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Phonological and Motor Errors in Individuals With Acquired Sound Production Impairment

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Purpose: This study aimed to compare sound production errors arising due to phonological processing impairment with errors arising due to motor speech impairment.
Method: Two speakers with similar clinical profiles who produced similar consonant cluster simplification errors were examined using a repetition task. We compared both overall accuracy and acoustic details of hundreds of productions with target consonant clusters to tokens with singletons. Changes in accuracy over the course of the study were also compared.
Results: In target words with consonant cluster simplification, the individual whose errors reflected phonological impairment produced articulatory timing consistent with singleton onsets. These productions improved when resyllabification was possible, but error rates were not affected by exposure. In contrast, the individual with motoric-based errors produced simplifications that contained the articulatory timing associated with clusters. Accuracy was not affected by the ability to resyllabify, but it did significantly improve following repeated production.
Conclusions: Our findings reveal clear differences between errors arising in phonological processing and in motor planning that reflect the underlying systems. The changes over the course of the study suggest that error types with different sources are responsive to different intervention strategies.

Key Words: phonological processing, motor planning, AOS, phonemic paraphasia, acoustics

The cognitive and neural processes involved in speech sound production—as well as impairment to these processes—have been widely studied both with respect to phonological processing mechanisms (e.g., Blumstein, 1973; Buckingham, 1986; Goldrick & Rapp, 2007) and to motor speech processing (e.g., McNeil, Robin, & Schmidt, 2009; Varley & Whiteside, 2001; Ziegler, 2002). Although there is frequently debate about the details of phonological processing and motor processing in speech production, there remains widespread agreement in both the clinical and psycholinguistic literatures that these constitute two separate (though potentially interacting) levels of processing. This distinction presupposes different representations and processes at these two levels. In this article, we draw on a general understanding of these two processing systems to guide research questions about individuals with sound production deficits that affect these levels.

The distinctions between abstract, context-independent aspects of sound structure encoded in phonology and motor aspects of articulation have been widely discussed in psycholinguistic accounts of language production. These accounts typically posit a phonological level in which speakers retrieve and encode phonological representations from long-term memory, and a later motor planning level in which phonological representations are translated into a series of motor commands that can be executed by the speech musculature. In the remainder of the introduction, we review proposals about these two levels regarding two factors—articulatory timing and syllabification—that are central components of spoken production and that form the basis of the present investigation. We then address current proposals of how deficits affecting these processing systems relate to clinical syndromes in adult neurogenic populations. Finally, we use characterizations of these two processing systems to

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make predictions about the types of errors we expect to see at each level in the present investigation.

Generating Articulatory Timing in Production

The standard view in psycholinguistics (Dell, 1986, 1988; Goldrick & Rapp, 2007; Levelt, Roelofs, & Meyer, 1999) and theoretical phonology (Chomsky & Halle, 1968; Prince & Smolensky, 1993/2004) has been that the lexicon stores word representations consisting of relatively abstract, context-independent representations of sound structure (e.g., phonemes). Whereas some of these proposals involve purely symbolic abstract elements (e.g., Chomsky & Halle, 1968), other proposals suggest that these context-independent representations more directly reflect articulatory details of speech (e.g., gestures; Browman & Goldstein, 1986, 1988, 1989), including spatial and temporal properties of the component gestures. Irrespective of these differences, each proposal includes both context-independent and context-specific representations of sound structure. We refer to the level that encodes context-independent sound structure as *phonological processing* for the purposes of this article. Disruptions at this level of processing should affect computations over context-independent sound structure units rather than either articulatory timing or the lexical entries themselves.

It is also widely agreed that articulation requires a detailed motor plan that can be used to generate speech output (Levelt et al., 1999). There has been a growing consensus that these representations incorporate context-specific details about the spatial and temporal overlap of adjacent sound structure elements, as in the gestural score of articulatory phonology. The processing system that generates these representations has been referred to as *phonetic encoding* (Levelt et al., 1999; Ziegler, Staiger, & Aichert, 2010) and as *motor planning* (McNeil et al., 2009)—we use the latter term throughout this article. Motor planning is the processing system most closely associated with apraxia of speech (AOS; see the Discussion section), which is thus fundamentally viewed as a motor speech disorder (McNeil et al., 2009; Wambaugh, Duffy, McNeil, Robin, & Rogers, 2006a, 2006b). Disruptions at this level of processing should impair the type of context-specific details represented here. It is worth noting that the traditional separation of these two levels as distinct and noninteractive is not consistent with recent evidence. Instead, various findings have shown that details of articulation can be affected by lexical properties, such as frequency and neighborhood structure (Baese-Berk & Goldrick, 2009; Munson & Solomon, 2004; Wright, 2004), as well as by whether multiple structures are competing for production (Frisch & Wright, 2002; Goldrick, Baker, Murphy, & Baese-Berk, 2011; Goldrick & Blumstein, 2006; Goldstein, Pouplier, Chen, Saltzman, & Byrd, 2007; McMillan & Corley, 2010; McMillan, Corley, & Lickley, 2009; Mowrey & MacKay, 1990; Pouplier, 2003; Pouplier & Hardcastle, 2005). Many of these findings have been explained as resulting from *cascading activation* in which activation levels originating at a higher level (e.g., either lexical or phonological) cascade down, affecting processing at a phonetic/motor level and ultimately affecting articulation. Although cascading activation provides a mechanism for the interaction of these processing systems, such accounts remain consistent with broad neural and functional distinctions among these systems while allowing for some amount of interaction. We address how different mechanisms of interaction from higher levels to lower levels could help account for the data reported here in the Discussion section.

Generating Syllable Structure in Production

The notion of the syllable is fundamental in phonological theory, as evidenced by the fact that several linguistic accounts rely on descriptions of the sound structure of a language that incorporate the syllable to explain a variety of phenomena, including sonority sequencing, prosodic details, and position-specific processes such as syllable-final devoicing (Blevins, 1995; also see van Oostendorp, Ewen, Hume, & Rice, 2011 [and chapters within]). There are also several branches of experimental evidence suggesting the relevance of the syllable in spoken production (Cholin, 2008; Cholin & Levelt, 2009; Cholin, Levelt, & Schiller, 2006; Laganaro, 2005, 2008; Laganaro & Alario, 2006; Levelt et al., 1999; Ziegler, 2002; Ziegler et al., 2010). A prominent view in psycholinguistics (Dell, 1988; Levelt et al., 1999) holds that the descriptions of both phonological processing and motor planning incorporate the syllable as a central unit but in different ways. In particular, phonological processing is responsible for syllabification, whereas motor planning is involved in deriving a representation of the motor features corresponding to a syllable that is ultimately produced. These syllable representations can be retrieved from a mental syllabary in case of familiar syllables or can be generated in case of novel syllables.

