the perspective of different degrees of reading skill (adults who are poor readers vs. adults with typical reading skills).

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Specific orthographic and phonological factors are processed differently by individuals with varying levels of reading proficiency. One factor, neighborhood density, is defined as the influence of the number of words that can be constructed by changing, adding, or deleting one phoneme or grapheme of a target word (Coltheart, Davelaar, Jonasson, & Besner, 1977; Davis, Perea, & Acha, 2009). For example, the word *river* has 10 orthographic neighbors, including *diver*, *liver*, *rover*, *rider*, and *rivet*, whereas the word *drive* has one orthographic neighbor, *drove* (Davis et al., 2009). Although phonological neighborhood effects are present in all speakers, even young children (Storkel, Maekawa, & Hoover, 2010), orthographic neighborhood effects fluctuate according to the individual's level of reading skill (Ziegler & Muneaux, 2007). Orthographic neighborhood density is associated with orthographic transparency—the degree of grapheme–phoneme correspondence in a given language's orthographic representations—in that words with more opaque spellings generally reside in sparse orthographic neighborhoods. Languages such as Italian (Zoccolotti et al., 1999), Greek, and Spanish (Ziegler & Goswami, 2005) fall on the transparent end of the continuum, whereas languages such as English and Danish (Borgwaldt, Hellwig, & de Groot, 2004; Ziegler & Goswami, 2005), which represent identical phonetic sequences in multiple ways, fall on the opaque end of the continuum. Poor readers are differentially influenced by orthographic transparency.

It is of crucial importance to note that modality—that is, whether information is heard or read—is another factor that may facilitate or disrupt phonological learning in individuals with different levels of reading skill. Orthographic and phonological dimensions may be processed differently as a function of reading proficiency; manipulations of modality may have a stronger impact on poorer readers because they rely on global or visually based coding rather than processing the fine-grained grapheme–phoneme mappings (Lavidor, Johnston, & Snowling, 2006). Interacting with language that is written rather than heard may also increase their struggle to access the sublexical components of language. In a similar manner, on a deeper level, manipulations of orthographic transparency may also more strongly affect poorer readers. Reading text containing the characteristic inconsistencies of opaque orthographic representations may exacerbate their reading difficulties.

On the other hand, the most proficient readers may be affected to a greater degree by manipulations of modality. Because much of their reading occurs in a way that is automatic, they may be more likely to experience a strong effect when that automaticity is compromised. Likewise, on a deeper level, it is possible that more skilled readers may be particularly influenced by transparency because only good readers demonstrate effects of orthographic neighborhood density (Ziegler & Muneaux, 2007; Ziegler et al., 2003) and are deeply influenced by phonological/orthographic inconsistencies (Bolger, Hornickel, Cone, Burman, & Booth, 2008).

Metalinguistic Versus Implicit Learning

When examining the influences of orthographic interference in individuals with varying levels of reading skill, it is important to consider the differences between metalinguistic and implicit learning. Much of the previous literature is based on metalinguistic processing—a level of learning in which knowledge can be consciously accessed, examined, and manipulated. For instance, participants were asked to count phonemes (Ehri & Wilce, 1980) or determine if a pair of words rhymed (Seidenberg & Tanenhaus, 1979; Zecker, 1999) in order to assess the ways in which their metalinguistic knowledge influenced their processing of orthography. These results provide the foundation for much of our knowledge concerning orthographic interference.

However, there are limitations to assessing exclusively metalinguistic skills. This type of knowledge is not the only type of processing that occurs in speakers and readers. In fact, measures of metalinguistic learning alone may be misleading because this type of awareness is not required for speaking. In addition, metalinguistic skills may be founded on alphabetic literacy, meaning that they may not be within the domain of all competent speakers. Two classic studies, Morais, Cary, Alegria, and Bertelson (1979) and Read, Zhang, Nie, and Ding (1986), demonstrated that adults who were not literate, and even adults who were literate but in a logographic system, were unable to segment phonemes. It is therefore apparent that drawing conclusions on the basis of metalinguistic measures may be misleading and may not pertain to individuals who demonstrate reading difficulties. Moreover, findings on the basis of metalinguistic learning may be confounded by the various mnemonic strategies that participants apply as they progress through the task. As a consequence, it is essential to assess implicit learning, which is a different level of processing and which may be more similar across individuals with varying levels of reading skills.

In contrast to previous works that measure metalinguistic awareness, a speech production task can directly quantify implicit language processing. Investigating speech production, including motor learning, may provide a window into this different level of learning. This is because the individuals who are assessed need not make conscious decisions about the stimuli; they need only produce them. Furthermore, it is uncommon for an individual to consciously apply a strategy, such as a mnemonic device, to guide his or her motor learning—that is, it is difficult to mindfully resolve to produce a word with greater speech movement stability or phonetic accuracy. Therefore, examining speech production may circumvent some of the limitations imposed by previous studies.

Measuring Speech Production Quantifies Implicit Learning

To quantify speech production, factors such as segmental accuracy and speech movement stability may be analyzed. Traditional theories conceptualize language and motor (including speech motor) skills as being discrete processes. These studies have either focused on lower level processes, such as kinematic forces, movement trajectories, and feedback control (e.g., Abbs, 1986; Barlow & Farley, 1989; Moll, Zimmermann, & Smith, 1977; Smith, 1992), or higher level linguistic processing and psycholinguistics as being independent from the motor implementation system (e.g., Bock, 1995; Levelt, 1989; Levelt, Roelofs, & Meyer, 1999; Shattuck-Hufnagel, 1987). In contrast, some more recent investigators have examined the phonetic aspects of speech production as a window into higher level aspects of language production. For example, studies of speech errors (e.g., Goldrick, Baker, Murphy, & Baese-Berk, 2011) and the lexical bias of slips of the tongue (e.g., McMillen, Corley, & Lickley, 2009) provide evidence for interactivity among lexical, phonological, and phonetic levels of production. Another paradigm, the motor theory of speech perception (Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967; Liberman & Mattingly, 1985), has also highlighted the interactions between perception and action. This theory proposes that humans perceive spoken words not by identifying acoustic patterns, but by recognizing the intended gestures of the speaker's articulators. Thus, the object of speech perception consists of gestural commands. These occur physically and provide the foundation for phonetic categories, meaning that speech perception and speech production are intimately linked (Galantucci, Fowler, & Turvey, 2006). To be more specific, methodologies that quantify speech motor changes, including both articulatory and phonetic–acoustic measures, have been used to directly analyze the influences of lexical, grammatical, and phonological factors on articulation.

The analysis of speech kinematics is a valuable tool with which to evaluate the connection between higher and lower level processes. This association has been apparent in many previous studies. For instance, speech movement stability has been found to increase in children as they mature (Smith & Goffman, 1998; Smith & Zelaznik, 2004) and to decrease in typical aging (Wohlert & Smith, 1998). Speech movement stability has also been found to change with shifts in linguistic-processing demands, including greater linguistic or prosodic complexity (e.g., Goffman, Gerken, & Lucchesi, 2007; Goffman, Heisler, & Chakraborty, 2006; Maner, Smith, & Grayson, 2000) or the inclusion of semantic cues (Heisler, Goffman, & Younger, 2010). Therefore, we chose to analyze participants' speech production via measures of segmental accuracy and speech movement stability in order to assess the impact of orthography on implicit learning. To be specific, percentage of consonants correct (PCC), which is a measure of segmental accuracy, and lip aperture (LA) variability, which is a measure of speech movement stability across multiple productions, were analyzed. Because these measures examine speech production and require the speaker merely to produce stimuli rather than make decisions, they may provide a window into implicit linguistic competence.

