Cognition 128 (2013) 287–301

Contents lists available at SciVerse ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/COGNIT

On the nature of sonority in spoken word production: Evidence from neuropsychology

Michele Miozzo [a,*], Adam Buchwald [b]

[a] Johns Hopkins University, Baltimore, United States
[b] New York University, New York, United States

ARTICLE INFO

Article history:
Received 14 May 2012
Revised 11 April 2013
Accepted 22 April 2013

Keywords:
Sonority
Phonology
Phonetics
Word production
Language production

ABSTRACT

The concept of sonority – that speech sounds can be placed along a universal sonority scale that affects syllable structure – has proved valuable in accounting for a wide spectrum of linguistic phenomena and psycholinguistic findings. Yet, despite the success of this concept in specifying principles governing sound structure, several questions remain about sonority. One issue that needs clarification concerns its locus in the processes involved in spoken language production, and specifically whether sonority affects the computation of abstract word form representations (phonology), the encoding of context-specific features (phonetics), or both of these processes. This issue was examined in the present study investigating two brain-damaged individuals with impairment arising primarily from deficits affecting phonological and phonetic processes, respectively. Clear effects of sonority on production accuracy were observed in both individuals testing word onsets and codas in word production. These findings indicate that the underlying principles governing sound structure that are captured by the notion of sonority play a role at both phonological and phonetic levels of processing. Furthermore, aspects of the errors recorded from our participants revealed features of syllabic structure proposed under current phonological theories (e.g., articulatory phonology).

© 2013 Elsevier B.V. All rights reserved.

1. Introduction

Pioneering investigations of 19th century linguists (Sievers, 1881; Whitney, 1865) recognized that speech segments can be ranked along a sonority scale, and that the relative sonority of sounds can explain a variety of phonotactic and cross-linguistic generalizations. Within theoretical linguistics, the concept of sonority has been argued to explain such diverse phenomena as syllable structure (e.g., Clements, 1990; Selkirk, 1982; Zec, 1995), phonotactic rules (e.g., Blevins, 1995), the emergence of prosodic features (e.g., Rialland, 1994), cross-linguistic variation (Greenberg, 1978), and diachronic changes (Crowley & Bowern, 2010). In turn, a number of experimental investigations has revealed sonority as one of the factors predicting the chronology of sequences mastered by young children (e.g., Goad, in press; Locke, 1983; Ohala, 1999; Pater, 2009), the rate and type of errors observed in individuals with developmental or acquired language impairments (e.g., Bastiaanse, Gilbers, & van der Linde, 1994; Buckingham, 1986; Béland, Caplan, & Nespoulous, 1990; Christman, 1994; Romani & Calabrese, 1998; Romani & Galluzzi, 2005; Romani, Olson, Semenza, & Granà, 2002; Stenneken, Bastiaanse, Huber, & Jacobs, 2005), and aspects of speakers' implicit knowledge of phonological grammar as measured by perception and production tasks (Berent, Lennertz, Jun, Moreno, & Smolensky, 2008; Daland et al., 2011) although it has been noted that sonority does not account for the entire range of variation in these investigations (Davidson, 2011; Davidson & Shaw, 2012).

---

* Corresponding author. Address: Department of Cognitive Science, The Johns Hopkins University, 237 Krieger Hall, 3400 North Charles Street, Baltimore, MD 21218, United States. Tel.: +1 410 516 5250; fax: +1 410 516 8020.

E-mail address: mm1150@columbia.edu (M. Miozzo).

0010-0277/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.cognition.2013.04.006

Despite the explanatory power of this notion, there is not clear agreement on exactly what sonority represents, with one prominent researcher (Clements, 2009) describing the current state of knowledge on the nature of sonority as "elusive" (p. 165). Attempts to explain sonority have generally been of two kinds: phonological accounts that view sonority as an organizational feature governing phonological representations, and phonetic accounts that aim at identifying the phonetic correlates of sonority (e.g., perceptual; articulatory). A third, more inclusive account proposes that while sonority may be a general organizing principle of phonology, some phonetic differences predict additional changes in production or perception of sequences that are not distinguished based on sonority sequencing alone.