Syllable frequency effects are typically believed to index retrieval of phonetic representations of syllables at the level of motor planning (Laganaro, 2008). Such effects have been reported in several investigations of unimpaired speakers (Cholin & Levelt, 2009; Cholin et al., 2006) and in speakers with AOS (Aichert & Ziegler, 2004; Staiger & Ziegler, 2008; Ziegler et al., 2010). That syllable frequency effects appear in AOS is expected on the view that AOS results from damage of motor planning, the level at which phonetic representations of syllables are allegedly encoded.

Relating Phonological Processing and Motor Planning to Adult Neurogenic Disorders

In the literature on acquired sound production disorders, a distinction is made between errors arising due to phonemic paraphasia (PP) and due to AOS. Despite some early descriptions of AOS as having a phonological component (Darley, Aronson, & Brown, 1975; Wertz, Lapointe, & Rosenbek, 1984), it is now typically held that AOS is, by definition, a motor speech impairment and is thus qualitatively different from PP (McNeil, Pratt, & Fossett, 2004; van der Merwe, 2009; Wambaugh et al., 2006a). Evidence in support of the distinctive basis of these impairments emerged primarily from case reports of AOS without concomitant aphasia (McNeil, Odell, Miller, & Hunter, 1995; Odell, McNeil, Rosenbek, & Hunter, 1990, 1991). These reports were instrumental in defining the differential diagnosis of PP and AOS and in identifying slow, dysprosodic speech with sound distortions and perceived sound substitutions as hallmarks of AOS (McNeil et al., 2009; Wambaugh et al., 2006a). The specific deficits observed in AOS are generally attributed to impairment to the motor planning system that possibly affect the retrieval and generation of syllables in the encoding process (Ziegler et al., 2010). For both PP and AOS, it is rare that these deficits occur in isolation in the absence of other impairment (Duffy, 2005).

Despite the identification of a set of features distinguishing AOS from PP, there exist well-documented obstacles to attribute the errors recorded from individuals with acquired sound production impairment to deficits affecting either phonological processing or motor planning. A first obstacle relates to the frequent co-occurrence of AOS and PP (McNeil et al., 2009). This complicates the ability to attribute error patterns of individuals to just phonological processing or motor planning. A second obstacle is that there are many similarities in the sound sequences that we expect to be vulnerable to error in deficits affecting either phonological processing or motor planning. For example, consider the case of onset consonant clusters (e.g., *small*). These sequences are widely known to be phonologically marked (Prince & Smolensky, 1993/2004), rarer cross-linguistically (Blevins, 1995), and typically acquired later in development (see Dinnsen & Gierut, 2008 [and articles within]) relative to singleton onset consonants. Therefore, in the case of impairment to phonological processing, we would expect these sequences to be particularly vulnerable to error. Yet, the articulatory coordination in consonant clusters is also more complex than the singleton onsets (Nam, Goldstein, & Saltzman, 2010). Because of the complexity of the motor sequences involved in producing clusters relative to singleton onsets, we also expect these sequences to be vulnerable to errors in motor planning.

As discussed below, however, this second obstacle may not be fully limiting. In fact, although errors are expected on similar sequences for impairments to phonological processing or impairments to motor planning, we may be able to identify features of these errors—related to acoustic and articulatory signatures, and factors reducing their frequency—that can be specifically associated to only one type of impairment.

Overview of Present Investigation

The present investigation focuses on the differences between errors arising from deficits affecting phonological processing versus motor planning. We examine onset consonant cluster sequences that are expected to be vulnerable to error for both levels of impairment but where we can use the hypotheses about articulatory timing and syllable computation discussed above to make two specific predictions about the details of the errors to be produced. A third prediction relates to the effects of repeated production of problematic sequences.

The first prediction derives from the claim introduced above that production errors—particularly consonant cluster simplification errors—that arise in phonological processing should reflect the acoustic and articulatory timing of the reduced onset target. In other words, deletions occurring in phonological processing take place prior to the generation/retrieval of articulatory plans and should thus reflect the timing of a singleton onset. In contrast, if the deletion error occurs in motor planning, the motor planning processes should have been attempted on the basis of the timing of a consonant cluster. For the purposes of the present investigation, we operationalized the notion of timing by using duration of particular portions of utterances. In particular, we address this by examining deletion errors in consonant clusters (e.g., *small* → *~~s~~mall*). In these errors, which are relatively common in individuals with acquired sound production disorders, we expect phonological processing errors to reflect the timing of a singleton nasal consonant (because the deletion occurs prior to generating the timing), whereas motor planning errors will contain timing reflecting the target cluster.

Second, we expect different degrees of sensitivity to syllable structure in errors arising in phonological processing versus motor planning. As discussed above, many accounts of production consider syllabification to be part of phonological processing, whereas the retrieval (and generation) of phonetic descriptions of syllables is part of motor planning. Thus, we expect conditions that can permit resyllabification to less complex structures to affect errors that arise in phonological processing but not those associated with motor planning because the processes supporting resyllabification are not available at this processing level.

Predictions concerning articulatory timing and syllable computation were tested using detailed acoustic analyses on the speech errors of individuals with sound structure impairment. There is ample evidence suggesting that repeated articulation is a critical component to the successful articulatory kinematic approaches to AOS treatment (for reviews of the evidence, see Wambaugh et al., 2006a, 2006b). Furthermore, it has been recently shown that individuals with AOS may improve in their production of complex syllables by producing other syllables with the same complex portion (Aichert & Ziegler, 2008). Thus, we expect that errors that arise from motor planning impairment should decrease as a consequence of repeated production of complex syllables. Treatment approaches to errors generated in phonological processing are more likely to focus on promoting awareness of particular contrasts rather than simply repeating complex sequences—thus, we expect these errors to be less sensitive to repeated exposure.

In sum, the present investigation addresses the following research questions:

1. Are there reliable differences in articulatory timing between speech errors arising in phonological processing and motor speech processing?
2. Do error types and error rates change as a result of resyllabification?
3. Does repeated exposure to consonant sequences affect production accuracy?