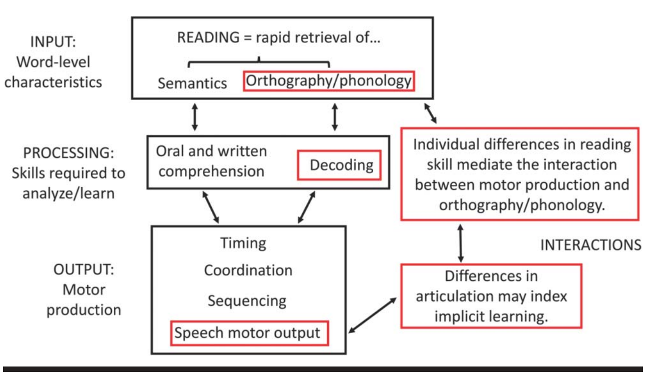
Previous work (Saletta, Goffman, & Brentari, 2015) involved investigating the connection between reading and speech production via a group of adults with typical reading skills. Participants produced nonwords that systematically varied in modality of presentation (either auditory or written) and, within the written modality, in orthographic transparency (relatively transparent or opaque spelling). The impact of these variables on the typical adults' speech production was assessed. Findings indicated that participants' segmental accuracy increased when they had read the stimuli but not when they had only heard them, indicating that modality influenced speech production. However, we did not find an effect of orthographic transparency.

Modeling the Interaction Between Language, Reading, and Speech Motor Output

Apart from the data from typical adult readers on the basis of our first study mentioned above (Saletta et al., 2015), existing models of speech production do not account for the influence of orthography. Most previous models of language and speech production indicate that processing stages proceed in a generally top-down manner. For example, Levelt et al. (1999) specify that conceptual preparation precedes lexical, morphological, phonological, and phonetic levels of processing, ultimately resulting in articulation and the production of a sound wave. Other models focus exclusively on psycholinguistic factors that are independent of speech motor control (e.g., Shattuck-Hufnagel, 1987) or on motor control as being independent of language (e.g., Abbs 1986; Moll et al., 1977). Last, models that do combine linguistic and motor aspects of processing, such as in the Smith and Goffman (2004) study, do not address the relationship of reading to these other factors.

Therefore, we propose a new model that incorporates three important differences from these previous works (see Figure 1). First, we modified the previous models to encompass the processing of written, in addition to spoken, language. It is clear that the processing of written language should share important characteristics with the processing of spoken language. Studies concerning the phenomenon of orthographic interference suggest that learning to read

Figure 1. Model of the interaction between language, reading, and speech motor output. Red boxes surround the elements investigated in the current study.



permanently changes the reader's processing of spoken as well as written language (Castro-Caldas & Reis, 2003; Shankweiler et al., 2008; Ziegler et al., 2003).

Second, we theorized that reading and speech motor output are interactive rather than linear processes. To be more specific, there is a bidirectional relationship between speech motor output and orthographic factors in that speech may change as a consequence of reading, and other types of learning and reading may change in concert with differences in speech skills. This means that not only do word-level characteristics drive processing, which in turn drives speech motor output, but speech production actually is an important index of implicit learning and processing. We expanded upon previous models in order to include speech motor planning and speech motor output, which may occur with or without the ability to access meaning.

Third, we proposed that individual differences in reading skill mediate this interactive sequence. Previous studies of individuals with dyslexia indicate that reading skill is a precursor of some spoken language processes, including nonword repetition and the manipulation of individual phonemes in verbal blending and segmenting tasks (Morais et al., 1979; Read et al., 1986). Perfetti and Hart (2002) speak to a specific difference between skilled and less skilled readers. These authors maintain that a skilled reader has many high-quality word representations, whereas a poorer reader has fewer. Therefore, it is not the individuals but the word representations that vary in quality.

Reading skill also affects homophone identification. A skilled reader may identify both members of a homophone pair, such as *gate* and *gait*, in such a way that activation will spread quickly between the two, leading to homophone confusion more quickly than for a less skilled reader. A less skilled reader, on the other hand, will experience homophone confusion that both builds more slowly and releases more slowly. The differences in orthographic transparency between the two members of the homophone pair may also contribute to changes in various readers' learning of the words. We integrated this finding into our model at the "processing" stage in that differences in reading skill between individuals may mediate the interaction between reading and speech motor output. These differences may include developmental factors and with mature speakers, reading proficiency. This model informs our hypotheses below.

The Current Investigation

The aim of the current study was to determine how individuals with varying degrees of reading skill implicitly process written language. The primary question is if children who are developing reading typically show processing comparable to that of adults with reading difficulties; both of these groups demonstrate lower reading proficiency than typical adult readers albeit for different reasons. Exposure to language in its written form changes both one's perception and production of spoken language, and if reading skills are acquired atypically, these changes will also be manifest in a different way. Although it is probable that manipulating the characteristics of the written word will affect some readers more profoundly than others, the direction of this difference is unknown. Our model in Figure 1 predicts that reading skill mediates the interaction between reading and speech production.

In this study, we utilized measures of speech production to quantify implicit linguistic processing as participants repeated and read aloud nonword stimuli that varied in orthographic transparency. We asked three questions:

1. How would variations of modality (exposure to a nonword in its written rather than in its auditory form) influence segmental accuracy and/or speech movement stability for individuals with poorer reading skills (i.e., children who are typical readers and adults who are poor readers) as compared with individuals with typical reading skills (i.e., children and adults who are typical readers)? We address this question from two perspectives: the developmental standpoint (i.e., the crucial comparison between children who are typical readers and adults who are poor readers) and the reading skill standpoint (i.e., the second comparison between adults who are typical readers and adults who are poor readers).
2. How would variations of specific orthographic characteristics (exposure to a nonword written in transparent versus opaque spelling) influence segmental accuracy and/or speech movement stability for young readers and adult low-proficiency readers as compared with adult readers with typical reading skills? Again, we look at this question from the perspective of development as well as reading skill.
3. Would individuals who demonstrate better reading skills also produce nonwords with greater speech movement stability? There are two possible hypotheses associated with this question. First, speech production may be unrelated to reading proficiency in adults who are skilled readers. Previous studies, such as that of Chakraborty, Goffman, and Smith (2008), support this prediction. These authors found that bilingual speakers—even those who demonstrated relatively low English proficiency and acquired English as a second language relatively late in life—demonstrated a high degree of stability in their speech motor output in English; that is, when required to produce sentences in English, even these low-proficiency speakers demonstrated LA index values that were similar to those of monolingual English-speaking adults. As an alternative, greater depth of language skills may in fact translate into greater speech movement stability in paradigms that involve reading aloud. This prediction has not previously been empirically assessed in adults with poor reading skills.

These questions map onto the theoretical model in Figure 1 in three ways. First, we sought to support the interactive nature of the language and motor systems by determining how manipulations of orthographic factors affect speech motor output. Second, we aimed to examine how differences in articulation may measure implicit rather than metalinguistic learning. Last, we proposed to explore the ways in which group differences in reading skill mediate these relationships.

Method

Participants

Approval for this study was granted by the Purdue University Institutional Review Board. Three groups of participants were compared: adults with typical levels of reading proficiency (Adult-Typ), children who were developing reading skills typically, and adults with a reported history of reading difficulties and who demonstrated low levels of reading proficiency (Adult-LP). Fifty-two individuals participated in the study with 17 in the Adult-Typ group who ranged in age from 19 to 64 years old (M = 29.73; SD = 13.16); 17 in the child group, who ranged in age from 6.00 to 8.83 years old (M = 7.45; SD = 0.91); and 18 in the Adult-LP group, who ranged in age from 19 to 62 years old (M = 32.82; SD = 13.89). The individuals in the Adult-Typ group were drawn from a prior study of orthographic processing (Saletta et al., 2015). All participants were native speakers of English and demonstrated typical nonverbal reasoning and oral language.

General Summary of Assessment Battery

Reading was tested via the *Woodcock Reading Mastery Tests–Revised* (Normative Update; WRMT-R/NU; Woodcock, 2011), with subtests including word identification, word attack, word comprehension (antonyms, synonyms, and analogies), and passage comprehension. The *Test of Word Reading Efficiency–Second Edition* (TOWRE-2; Torgesen, Wagner, & Rashotte, 2011), with subtests including sight word reading and decoding, was also used to test reading. Nonverbal reasoning was assessed via the *Test of Nonverbal Intelligence–Fourth Edition* (TONI-4; Brown, Sherbenou, & Johnsen, 2010). Oral language was tested for the adults via the *Test of Adolescent and Adult Language–Third Edition* (TOAL-3; Hammill, Brown, Larsen, & Wiederholt, 2011), with subtests including speaking grammar and listening grammar, and the *Peabody Picture Vocabulary Test–Fourth Edition* (PPVT-4; Dunn & Dunn, 2007). Oral language was tested for the children via the *Clinical Evaluation of Language Fundamentals–Fourth Edition* (CELF-4; Semel, Wiig, & Secord, 2003), with subtests including concepts and following directions, word structure, recalling sentences, and formulating sentences.

Participants in the Adult-Typ group received the WRMT-R/NU and the TOAL-3. They reported no history of reading or learning difficulties, and their performance on all subtests of the WRMT-R/NU was within normal limits as defined by a standard score greater than or equal to 85.

Child participants received the WRMT-R/NU, TOWRE-2, CELF-4, and TONI-4. They had no history of reading or learning difficulties, and their performance on all of the standardized test measures was within normal limits as defined by a standard score greater than or equal to 85.

Participants in the Adult-LP group received the WRMT-R/NU, TOWRE-2, TOAL-3, PPVT-4, and TONI-4. These individuals reported a positive history of dyslexia or other reading difficulties. In addition, these participants either achieved less than a standard score of 85 on one or more subtests of the WRMT-R/NU and/or demonstrated a significant discrepancy between their reading comprehension skills and their decoding skills. Participants were considered to have this type of discrepancy if their reading comprehension skills (as operationalized by their performance on the WRMT-R/NU word comprehension or passage comprehension subtests) were at least four grade levels above their decoding skills (as operationalized by their performance on the WRMT-R/NU word attack subtest or TOWRE-2 decoding subtest). This definition is based on the simple view of reading (Catts, Adlof, & Ellis Weismer, 2006; Gough & Turner, 1986; Hoover & Gough, 1990), which states that the act of reading consists of two components: decoding and language comprehension. Individuals with dyslexia typically demonstrate average or above-average linguistic comprehension skills but poor decoding skills (Catts, Kamhi, & Adlof, 2012). This discrepancy model is consistent with many previous studies of children and adults with reading difficulties (e.g., Badian, 1999; Bell & Perfetti, 1994; Spring & French, 1990).

Group Comparisons on the Basis of Behavioral Testing

Post hoc observations of the data revealed that, although still within the normal range, participants in the Adult-LP group showed lower nonverbal performance as measured by standard scores on the TONI-4 compared with the children, $F(1, 35) = 9.93$, $p = .003$. The two adult groups were similar in their oral language skills as quantified by their raw scores on the TOAL-3 (both Fs < 2.17, both ps > .15). Comparisons on reading measures revealed that each group was significantly different from the other two groups in their raw scores on all of the WRMT-R/NU subtests (all Fs > 15.55, all ps < .001). In every case, the Adult-Typ raw scores were the highest, the child scores were the lowest, and the Adult-LP scores were in the middle. The child group achieved lower raw scores than the Adult-LP group on both of the TOWRE-2 subtests (both Fs > 7.50, both ps ≤ .01). See Table 1 for ranges and values of the standardized measures for each group.

Equipment

Three-dimensional kinematic data were collected at 250 samples/s using a three-camera 3D Investigator motion capture system (Northern Digital Inc., Waterloo, ON, Canada). Small (6 mm) infrared light-emitting diodes were attached with antiallergenic adhesive to the upper

Table 1. Results of behavioral testing.

Measure	Adult-Typ		Adult-LP		Child	
	Range	*M* (*SD*)	Range	*M* (*SD*)	Range	*M* (*SD*)
TONI-4	—		78–110	94.33 (9.64)	95–125	106.82 (8.86)
WRMT-R/NU Word ID	94–133	98.29 (3.92)	42–105	88.44 (13.03)	110–136	119.35 (6.74)
WRMT-R/NU word attack	87–132	104.29 (11.46)	69–102	90.89 (9.37)	108–136	118.94 (9.00)
WRMT-R/NU word comprehension[a]	518–561	545.06 (10.79)	493–555	529.06 (15.14)	438–510	484.88 (18.40)
WRMT-R/NU passage comprehension	86–143	111.65 (13.89)	75–124	96.83 (12.56)	102–128	112.41 (7.76)
TOWRE-2 sight word	—		34–102	77.00 (16.66)[b]	103–143	115.24 (10.08)
TOWRE-2 decoding	—		9–51	77.50 (10.68)[b]	96–137	108.29 (9.76)
CELF-4 concepts and following directions	—		—		8–14	11.71 (1.57)
CELF-4 word structure[b]	—		—		8–13	11.35 (1.57)
CELF-4 recalling sentences[b]	—		—		8–17	11.00 (2.40)
CELF-4 formulating sentences[b]	—		—		8–14	11.53 (1.91)
PPVT-4	—		74–118	103.33 (11.54)	—	
TOAL-3 listening grammar[c]	12–34	23.24 (5.93)	10–35	22.61 (7.41)	—	
TOAL-3 speaking grammar[c]	14–23	19.76 (2.51)	13–26	18.22 (3.56)	—	

Note. Ranges, means, and standard deviations are reported for each group. TONI-4 = Test of Nonverbal Intelligence–Fourth Edition; WRMT-R/NU = Woodcock Reading Mastery Tests–Revised (Normative Update); TOWRE-2 = Test of Word Reading Efficiency–Second Edition; CELF-4 = Clinical Evaluation of Language Fundamentals–Fourth Edition; PPVT-4 = Peabody Picture Vocabulary Test–Fourth Edition; TOAL-3 = Test of Adolescent and Adult Language–Third Edition. Em dashes indicate that the specific standardized test was not administered to the group.