We examined the production of consonant clusters in two participants who received the diagnosis of AOS, and we carried out detailed acoustic analyses on their speech errors. Each of these research questions was addressed by a specific experiment below. Our results demonstrate that despite their apparent similarities, the errors produced by the two participants conform to alternative predictions and therefore strongly support the distinction between errors arising at the levels of phonological processing versus motor planning.

Method

Case Reports

DLE (born in 1934) is a left-handed man who received a college degree in engineering. DLE worked in mechanical engineering and became the chief executive officer of an international machine parts manufacturing company. In 2001, he suffered a middle cerebral artery infarct. Magnetic resonance imaging scans revealed a lesion affecting the entire inferior frontal gyrus and insula and much of the precentral gyrus, sparing the superior frontal gyrus, a significant portion of both the middle frontal gyrus, as well as the medial surface of the frontal lobe, thus largely sparing the supplementary motor area. In the parietal lobe, the lesion damaged the postcentral gyrus and the inferior parietal lobule, including the supra-marginal gyrus. Damage to the temporal lobe was restricted to the posterior and superior areas of the superior temporal gyrus. There was also left thalamic damage, principally affecting the lateral, anterior portion. HFL (born in 1950) is a right-handed man who earned a medical doctorate and worked as a radiologist prior to his cerebrovascular accident. A neurologist's report indicated that he suffered a left middle cerebral artery infarct in 2007 leaving him with right-sided hemiplegia. Brain scans were not available. Each individual was diagnosed with nonfluent aphasia. DLE and HFL were previously reported in Buchwald and Miozzo (2011).

Table 1 presents demographic data about each individual as well as their performance on naming, comprehension, and articulation tasks. These data clearly indicate that each individual has both aphasic symptoms as well as motor speech difficulty, with HFL having more severe anomic symptoms as indicated by his extremely poor picture naming ability. The most common

Table 1. Demographic information and results from standardized tests.

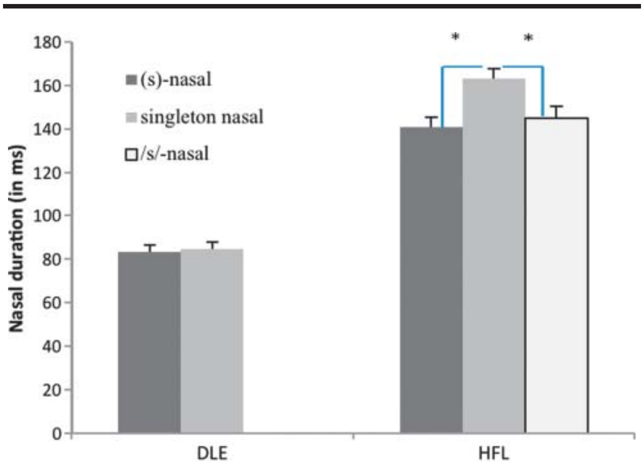
Variable	Participant: DLE	Participant: HFL
Age (years)	76	60
Education (years)	17	21
Time post onset (months)	84	30
Handedness	Left	Right
Naming: BNT		
BNT (full)	33/60	
Short form		1/15
Comprehension: PPVT–R	43rd percentile	4th percentile
Minimum pair discrimination: PALPA 2	71/72	72/72
Articulation: ABA–2		
Subtest 1	Mild	Mild
Subtest 2A	Severe	Moderate
Subtest 2B	Moderate	Severe
Subtest 3A	Mild	Mild
Subtest 3B	Moderate	Moderate
Subtest 4	Severe	Severe
Subtest 5	Moderate	Severe
Aphasia quotient:		
WAB	54.6 (Broca's)	
WAB–R		41.1 (Broca's)

Note. The naming results come from the Boston Naming Test (BNT; Kaplan, Goodglass, & Weintraub, 1983); the Peabody Picture Vocabulary Test—Revised (PPVT–R; Dunn & Dunn, 1981); the Psycholinguistic Assessments of Language Processing in Aphasia, Task 2 (PALPA 2; Kay et al., 1992); the Apraxia Battery for Adults, Second Edition (ABA–2; Dabul, 2000); the Western Aphasia Battery (WAB; Kertesz, 1982); and the Western Aphasia Battery—Revised (WAB–R; Kertesz, 2006).

errors produced by DLE in spoken picture naming were phonologically related words (conventionally defined as errors sharing at least 50% of target phonemes; e.g., *cannon* → *gannon*; 47/130, 36%; no responses [23%] and perseverations [20%] were the other types of DLE's frequent errors). The accuracy of both participants in producing singleton consonants in repetition tasks was significantly higher than on consonants that appeared in clusters, as was reported in Buchwald and Miozzo (2011).

In spontaneous speech, each speaker was dysfluent, and HFL's utterances were mostly limited to individual words and a few speech formulas (e.g., "thank you"). HFL received a diagnosis of moderate/severe AOS by a speech-language pathologist certified by the American Speech-Language-Hearing Association, whereas DLE received a diagnosis of mild AOS. With respect to the core features associated with AOS identified by Wambaugh et al. (2006a), each individual exhibited additional symptoms suggestive of AOS, including distortions and dysprosodic speech in both spontaneous speech and in the experimental tasks, as well as apparent phonemic substitution errors. Despite each individual exhibiting these symptoms, a clear difference was present where HFL exhibited these symptoms with greater frequency, and his distortions and dysprosody were clearly more pronounced. This is seen in his productions of nasal consonants presented below (see also Figure 1). In addition, HFL frequently exhibited groping in his speech production; this was observed only infrequently in DLE. No dysarthrias were diagnosed for either participant.

Figure 1. Nasal durations for DLE and HFL for different stimulus types. (s)-nasal refers to tokens with a target /s/ that was deleted; /s/-nasal refers to tokens with a target /s/ that was not deleted. DLE did not have enough of these tokens for the comparison. Error bars represent standard errors, and asterisks reflect significant differences.



These two individuals were selected to participate in this study because they both frequently made deletion errors in consonant cluster production. In particular, /s/-clusters were frequently produced without the /s/ (e.g., *small* → ~~*s*~~*mall*). (Following standard conventions from theoretical phonology, we use slashes around a sound to indicate the underlying/target representation, and we use square brackets to indicate the surface representation/production.) As discussed in the introduction, errors on consonant clusters would be expected to arise both in phonological processing impairment and in motor planning impairment. However, there are several differences expected on the basis of the level that these errors arise that we explore below.