[a]W-scores—which is an alternative way to scale a raw score and can serve as a metric to measure an individual's development over time—are reported for this subtest. [b]Raw scores are reported for these subtests because these tests are normed up to age 24;11 (years;months) only. [c]Scaled scores are reported for these subtests.

lip and lower lip and a lightweight splint attached under the jaw at midline. Five additional infrared light-emitting diodes were placed on the forehead and goggles worn by the participant in order to create a three-dimensional head coordinate system and subtract head motion artifact, according to the methods of Smith, Johnson, McGillem, and Goffman (2000). In addition, it was confirmed that movement records aligned with nonword productions by collecting a time-locked acoustic signal at 16,000 samples/s. Video and audio recordings were also collected in order to analyze segmental accuracy.

Stimuli

Stimuli were varied to be either transparent or opaque to assess the question of differential responses to orthographic transparency as a function of age and reading proficiency. Each of the target nonword stimuli was disyllabic and trochaic, and each syllable followed a consonant–vowel–consonant pattern. To facilitate kinematic analysis, each target began with a labial consonant. The first syllable was present only in order to increase the complexity of the nonword, and the second syllable in each nonword was subjected to the relevant manipulations. All stimuli were also controlled for phonotactic probability, phonological neighborhood density, and orthographic neighborhood density.

All of the nonword stimuli are listed in the Appendix. The first syllables of each nonword were drawn from the list of 120 high-probability nonsense syllables presented by Vitevitch, Luce, Charles-Luce, and Kemmerer (1997). Each target nonword's second syllable was created by changing the initial consonant of a pair of homophones. For example, the homophone /kæʃ/ (*cash*/*cache*) was changed to /væʃ/ (*vash*/*vache*); this syllable made up the second syllable of the nonword stimulus /fʌlvæʃ/. The degree of orthographic transparency or opacity was quantified on the basis of the number of orthographic neighbors of each spelling. To continue the above example, the spelling of the nonword /væʃ/ as *vash* has 12 orthographic neighbors, and the spelling *vache* has two orthographic neighbors; thus, *vash* is more transparent than *vache*. The syllable's more transparent spelling (e.g., *fulvash*) was used in the transparent condition, and its more opaque spelling (e.g., *fulvache*) was used in the opaque condition. Last, the key syllable in each nonword was controlled for phonological neighborhood density, positional segment frequency, and biphone probability as determined using the online Speech and Hearing Lab Neighborhood Database of Washington University in St. Louis (Retrieved from https://web.archive.org/web/20160102181352/http://neighborhoodsearch.wustl.edu/neighborhood/Home.asp [original page no longer available]).

Along with the two target nonwords (each repeated 10 times), each condition was associated with 10 fillers (nonwords that were permissible in English and had phonetic characteristics similar to the target words). Fillers were not analyzed but were included to increase the difficulty of the task. These stimuli were either one or three syllables in length and were created on the basis of the list of high-probability syllables in Vitevitch et al. (1997). The one-syllable filler words were /tʃʌn, sʌʃ, θin, lel, wes/, and /rem/. The three-syllable filler words were /hʌspəvet, gestədʒən, kʌkləfis/, and /rigləsep/.

Procedure

The procedures were designed to evaluate the effects of modality and transparency on speech production (Saletta et al., 2015). Two measures—segmental accuracy and speech movement stability—were used to evaluate these effects. Primary comparisons included (a) how participants responded to manipulations of modality (i.e., experience with listening to vs. reading the stimuli) and (b) how participants responded to manipulations of orthographic representation (i.e., experience with reading nonwords written in transparent vs. opaque spellings).

Participants heard six nonwords described as the names of make-believe aliens. Each nonword was associated with a specific illustration of an alien character (Ohala, 1996). Participants listened to each character's name and then said its name in the sentence, *Bob saw a (insert name) before*. This carrier sentence, which contains several labial consonants, was used to facilitate kinematic analysis. Producing the nonword within the carrier sentence rather than on its own also increased linguistic complexity and provided semantic context.

Manipulations in modality and orthographic transparency were integrated into the procedures. As shown in Table 2, the task was divided into three conditions: auditory-only presentation, transparent spelling, and opaque spelling. Two nonwords were associated with each condition. Each condition was further divided into three phases: pretest, learning, and posttest. In each phase, words were presented 10 times each in a quasirandom order with no more than two of the same words occurring consecutively. During the pretest phase, participants heard each nonword and repeated it in the carrier sentence multiple times. During the learning phase, participants either read each nonword (in the transparent and opaque spelling conditions) or heard each nonword (in the auditory-only condition to control for the number of exposures to the stimuli across conditions) and repeated it in the carrier sentence multiple times. The posttest phase was identical to the pretest phase. Thus, the learning phases of the written conditions contained the crucial manipulations of the nonword stimuli.

The visual stimuli were presented briefly so that the written phases would be similarly transient to the auditory phases. For the Adult-Typ group, the text disappeared after 1 s. However, because preliminary data revealed that the other two groups would need more time to read the words, the text disappeared after 2 s for the child and Adult-LP groups, and in this study, the critical measures involved these two groups.

Table 2. Structure of each session.

Phase	Auditory	Transparent	Opaque
Pretest	Hear/repeat	Hear/repeat	Hear/repeat
Learning	Hear/repeat	Read/repeat	Read/repeat
Posttest	Hear/repeat	Hear/repeat	Hear/repeat

Note. There were three phases (pretest, learning, and posttest) within three conditions (auditory only, transparent orthography, and opaque orthography). Note that the learning phases of the transparent and opaque conditions contained the crucial manipulation.

Three versions of the task were used to counterbalance the order of conditions as well as which nonwords were associated with each condition. The numbers of participants viewing each version were generally equivalent across groups.

Outcome Variables

Two outcome variables were used to evaluate the effects of modality and transparency/opacity on age and proficiency. These included segmental accuracy and speech movement stability. PCC quantifies segmental accuracy by determining how many consonants (out of four in each target nonword) were produced accurately. An independent coder transcribed 20% of the sessions in order to establish reliability of phonetic transcription. The transcriptions of the first author and the independent coder were in agreement for 97% of the consonants.