Repetition Task

The repetition task was chosen because both participants could perform it easily and because it permitted us to directly address their sound production impairment (rather than their lexical access impairment, as is evident from their naming performance). All experimental data reported below come from spoken repetition. Verbal stimuli were spoken one at a time by the experimenter and were immediately repeated by DLE and HFL. The experimenter repeated the stimulus upon the participant's request. For each participant, words were recorded over the course of weekly testing sessions over 6 months. The recording equipment was a Zoom H4N digital recorder with DLE, and a Marantz 660PMD with Shure SM10A head-mounted microphone with HFL. The acoustic analyses conducted on the wave files were performed in Praat (Boersma & Weenink, 2011). The procedure used in our investigation was approved by the institutional review board at Johns Hopkins University (DLE) and New York University (HFL).

Each individual was tested by a different experimenter. To verify that differences in the articulation model from the experimenter cannot account for the performance in the production task—a possibility suggested by a variety of findings indicating that speakers alter their productions on the basis of their interlocutor's productions (e.g., Goldinger, 1998; Pardo, 2006)—we performed the same analyses on the productions of the experimenters that we did on the productions of the experimental participants. We report these data in the Results section for each analysis.

The data presented below focus on tokens with target /s/-initial clusters for which both individuals frequently deleted /s/. The presence of /s/ for each token was assessed by two trained research assistants who used perceptual analysis as well as the visual information in the spectrogram and waveform to evaluate whether /s/ was present. Tokens with a perceptible fricative that had a locus of energy in the 5000–8000 Hz range were scored as /s/; any other fricative produced in place of /s/ was considered a cluster error. When acoustic comparisons were made involving /s/-deletions, these comparisons were limited to tokens containing no onset error other than the deletion of the /s/. Tokens used to compare /s/-deletions with accurately produced stimuli were never elicited in the same session. For both individuals, the repetition task consisted of mostly (~75%) filler words that did not begin with /s/-clusters. This was done to vary the onset in the words that they were presented with. For each individual, their accuracy on singleton consonants was significantly higher than on consonants that appeared in clusters as was reported in Buchwald and Miozzo (2011). In addition, each participant accurately produced greater than 85% of singleton /s/ onsets on a test of 40 words with /s/ onsets.

Auditory Perception

To verify that errors in repetition came from an articulatory deficit rather than an auditory word recognition deficit, we extensively probed participants' auditory comprehension using minimal pair discrimination tasks involving words (see Table 1 for summary). Word pairs were spoken one at the time by the experimenter, and participants made a same/different decision task. Same and different pairs occurred with identical probabilities (.5 each). Participants performed within controls' range in a standardized task from the Psycholinguistic Assessments of Language Processing in Aphasia, Task 2 (Kay, Lesser, & Coltheart, 1992). Two other lists were specifically developed to test the perception of words with /s/-initial clusters in addition to the control words tested in Experiments 1 and 2. The different pairs in the first list served to test materials used in Experiment 1, and they were formed by words with /s/-nasal onset and by words with singleton nasal onsets (e.g., *small~mall*; *snail–nail*). Both individuals were excellent at this task (DLE: 78/80, 97.5%; HFL: 80/80, 100%). The different pairs in the second list (from Buchwald & Miozzo, 2011) tested the materials of Experiment 2 and included words with /s/-stop onsets and words with either voiced or voiceless singleton onsets (e.g., *spill~bill*; *spill~pill*). The performance of DLE and HFL was excellent with these lists (Buchwald & Miozzo, 2011; see Table 1). Taken together, the results from the same/different tasks indicate that both participants were able to perform the type of auditory word discrimination required for repetition tasks.

These data are also relevant for contextualizing HFL's performance on the Peabody Picture Vocabulary Test—Revised (Dunn & Dunn, 1981; see Table 1). This comprehension task was presented to HFL aurally, where a spoken word is shown within an array of four pictures that include the target semantically related foils. We can rule out that HFL's score in the Peabody Picture Vocabulary Test—Revised stemmed from a word perception deficit. Thus, this performance most likely resulted from a problem in accessing word semantics.

Procedure and Data Analysis

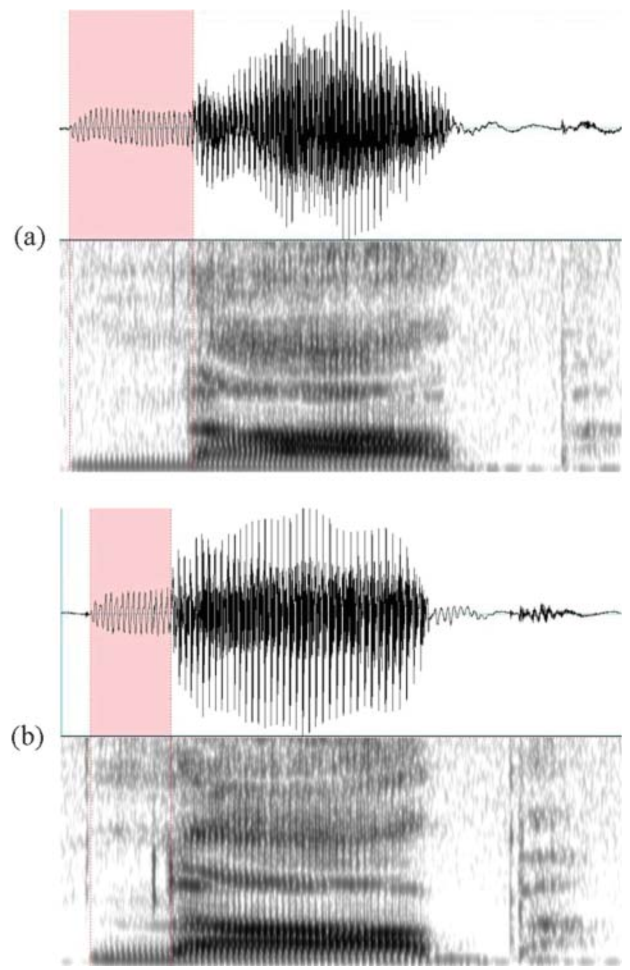
Articulatory Timing

To determine whether the error productions (e.g., *small* → *~~s~~mall*) of these individuals reflected the articulatory timing of singletons (as predicted for phonological processing errors) or clusters (as predicted for motor planning errors), we generated word lists that matched words beginning with onset clusters (e.g., *small*) with words beginning with the singleton that followed the /s/ (e.g., *mall*). These lists were used to compare the error productions in which the consonant cluster is simplified (e.g., *small* → *~~s~~mall*) with singleton consonants in the same context (e.g., *mall*), thereby allowing us to assess whether the tokens with deletion are produced with the timing of a singleton or the timing of a cluster.

/s/-nasal onsets and nasal singletons provide a clear opportunity to test the predictions about articulatory timing that are the focus of our investigation, as previous research has reported that the nasal in /s/-nasal clusters is shorter than the nasal singleton (O'Shaughnessy, 1974). Thus, if the articulatory timing in deletion tokens is based on the timing of a cluster (i.e., a motor planning error), the nasal duration in the deletion tokens (e.g., *small* → *~~s~~mall*) should be shorter than in the singleton onsets (e.g., *mall*). In contrast, if the timing is based on a singleton onset (i.e., it is a phonological processing error), no difference in nasal duration should be obtained.

Data analysis. Stimuli from three different response categories were measured: singleton nasal tokens (e.g., *mall*), /s/-deletion tokens (e.g., *small* → *~~s~~mall*), and accurately produced /s/-nasal tokens (e.g., *small* → *small*). Trials with /s/-nasal targets that had any other errors in the onset (e.g., fricative substitution; error on the nasal consonant) were not included in these analyses. The words were matched for nasal place of articulation, following vowel, number of segments, and voicing of the coda, as these factors may influence the overall word duration and the duration of the individual components. Unfortunately, DLE was unable to accurately produce enough /s/-nasal tokens to include in the analysis, so we only compared singleton nasals with nasals in /s/-deletions for his productions. The comparisons were made between the voiced portions of the nasal consonants, and the offset of the nasal was identified at the onset of the vowel, indicated in the waveform by increased amplitude (see Figure 2 for an example). One trained research assistant measured all tokens from both speakers. These measurements were verified by a second coder who examined 40% of the stimuli from each participant, with greater than 90% agreement within 5 ms.

Figure 2. Nasal duration measurements. These two images represent the nasal duration measurements on two productions from HFL. Panel a presents the waveform and spectrogram from a production of *knob,* whereas Panel b presents the waveform and spectrogram from a production of ~~s~~*nob* in which he deleted the /s/. Each image shows 650 ms.



Syllable Structure Effects

To further explore the difference between errors arising at the levels of phonological processing versus motor planning, we presented both DLE and HFL with a modified word repetition task in which we asked them to produce /s/-stop initial words (nouns) preceded by the indefinite article "a"—as in *a spill*. Although this increases the morpho-syntactic complexity of the utterance being repeated, the critical sound structure difference between these tokens and the isolated words is the presence of an additional syllable with schwa as its nucleus (e.g., /spɪl/ vs. /əspɪl/).

The presence of the additional syllable provides a window for us to better characterize the errors that the participants are making. As stated above, consonant clusters are complex both phonologically and in motor speech production, and the results reported above indicate that DLE's errors arise as a result of vulnerability due to phonological complexity, whereas HFL's errors arise as a result of vulnerability due to motor planning complexity. If the cause of the deletion was that the presence of a consonant cluster was problematic phonologically (as for DLE) and the deletion simplified the structure, then one possible solution available in producing *a spill* is that a speaker could resyllabify this form to put the /s/ in the first syllable (e.g., [əs.p^{h}ɪl]) rather than in the second syllable, thereby removing the complex consonant cluster in the onset position but still producing all elements of the target structure. We note that this syllabification is not the standard syllabification in English, in which both consonants would be in the onset of the second syllable (following the principle of onset maximization). Given that HFL's errors arise because of problems that occur after syllabification, he should be less likely to adopt this as a strategy to produce these forms.

The phonology and phonetics of American English provide a straightforward test for us to determine the syllabification of the /s/. Syllable-initial voiceless stops in English are aspirated with a long voice onset time (VOT), whereas voiceless stops preceded by /s/ are unaspirated with a short VOT (Lisker & Abramson, 1964). Thus, if the /p/ of *spill* is produced as a singleton onset (i.e., it is heterosyllabic with [s]), it will be aspirated (e.g., [əs.p^{h}ɪl]), whereas if it is tautosyllabic with the /s/, then it will be unaspirated (e.g., [ə.spɪl]). This is the same acoustic contrast as the voicing contrast in English. Thus, to evaluate whether the /s/ has been resyllabified, we can compare the VOT in tokens where the /s/ is preceded by the indefinite article (*a spill*) with singleton voiced (*bill*) and voiceless stop onsets (*pill*).

Data analysis. The experimental stimuli were elicited using a repetition task in which the participants repeated words with /s/-stop clusters preceded by the indefinite article "a" (e.g., *a spill*; *a steak*; *a skate*). The repetition procedures were the same as in Experiment 1. Two types of analyses were carried out. First, we compared the rate of /s/-deletions for the same words repeated with the article (*a spill*) or in isolation (*spill*). Second, for tokens with /s/ present in article + noun responses, a trained research assistant measured the VOT of the stops in noun initial cluster (e.g., the /p/ in *a spill*), and 25% were verified by the first author who confirmed the measurements. The VOT of those stops in article + noun tokens with both /s/ and stops produced correctly were compared with the VOT of singleton voiced stops (*bill*) and voiceless stops (*pill*) from words matched on place of the consonant, height of the following vowel, length in phonemes, and voicing of the final consonant. These singleton tokens were a subset of the tokens collected for the project reported in Buchwald and Miozzo (2011);

for this analysis, we selected the subset of those singletons that could serve as the controls for the article + noun tokens that we elicited for this project. In the Results section, we report the VOTs of both the patients and the experimenters just for the tokens used in the analysis.

Effect of Repetition

The last predictions we examined related to the repeated exposure throughout testing sections to problematic /s/ initial clusters. These predictions are grounded in evidence indicating that individuals with AOS may improve in producing complex syllables by producing other syllables that contain the same complex portion (Aichert & Ziegler, 2008). To the best of our knowledge, no such findings have been reported as recommended treatments for phonological processing impairment. In keeping with prior findings, we hypothesized that the repeated articulation of /s/-initial clusters would facilitate accurate production of these clusters in HFL whose deletion errors arise due to his motor planning deficit, but not for DLE whose errors arise due to phonological processing impairment.

Data analysis. Each speaker was seen weekly for approximately 5 months (22 sessions) during which we recorded their attempted productions of /s/-initial consonant clusters. For each participant, approximately the same number of clusters was produced in each session. To assess the change over time, we looked at accuracy over three session windows. Onset cluster accuracy was measured irrespective of accuracy of the remainder of the word.