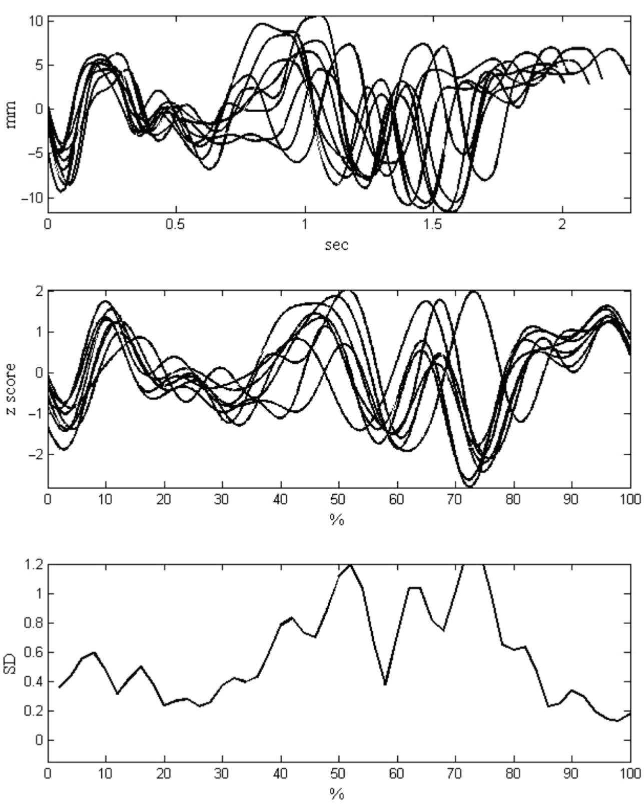
To measure speech movement stability, we computed the LA variability index. This measure is based on a composite of spatial and temporal variability, which is used to quantify the movement of the upper lip, lower lip, and jaw as they interact during speech (Smith & Zelaznik, 2004). The kinematic data were processed in MATLAB (The Mathworks, Natick, MA). The sentences were manually segmented from each phase of the procedure and sorted by condition and phase in preparation for automated measurement.

First, movement onsets and offsets of each sentence were manually selected by visually inspecting the velocity record for local minima. An algorithm then established the minimum value, determining the point at which velocity crossed zero within a 100-ms window of the point that was manually selected. The movement trajectories were then linearly time normalized by setting each extracted record to a time base of 1,000 points and using a cubic spline to interpolate between points. Amplitude normalization was accomplished by setting $M = 0$ and $SD = 1$. After normalizing the data, the standard deviations were computed at 2% intervals in relative time across the 10 records and added together. The sum of the 50 standard deviations is the LA variability index. Higher values of this index reflect greater movement variability (see Goffman et al., 2007; Goffman & Smith, 1999; Smith & Goffman, 1998; Smith & Zelaznik, 2004). Figure 2 illustrates this approach. Kinematic analyses were conducted at the sentence level because effects of language load often appear in multimovement contexts.

Statistical Analyses

All variables were analyzed using a mixed design analysis of variance (ANOVA). The between-participants factors were group (Adult-Typ, Child, and Adult-LP). The within-participant factors were condition (auditory only, transparent spelling, opaque spelling), phase (pretest and posttest), and nonword (first or second nonword). Follow-up ANOVAs were used for pairwise comparisons when

Figure 2. Examples of extracted movement sequences from a child producing the utterance, "Bob saw a /fʌlvæʃ/ 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 (LA) variability index values.



effects were present. Because data expressed as proportions are not normally distributed, an arcsine transformation was applied to the PCC data (Rucker, Schwarzer, Carpenter, & Olkin, 2009). The α level was set to .05. We also report effect sizes for all results.

Influences of two important aspects of reading skill, decoding and comprehension, were assessed. We used linear regression to determine if a relationship existed between speech movement stability and decoding and comprehension. In this case, the α level was changed to .025 using a Bonferroni adjustment in order to adjust for a potential Type I error that may result from conducting multiple correlations on related dependent variables (Tabachnick & Fidell, 2007).

Results

Missing Data

When processing the kinematic data, some productions could not be used, such as those including disfluencies or phonetic substitutions that differed in place of articulation. Overall, because of insufficient numbers of analyzable articulatory kinematic productions, 3% of data was missing from the Adult-Typ group, 3% from the Child group, and 4% from the Adult-LP group. These data were included in the PCC analysis.

To evaluate questions of modality (Question 1) and orthographic opacity/transparency (Question 2) on speech production, we assessed PCC and speech movement stability. Segmental accuracy and stability are addressed separately as follows.

Dependent Measure: PCC

Segmental accuracy data are reported on Figure 3. For the arcsine-transformed PCC data, there was a main effect of group, $F(2, 49) = 24.21$, $p < .001$, $\eta_p^2 = .50$. Post hoc analysis using Tukey's honestly significant difference (HSD) indicated that all three groups were different, with the Adult-Typ group demonstrating the most accuracy, the Child group demonstrating the least accuracy, and the Adult-LP group in the middle (all $ps \leq .05$). There was no main effect of condition, $F(2, 48) = 2.58$, $p = .09$, $\eta_p^2 = .10$. There was a main effect of phase, $F(1, 49) = 100.14$, $p < .001$, $\eta_p^2 = .67$, as participants became more accurate from the pretest to the posttest phase. There was no main effect of nonword, $F(1, 49) = 0.62$, $p = .43$, $\eta_p^2 = .01$.

There was an interaction of Condition × Phase, $F(2, 48) = 16.57$, $p < .001$, $\eta_p^2 = .41$. To clarify this interaction, follow-up ANOVAs were conducted. These analyses indicated that participants became more accurate from pretest to posttest in the transparent condition, $F(1, 51) = 52.09$, $p < .001$, and the opaque condition, $F(1, 51) = 38.45$, $p < .001$, but not in the auditory condition, $F(1, 51) = 3.60$, $p = .06$. There were no other interactions (all $Fs < 3.82$, all $ps > .05$).

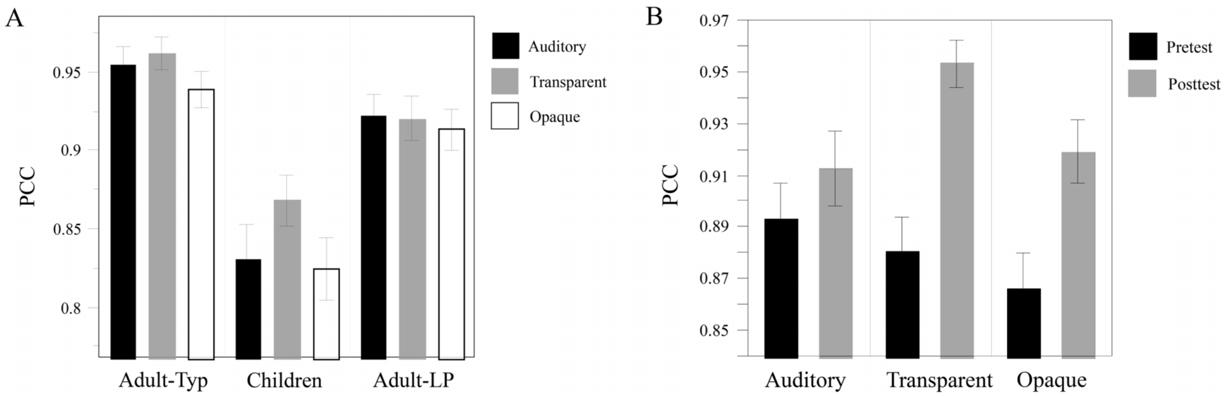
In addition, pretest/posttest PCC difference scores were analyzed as a more direct index of within-individual change. The difference score is particularly relevant to assessing learning as a consequence of orthographic cues. PCC difference scores are reported in Figure 4. In difference scores, there was no main effect of group, $F(2, 49) = 1.37$, $p = .26$, $\eta_p^2 = .05$. There was a main effect of condition, $F(2, 48) = 8.51$, $p = .001$, $\eta_p^2 = .26$. Post hoc analyses using Tukey's HSD indicated that participants showed greater difference scores (reflecting increased learning from pretest to posttest) in the two written conditions (both $ps < .04$), as compared with the auditory condition ($p = .41$). There was no main effect of nonword, $F(1, 49) = .94$, $p = .34$, $\eta_p^2 = .02$. There were no interactions (all $Fs < 1.80$, all $ps > .14$).