Results

Articulatory Timing

DLE produced the entire /s/-nasal cluster accurately in 16.3% of tokens (41/252) and deleted the /s/ in 69.8% of tokens (176/252). In contrast, HFL accurately produced the entire /s/-nasal cluster in 54.1% of his tokens (112/207) and deleted the /s/ in only 30.9% of tokens (64/207). The acoustic analyses that form the critical part of this investigation were conducted only on tokens with no other clear errors and no perceptible dysfluencies or groping and no other distortions in the recording. This limited the number of /s/-deletions to 79 for DLE and to 47 for HFL. Unfortunately, there were not enough accurate productions for DLE to use in this analysis, as only seven tokens remained with accurate /s/-nasal cluster production; we were still able to recover enough accurate /s/-nasal clusters to compare with all 47 of HFL's deletions.

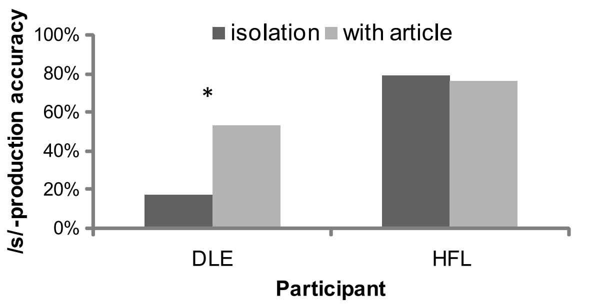
The data presented in Figure 1 depict the nasal duration for these two participants and reveal a clear difference between the two participants. Separate analyses were conducted for each individual, with nasal duration as the dependent variable and stimulus type as the dependent variable. For DLE, a paired t test indicated no differences between the nasal duration of /s/ nasal tokens (*small* → ~~*s*~~*mall*) and singleton nasal tokens (*mall*), $t(78) = 0.02$, *ns*. For HFL, an analysis of variance indicated a significant main effect of stimulus type, $F(2, 146) = 6.24$, $p = .003$. Planned comparisons revealed that the nasals in the /s/-deletion stimuli were significantly shorter than the singleton nasals, $t(41) = -2.85$, $p = .007$, and did not differ from the nasals in accurately produced clusters, $t(46) = -0.56$, $p = .58$. Thus, these data indicate that HFL produced the articulatory timing associated with a target cluster in his /s/-deletion tokens (see Figure 2 for an example), whereas DLE produced the same timing that he produced for a singleton. Although the data for DLE are consistent with the predictions associated with phonological processing errors, we were unfortunately unable to compare his nasal duration in /s/-deletion tokens with the nasal duration in accurately produced clusters, so we were unable to fully evaluate whether the nasal durations in the deletion tokens were longer than nasal duration in accurately produced /s/-nasal clusters. It is also worth noting that HFL's nasal durations were quite long, consistent with the description of slowed speech and prolonged segments in his productions.

To verify that the acoustic patterns associated with the two speakers could not be attributed to differences in how the experimenters produced the tokens, we compared the nasal duration in the elicitation tokens for /s/-nasal clusters and singleton nasals separately for each speaker for the precise tokens analyzed in this section. These data clearly showed that the experimenters' model tokens exhibited the expected patterns for American English. In particular, DLE's experimenter showed a significant difference between the longer nasal duration in nasal singletons ($M = 95.6$ ms, $SD = 22.4$) and the nasal duration in /s/-nasal clusters ($M = 69.2$ ms, $SD = 18.5$), $t(78) = 11.16$, $p < .0001$. Similarly, HFL's experimenter exhibited a significantly longer nasal duration in singletons ($M = 115.0$ ms, $SD = 30.6$) than in clusters ($M = 59.6$ ms, $SD = 15.77$), $t(45) = -5.55$, $p < .01$.

Syllable Structure Effects

/s/ production accuracy. The data revealed a clear difference between the two participants with respect to the effect of the article on their /s/ production. As shown in Figure 3, the presence of the article led DLE to produce /s/ significantly more frequently in /s/-initial clusters leading to more accurate production of the same words (isolation: 33/190, 17.4%; with article: 101/190, 53.2%), $\chi^2(1) = 51.75$, $p < .0001$, whereas the presence

Figure 3. /s/-production accuracy as a function of stimulus presentation type. Words were either presented in isolation (e.g., *spoon*) or presented with the indefinite article (e.g., *a spoon*). An asterisk reflects significant differences.



of the article did not affect HFL's performance (isolation: 330/417, 79.1%; with article: 38/50, 76.0%), $\chi^2(1) = 0.11$, *ns*.

Aspiration in /s/ production. To assess the syllabification produced by each participant on tokens with the article, we compared VOTs corresponding to, for example, the stop /p/ in *a spill,* the voiced stop /b/ in *bill*, and the voiceless stop /p/ in *pill*. Paired *t* tests were used for these comparisons. For DLE, the VOTs of the stops in the words presented with articles ($N = 34$; $M = 53.0$ ms) were significantly longer than those of the voiced (i.e., unaspirated) stops ($M = 34.9$ ms), $t(33) = 3.94$, $p = .0003$, and did not differ from the aspirated stops ($M = 51.0$ ms), $t(33) = 0.45$, $p = .65$. These two paired *t* tests suggested that DLE produced stops with aspiration in these sequences. For HFL, the VOTs of the stops in words presented with articles ($N = 25$; $M = 20.1$ ms) did not differ from the unaspirated stops ($M = 22.0$ ms), $t(24) = 0.35$, $p = .37$, but were significantly shorter than the aspirated stops ($M = 85.5$ ms), $t(24) = 9.40$, $p < .0001$, suggesting that HFL produced stops without aspiration in these sequences. These data indicate that DLE resyllabified the /s/ into the coda of the syllable with the indefinite article thus producing a syllable-initial aspirated stop, whereas HFL produced the /s/ and the stop in the same syllable. The differences in syllable structures that we observed between DLE and HFL are the ones expected if DLE and HFL have impairments resulting from damage to phonological processing and motor planning, respectively.