Overall, the PCC results indicate that the three groups differed in their phonological processing at baseline. However, all three groups exhibited greater phonological learning when they were able to access the nonwords' orthographic representations than when they were only presented with the word in its auditory form.

Dependent Measure: LA Index

For the LA index data, there was a main effect of group, $F(2, 35) = 18.19$, $p < .001$, $\eta_p^2 = .51$. Post hoc

Figure 3. Percentage consonants correct (PCC) data; higher scores indicate greater accuracy. Error bars reflect standard errors. Panel A shows group differences by condition and Panel B shows the Condition × Phase interaction.



analyses using Tukey's HSD indicated that all three groups were different, with the Adult-Typ group demonstrating the greatest stability, the Child group demonstrating the least stability, and the Adult-LP group in the middle (all *p*s < .02). There was no main effect of condition, $F(2, 34) = 0.59$, $p = .59$, $\eta_p^2 = .03$. There was a main effect of phase, $F(1, 35) = 24.25$, $p < .001$, $\eta_p^2 = .41$, as participants became more stable from the pretest to the posttest phase. There was no main effect of nonword, $F(1, 35) = .29$, $p = .60$, $\eta_p^2 = .01$.

There were interactions of Group × Condition × Phase, $F(4, 68) = 2.65$, $p = .04$, $\eta_p^2 = .14$, and Group × Condition × Word, $F(4, 68) = 3.20$, $p = .02$, $\eta_p^2 = .16$. There were no other interactions (all *F*s < 2.54, all *p*s > .09). Speech movement stability data are reported in Figure 5.

In addition, to directly assess learning, pretest/posttest difference scores for the LA index values were calculated. There were no main effects (all *F*s < 1.64, all *p*s > .21).

For LA index difference scores, there was an interaction of Group × Condition, $F(4, 68) = 3.16$, $p = .02$, $\eta_p^2 = .16$. Follow-up ANOVAs indicated that the Adult-LP group drove this interaction as there was an effect of condition that approached significance for this group, $F(2, 26) = 3.25$, $p = .055$. Post hoc analysis using Tukey's HSD indicated that for the Adult-LP group, the two written conditions differed from one another, with the transparent condition associated with the greatest positive change and the opaque condition associated with the least change ($p = .04$). In contrast, the speech movement stability of the Adult-Typ group did not change by condition, all *F*s < 2.49, all *p*s > .11), and the speech movement stability of the Child group did not change by condition (all *F*s < 2.91, all *p*s > .12). There were no other interactions (all *F*s < 2.09, all *p*s > .14). LA index difference scores are reported in Figure 6. These results reveal that although the three groups differed in their motor stability at baseline, they all improved in motor stability with practice. In addition, exposure to the transparent versus opaque forms of the orthographic representations caused the Adult-LP group to change their motor processing; the two typical groups did not show this effect.

Figure 4. Percentage consonants correct (PCC) pretest–posttest difference scores (positive scores indicate greater accuracy). Error bars reflect standard errors.

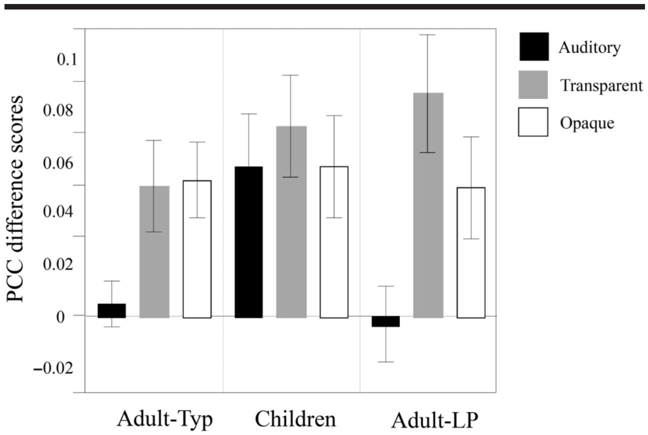


Figure 5. Lip aperture (LA) index values (lower scores indicate greater articulatory stability). Error bars reflect standard errors.

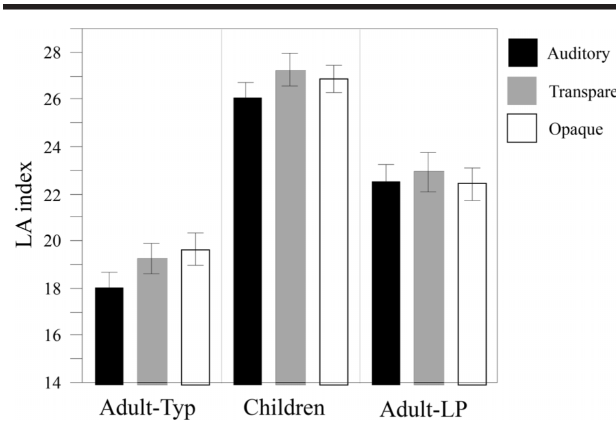
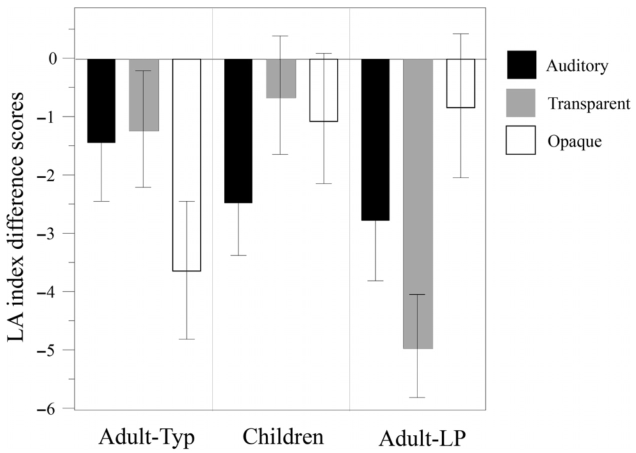


Figure 6. LA index value pretest–posttest difference scores (negative scores indicate greater articulatory stability). Error bars reflect standard errors.