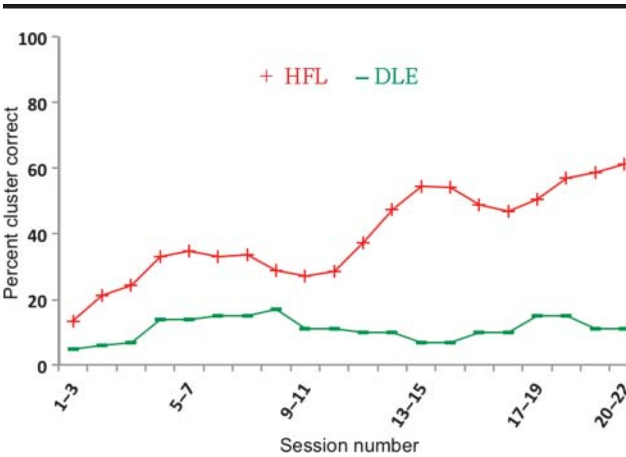
As in the articulatory timing study, we verified that DLE's pattern of producing the /s/-stop words with the /s/ and the stop in different syllables was not influenced by the speech patterns of the experimenter eliciting the words. In this case, because DLE produced the noncanonical syllabification, we measured the VOTs of the elicitation tokens given above. These paired *t* tests revealed that the experimenter's VOT in article + /s/-stop tokens ($M = 18.0$ ms) was significantly shorter than the VOT in aspirated voiceless stops ($M = 118.3$ ms), $t(34) = -22.60$, $p < .0001$, and did not differ from the VOT in the voiced stops ($M = 19.3$ ms), $t(34) = -0.99$, *ns*. Thus, it remains unlikely that DLE's resyllabification was affected by the experimenter's elicitation model.

Effects of Repetition

Figure 4 presents the accuracy in /s/-cluster production for both DLE and HFL as a function of session number. In total, DLE attempted 410 tokens with /s/-initial clusters, and HFL attempted 790 tokens. Each point in the figure refers to a three-session window, so the first point is the mean over Sessions 1–3, and the last point is the mean over Sessions 20–22. To determine whether there was a significant difference in the relationship between session number and /s/-cluster accuracy for the two speakers, we computed a correlation for each speaker between the accuracy on /s/-clusters and the session number. The correlation was strong for HFL ($r = .92$, $p < .0001$) and was weak for DLE ($r = .17$, $p = .47$, *ns*). To ensure that the higher number of tokens in the analysis was not the cause of this pattern, we limited our analysis to the first 410 tokens for HFL; the correlation between accuracy and session number was still extremely strong ($r = .86$, $p < .0001$).

These data reveal a clear difference in how the performance of these two individuals changed in response to repeated exposure to consonant clusters. It is critical to note that there was no feedback associated with the repetition task in which these utterances were elicited; thus, there was no explicit treatment associated with this study. Nevertheless, the repeated articulation of these symptoms—a typical component of the articulatory kinematic approaches to AOS treatment (Wambaugh et al.,

Figure 4. Changes in cluster production accuracy over the course of the study. Each data point reflects performance in three-session windows where the first data point is from Weeks 1 to 3, and the last data point is from Weeks 20 to 22.



2006b)—was associated with a clear improvement of the individual whose errors can be attributed to motor speech processing but not for the individual whose errors can be attributed to phonological processing.

Discussion

The data reported here from participants DLE and HFL are consistent with the claim that systematic consonant cluster simplification errors can arise due to either phonological processing impairment (DLE) or motor planning impairment (HFL). This conclusion is based on three key pieces of evidence obtained in our investigation. First, we reported that the nasals in words with /s/-deletion from target /s/-nasal clusters (e.g., *snap* → *~~s~~nap*) are produced with the timing of singletons in phonological deletions but with the timing of the cluster in deletions occurring in motor speech production. This is consistent with the description of phonological processing as acting over representations that do not yet encode articulatory timing properties, and motor planning as being a level at which articulatory timing is encoded. Second, we reported that the opportunity to resyllabify a sequence and change the onset consonant cluster into a heterosyllabic consonant sequence facilitates accurate production of the consonants for errors arising due to phonological impairment but not for motor planning errors. These patterns reflect the hypothesized function of these processing systems: Phonological processing includes syllabification processes (Levelt et al., 1999), whereas motor planning involves the retrieval (or generation) of the syllables from the mental syllabary (see Ziegler et al., 2010). Finally, repeated articulation of words beginning with /s/-initial clusters produced a noticeable decline of motor planning errors, but it had virtually no effects on the likelihood of phonological errors.

As we noted in the introduction, a variety of recent research has suggested that although there is a distinction that can be drawn among phonological and motoric processes, they do interact in that differences in activation at the phonological level can alter production details (Goldrick & Blumstein, 2006; McMillan & Corley, 2010). For example, Goldrick and Blumstein (2006) reported that voicing errors (e.g., /k/ → [g]) were produced with longer VOTs than accurately produced voiced consonants (e.g., /g/ → [g]), and they argued that this reflected the partial activation from the target /k/ in the case of the errors. Other errors that appear in tongue twister sequences have been explained as co-productions of two different gestures (Pouplier & Goldstein, 2010). In each case, elements of two different targets are produced, resulting in what appears to be a "partial" (or "blend") error. Given these previous findings, we may have expected DLE's deletion errors to reflect partial activation of the deleted sound structure unit. In our data, there is no indication of the deleted /s/ affecting the production of the remaining sequence, as no differences were obtained between the singleton nasal (*mall*) and the nasal following /s/-deletion (*~~s~~mall*), and the stop in the article + noun sequence was not different from the singleton aspirated stop. It is not immediately clear why the present data appear not to be affected by the original sound structure sequence, although it is possible that the apparent errors that occur in the case of phonological impairment are qualitatively different from those occurring in tongue twister tasks.

It is worth noting that DLE and HFL presented with both aphasic deficits and AOS (although the AOS was mild in the case of DLE). Thus, deficits to phonological processing and motor planning may generate clinical profiles that overlap considerably, though not completely as demonstrated here by analyses of consonant cluster simplification errors. In the remainder of the Discussion section, we examine the implications of our findings for understanding phonological processing and motor planning, and deficits to these systems.

One additional issue worth discussion with respect to the present analysis is that it focuses on acoustic measures to make inferences about articulatory behavior. In particular, VOTs that were examined in the study do not permit the unambiguous identification of laryngeal behavior. As has been widely noted, the coordination of oral and laryngeal gestures in /s/-stop sequences is critical in predicting the unaspirated stop variant in the accurate production of these sequences (Browman & Goldstein, 1986). The unaspirated variant of stops in /s/-stop clusters has been argued to arise because there is a single glottal opening gesture for the entire /s/-stop cluster rather than one opening gesture for each consonant (Browman & Goldstein, 1986), and the duration of VOT and other correlates of aspiration depends on stress and word position to some degree (Cooper, 1991). The present research did not vary either stress or word position.

With respect to an articulatory phonology account of the patterns here, DLE appears to delete the oral gesture associated with the /s/, and he produces the gestural coordination of the oral and laryngeal gestures associated with a singleton voiceless stop. In contrast, HFL also deletes the oral constriction associated with the fricative, but the oral and laryngeal gestures he produces appear to be coordinated as they would have been were the gesture associated with the fricative still present. It is important to note that this indicates that the data presented here are consistent with an articulatory phonology account in which coupling (or coordination) relations among adjacent gestures are specified at some point in processing (Goldstein, Byrd, & Saltzman, 2006), and the deletion of a gesture can occur either prior to or after these coupling relations among adjacent gestures are specified; in the data reported here, DLE's errors are consistent with errors arising before the coupling relations are specified, and HFL's deletions occur after the coupling relations have been specified.

Similarly, measuring nasal duration does not unambiguously identify the timing of velum lowering with respect to the oral and laryngeal gestures involved in /s/-nasal cluster production, and it remains possible that the apparent deletion of /s/ in /s/-nasal clusters arises because of the velum lowering too early and there not being enough pressure in the oral cavity to generate frication for the /s/ (Solé, 2007). Despite these limitations, the contrasting error patterns documented here (and in Buchwald & Miozzo, 2011, discussed below) are precisely those expected by the proposal that context-specific features, such as aspiration, are encoded in motor planning but not in phonological processing, and that the point in processing when deletions occur provides a principled explanation of the contrast between these two individuals. The consistency of the contrast between DLE and HFL in producing different cluster types in different contexts further supports the notion that the contrast arises due to systematic differences in the level of processing where the deletions occur rather than due to idiosyncratic articulatory behavior.

Acoustic and Perceptual Signatures of Different Error Types

Our data reveal that phonological processing errors arise at a level where articulatory timing is not encoded, whereas motor planning errors arise at a level where articulatory timing is specified. In particular, in the case of phonological errors, deletion of /s/ within a consonant cluster leads the remaining consonant to be produced with the timing of a singleton consonant, whereas in motoric errors, the target timing associated with the consonant cluster remains. Converging evidence for this conclusion comes from a prior investigation of DLE and HFL (Buchwald & Miozzo, 2011) that also focused on deletion errors, specifically omissions of /s/ in /s/-stop onsets (e.g., *s̲pill*) and VOT of the resulting stop (when presented in isolation). DLE's phonological errors led to the production of an aspirated voiceless stop (e.g., *pill*), whereas HFL's motor planning errors yielded unaspirated stops (e.g., *bill*).

Taken together, the present findings and the data reported in Buchwald and Miozzo (2011) indicate that phonological cluster reduction errors lead to the timing of a singleton, whereas motor planning errors lead to the timing of a cluster regardless of whether there is an allophonic difference between these two (as in /s/-stop clusters) or not (as in /s/-nasal clusters). Although VOT has been previously examined quite extensively with respect to a variety of sound production errors in both aphasia and in AOS (Blumstein, Cooper, Goodglass, Statlender, & Gottleib, 1980; Blumstein, Cooper, Zurif, & Caramazza, 1977; Wambaugh, West, & Doyle, 1997), data obtained from DLE and HFL expand on previous work by making clear predictions about the type of articulatory timing and resyllabification expected when phonological processing or motor planning is damaged.

Although the deletions errors were recorded here from only two participants, the systematicity and consistency of their deletion errors suggest a straightforward possibility for classifying errors as occurring due to phonological processing impairment or motor planning impairment. In particular, the difference between *pill* and *bill* outputs is perceptible by English speakers, and for these clusters, it may be possible to evaluate whether deletion errors in /s/-stop clusters lead to one of these cognates in the context of an initial clinical screening for individuals who make these common consonant cluster reduction errors (Romani & Galluzzi, 2005; Romani, Galluzzi, Bureca, & Olson, 2011). Unfortunately, the acoustic differences regarding /s/-nasal clusters are not as easily perceived by English speakers and are thus a less practical tool for determining the level of the error, although they may be useful in further research to employ as an additional test to confirm the primary perceptual assessment. Although we recognize that we have reported two particularly straightforward cases here that may be less common, we believe that this is a promising avenue that we are continuing to explore in a larger population of speakers.

Clinical Implications of Identifying Sound Production Error Types in Impaired Speakers

The data presented in Figure 4 reveal that repeated production of difficult sound structure sequences benefits the production of these sequences for individuals whose errors arise during motor planning. These data are consistent with several lines of evidence regarding treatment of AOS, including the finding that repeated articulation is a central component to effective articulatory kinematic intervention (Wambaugh et al., 2006a) and that the production of complex syllables may improve by producing other syllables that contain the same complex portion (Aichert & Ziegler, 2008). Thus, individuals who are making motor planning errors may be approached in these ways. Given that the data reported in Figure 4 come from repeated exposure in a research project and not systematic therapeutic intervention, it is likely that targeting the complex sequences in an intervention will yield results at least as strong as those reported above.

The data of DLE presented in Figure 4 suggest that individuals with errors arising in phonological processing may not necessarily benefit from the repeated articulation of problematic onset sequences. In this respect, DLE's results contrast with those of HFL. As we observed earlier, it is unlikely that the differences between the participants derived from the fewer number of trials administered to DLE. Interestingly, however, DLE improved markedly when he was able to resyllabify the consonant into the coda of the previous syllable. Although this may create a noncanonical production of the target sequence, it may still be useful to consider as a compensation strategy when the alternative is to delete one of the segments in a word. Additional evidence is necessary to determine whether this repair strategy is generally available to individuals whose consonant cluster reduction errors are driven by phonological processing impairment, and it would also be worth determining whether individuals such as DLE would show a benefit for repeated production of clusters if they were presented with the indefinite article. It also remains unclear whether increasing the number of cluster attempts for DLE would have changed the pattern in Figure 4, but the lack of any trend toward improvement suggests otherwise.

Conclusion and Future Directions

The data reported here indicate possible new directions to explore the differential diagnosis of PP errors and AOS errors by integrating methods of communication sciences and disorders with linguistic and psycholinguistic theory. Although the data reported here follow only two cases, the consistent patterns of the productions of these individuals likely reflect a window through which we can see the underlying systems generating sound production errors. In addition, the results reported here provide promising avenues to explore how we can treat the particular errors that individuals make; this may be especially critical for salient errors, such as consonant cluster simplification, that can lead to lexical confusions and can be an impediment to effective communication.

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