Relationship Between Reading Skills and Speech Production

A linear regression was conducted to determine if reading skills—to be specific, the word attack and word comprehension subtests of the WRMT-R/NU—predicted speech movement stability. It was anticipated that the children's inherently weaker reading skills would drive the results if they were included in the regression; therefore, the regressions were run on the two adult groups separately from the child group. The regressions indicated that speech movement stability was correlated with both decoding, $F(1, 33) = 8.31$, $p < .01$, $R^2 = .20$, and comprehension, $F(1, 33) = 7.45$, $p = .01$, $R^2 = .18$ (see Figure 7). Given the *p* value of .025 on the basis of the Bonferroni-type adjustment, these results were significant. The same regressions run on the child group did not yield significant results (both $ps > .14$, both $R^2\text{s} < .37$).

Discussion

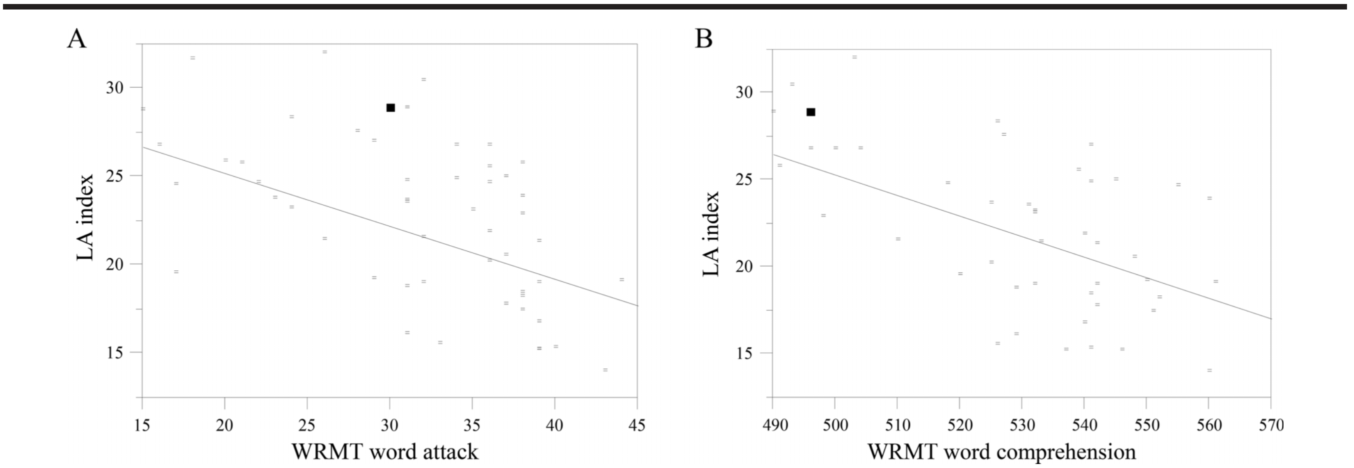
The purpose of this study was to investigate the influences of orthographic factors on the production of nonwords by individuals who varied in reading skill. We addressed the ways in which reading proficiency and exposure to nonwords that contained manipulations of modality and orthographic transparency influenced implicit processing. We tested the performance of typical readers and relatively poor readers (children who were developing reading skills typically and adults who demonstrated low levels of reading proficiency). Our question is important because it contains both theoretical and clinical implications. To be specific, these data support our expanded model of the interactive process between reading, processing, and speaking; the idea that spoken and written language processing are organized differently in individuals with reading difficulties as compared with children and adults with typical reading skills; and the perspective that word- and phonological-level factors and speech movement stability are connected.

In the experimental task, participants heard and read aloud nonwords that systematically varied in modality of presentation (auditory vs. written) and orthographic transparency (relatively transparent vs. opaque spelling). Measures of segmental accuracy and speech movement stability were used to quantify orthographic effects on speech production.

All Three Groups Differ in Phonetic Accuracy and Speech Movement Stability

The three groups of participants differed from one another on both dependent measures. In both cases, the Adult-Typ group demonstrated the best performance,

Figure 7. Panel A shows the regression line representing the correlation between Woodcock Reading Mastery Tests–Revised (WRMT-R/NU) word attack raw scores and overall lip aperture (LA) variability in the two adult groups. Panel B shows the regression line representing the correlation between WRMT-R/NU word comprehension w-scores and overall LA variability in the two adult groups.



the Child group demonstrated the weakest performance, and the Adult-LP group demonstrated intermediate performance. Thus, the groups did not cluster in such a way as to associate the two adult groups or the two typical groups; rather, the three groups exhibited distinct performance.

The Adult-LP group was globally weaker than the Adult-Typ group in speech movement stability even in the auditory condition that did not involve any reading. This result was not predicted on the basis of previous studies of adult second-language learners (Chakraborty et al., 2008), which indicated that differences in oral language skill did not predict speech movement stability. This study's Adult-LP group exhibited LA index values that were significantly different from those of the two typical groups despite demonstrating similar oral language functioning. Children with even lower reading proficiency did not show the same pattern. Therefore, we may conclude that atypical developmental history, unlike second-language proficiency, may be associated with increased speech movement variability. To address our developmental question, these data indicate that poor adult readers do not display typical developmental processes.

Reading Skills Are Correlated With Speech Movement Stability

In addition, the results of the regression illuminated specific relationships of individual differences in reading proficiency on speech production. Reading skills (both decoding and comprehension) were correlated with overall speech movement stability in the two adult groups. This finding indicates that even individuals with typical nonverbal cognition and oral language skills may be differentiated on the basis of their speech motor output. These data also indicate that motor learning (speech movement stability) and phonological learning (decoding and comprehension) are linked in adult speakers even though it is not necessarily intuitive that a higher level cognitive process and a lower level motor output process should be this closely connected. However, the causal direction of these two aspects of learning has yet to be determined.

Exposure to Orthography Changes Speech Production

The PCC and LA index data indicated that participants experienced changes in their speech production as a consequence of exposure to the nonwords in written form. In only the Adult-LP group, these changes occurred as the result of exposure to the nonwords written with a transparent orthography. It is of crucial importance that these changes occurred after the reading phase and persisted even after the removal of the written text. This suggests that participants were fundamentally influenced by the exposure to orthography. These changes did not simply happen in the course of the reading task itself, indicating that participants must have integrated the nonwords' orthographic factors into their lexical representations of the nonwords. In contrast, participants did not significantly increase in segmental accuracy in the auditory condition, indicating that practice alone did not advance phonological learning but that this improvement is due to the specific experience of reading. In this context, phonological learning involves slow-mapping and building a long-term connection between the orthographic and lexical representations of the nonwords.

We questioned if changes in speech production would occur to these three groups of readers as the result of manipulations of modality (Question 1) and/or orthographic transparency (Question 2). One possible prediction was that poorer readers would be influenced by manipulations of modality to a greater extent than skilled readers because they relied more heavily upon the visual characteristics of written words (Lavidor et al., 2006). An alternative perspective (Kamhi & Catts, 2012) suggests that skilled readers may have been more influenced by these manipulations because they relied to a greater extent on holistic visual processing than upon phonological mediation.

To address the first component of this question (modality), the PCC data (reflecting phonological learning) indicated that all three groups became more accurate with practice in the two written conditions but not in the auditory condition—that is, participants with various levels of reading proficiency benefited from the addition of written cues more than exclusively auditory cues. This suggests that individuals with all skill levels respond to manipulations of modality.

Therefore, the data obtained in the current study do not ultimately support either of the above views. Rather, participants of all skill levels, even those who demonstrated a relatively low level of literacy, experienced facilitative effects of the exposure to writing. This may be the case because they were able to use orthography intentionally as a mnemonic device to support phonological learning (consistent with Alario, Perre, Castel, & Ziegler, 2007). Even the individuals in the Adult-LP group were able to use these cues, perhaps because metalinguistic strategies are taught in even the very earliest reading and language arts instruction and perhaps because most of these participants had received language and/or reading intervention at some point in their education.

To address the second component of this question (transparency), the LA index data (reflecting motor learning) indicated that all three groups became more stable with practice. The difference score data, which directly assessed learning, indicated that the Adult-LP group experienced the greatest positive change in the transparent condition and the least change in the opaque condition, and both typical groups became more stable regardless of transparency.

Again, two competing views were reviewed. One possible prediction was that poorer adult readers might experience a greater influence of manipulations of orthographic characteristics because they experience difficulties in processing sublexical factors (Fowler, 1991) and automatically identifying written words (Ventura, Morais, & Kolinsky, 2007). The other expectation was that more skilled readers might be particularly influenced by this type of manipulation because they experience deeper effects of orthographic neighborhood density (Ziegler & Muneaux, 2007; Ziegler et al., 2003) and may be more affected by phonological/orthographic inconsistencies (Bolger et al., 2008). The findings of the current study support the first of these two options as the Adult-LP group demonstrated differences in speech movement stability as the result of the manipulation of orthographic factors. Children with typical reading skills do not use the same strategies as adults who are poor readers as they were not affected by manipulations of orthographic transparency.

Theoretical Implications: Reading and Speech Movement Stability Are Interactive

Our results can be interpreted in light of the model proposed in Figure 1. To be specific, we have based our work on previous models of language and speech (e.g., Levelt et al., 1999; Shattuck-Hufnagel, 1987; Smith & Goffman, 2004) but have taken them a step further by integrating the processing of written language. In addition, our data indicate that reading and speech motor output are interactive as opposed to strictly top-down processes. The nonwords' orthographic characteristics appeared to influence both higher level linguistic processes and lower level speech motor output. In other words, word- and phonological-level factors have an effect on speech movement stability. These types of interactivity occur even when they are not strictly necessary for a given task. That is, phonological, semantic, and orthographic representations all affect one another as words are spoken even if all of these domains do not need to be activated (as, for instance, orthography does not need to be activated in a task involving speaking alone). Thus, even if the task does not require the use of semantics or spelling as was true regarding the nonword repetition task in the current study, orthographic characteristics will still influence speech production and should still be a component of the interactive model. Furthermore, these results confirm that measures of speech production, which have previously been used to provide evidence into sentence, word, and phonological effects, can also be used to explore the effects of orthographic manipulations. Last, our findings support the concept that the interaction between decoding and speech motor output is mediated by individual differences in reading skill. The results from the regression analyses indicate that individuals with stronger reading skills also produced the nonwords with greater speech movement stability. Adults with poor reading skills do not use the same reading or speaking strategies as children with typical reading skills.

Limitations and Future Directions

This experimental study was designed to address a theoretical model and thus needs to be contextualized. The task itself involved sentence imitation, which is not an activity in which readers engage in daily life. In addition, because it was required that sentences be repeated, working memory factors may have interacted with the results; future work would benefit from inclusion of a working memory measure. Our model is based on data from our single study. Future studies should raise falsifiable hypotheses to contribute to our model. When generalizing conclusions from our data, the reader should keep in mind these boundaries as well as the theoretical nature of the article. It is also important to contextualize this work in relation to other research considering the influence of motor processing on perception. These include the motor theory of speech perception, which states that listeners understand speech by recognizing the speakers' underlying gestural commands rather than by identifying acoustic patterns (Galantucci et al., 2006; Liberman et al., 1967; Liberman & Mattingly, 1985). This research addresses a specific problem but is theoretically consistent with other prominent accounts.

Further research is necessary to connect our proposed model with aspects of reading beyond straightforward decoding. According to the simple view of reading (Hoover & Gough, 1990), reading is a complex activity requiring the decoding of graphic shapes into linguistic units. This process consists of only two components: decoding and linguistic comprehension. According to Perfetti (2007), these components are inextricably connected at every level of processing, including the reading of words and sentences. The effectiveness of an individual's word identification skill is what causes skilled comprehenders to differ from less skilled comprehenders (Perfetti & Hart, 2001).

This broader context compels us to include aspects of reading beyond word attack in our model. To be specific, reading comprehension at the sentence or discourse level depends on efficient word reading—that is, word-level knowledge, as operationalized by lexical quality (i.e., the reader's knowledge of the given word, including its form, meaning, and use), has consequences for broader reading comprehension. The lexical quality of a word is high if it has fully specified and redundant orthographic and phonological representations; that is, one representation is from spoken language, and the other is recoverable from orthographic-to-phonological mappings (Perfetti & Hart, 2002). Efficient sublexical processing mechanisms include cognitive resources (working memory, integrative processes, and syntactic repairs), access of meaning through orthography, form knowledge (including knowledge of grammatical class, spellings, and pronunciations), meaning knowledge, and practice and experience. These mechanisms facilitate rapid, low-resource retrieval of the word's identity and access of meaning (Perfetti, 2007). For future works, we intend to broaden our model to examine and further develop semantics as a characteristic of word-level input and oral and written comprehension as processing skills.

Last, future work should relate this paradigm to clinical aspects concerning children with dyslexia or other language-learning difficulties in order to disambiguate which components of these difficulties have their source in childhood and later resolve and which other factors become exacerbated and magnified as academic demands increase. These mechanisms may differentially influence individuals with and without reading disorders. These future directions represent important steps in designing and improving methods of identification and intervention for children and adults who experience reading difficulties.

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Appendix

Characteristics of Target Nonwords

Homophone pairs (second syllable)	Transcription	High-density spelling	Low-density spelling	Number of phonological neighbors	Number of orthographic neighbors for high-density spelling	Number of orthographic neighbors for low-density spelling	Positional segment frequency	Biphone probability of medial consonants
strait/straight	/fispet/	*feespait*	*feespaight*	34	15	1	.1796	.0081
peek/pique	/mʌnfik/	*munfeek*	*munfique*	20	6	1	.1318	.0022
ate/eight	/baɪnvet/	*binevate*	*bineveight*	19	12	1	.1176	.0113
loot/lute	/pʌlvut/	*pulvoot*	*pulvute*	26	18	9	.1305	.0015
cash/cache	/fʌlvæʃ/	*fulvash*	*fulvache*	15	12	2	.1096	.0015
side/sighed	/bispaɪd/	*beespide*	*beespighed*	5	13	0	.1566	.0081