Much of the recent empirical research examining sonority and other factors that govern sound structure processing (e.g., Berent et al., 2008; Davidson & Shaw, 2012) has focused on the production and perception of non-native stimuli and/or phonotactically illegal stimuli, often involving consonant clusters (e.g., ∗*bnif*). In these studies, the logic is that unimpaired individuals have little difficulty with attested clusters in their language regardless of their sonority profile, so performance differences on clusters that are phonotactically-illegal are used as a window through which we can see the influence of sonority on cognitive processing. These studies typically suggest that sonority can account for some variation in performance on these phonotactically-illegal sequences, although other language-independent phonetic factors also appear to affect non-native cluster processing (see Davidson, 2011 for a review).

The present study aims to contribute to the debate on the nature of sonority by elucidating the locus of sonority-based effects within psycholinguistic accounts of the spoken production system. By examining the performance of individuals with impairment, we were able to observe performance differences with stimuli that are permissible within the native language but vary in terms of their sonority profile (e.g., comparing *slip* vs. *clip*); thus, we investigated how familiar, phonotactically-legal sequences are processed to identify factors contributing to these differences. We took advantage of the errors observed in individuals whose acquired speech production impairment primarily affected either phonological or phonetic processes. Evidence that only one or both of these impairments are affected by sonority would provide useful evidence for narrowing hypotheses on the locus of sonority, therefore contributing to constrain theories on sonority.

1.1. What is the locus of sonority?

A detailed description of the many accounts of sonority is beyond the scope of this paper. Here, we focus on the primary motivations that led to proposals about sonority as a phonological or a phonetic construct, an issue that is complicated by a lack of universal consensus on the lines along which phonology and phonetics divide. For the purposes of the present investigation, we operationalize the phonological/phonetic distinction with reference to basic ideas that have reasonably wide consensus. Phonology operates over a finite number of distinct sound elements (e.g., phonemes; gestures) that have contrastive function (i.e., distinguishing words with different meanings). Phonological elements are abstract in that they are context-independent; at this level, details about how adjacent sound units coordinate with one another are not yet specified. In many linguistic theories (e.g., Optimality Theory; Prince & Smolensky, 1993), phonology represents the domain of phonological grammar, and the level where segmental structures (e.g., syllable) and prosodic features (e.g., stress) are computed. Within the psycholinguistics literature, the phonological representations of lexical items are stored with these context-independent representations and eventually subjected to adjustments to conform to phonological grammar (e.g., aspiration of word initial voiceless stop consonants) before serving as input to phonetic processes (Dell, 1986; Indefrey, 2011; Levelt, Roelofs, & Meyer, 1999). In contrast, phonetics relates to the temporal and spatial characterization and coordination of sound elements that enable generating speech sequences with the proper articulatory and acoustic properties. These representations encode the temporal and spatial coordination of adjacent elements. Within psycholinguistics, the few accounts that have attempted to describe these phonetic representations (e.g., Levelt et al., 1999) have done so with reference to the gestural score representations of articulatory phonology (e.g., Browman & Goldstein, 1988; Browman & Goldstein, 1992, 1995).

With respect to sonority as a phonological theory, one key argument has come from sonority rankings that are stated in terms of phonemes and that account for a variety of within-language and cross-linguistic phonological generalizations. Thus, the support for the explanatory nature of sonority has been widely considered to be theoretical rather than empirical; it can help provide an explanatory account for several linguistic phenomena (Anderson, 1982; Vaux & Wolfe, 2009). Whether sonority directly corresponds to phonetic features is not an issue from this perspective, insofar as sonority demonstrates sufficient degrees of explanatory power.

The alternative view is that sonority describes phonetic content, and therefore correlates to acoustic and/or articulatory properties of physical speech. Within this approach, however, many different physical correlates have been proposed. For example, Sievers (1881) linked sonority to audibility, proposing that more audible sounds rank higher in the sonority scale. Later researchers have further articulated this idea. Heffner (1950) equated sonority with acoustic energy, a notion Ladefoged (1993) further specified in terms of relative loudness compared to sounds similar for length, stress, and pitch. In a more recent proposal, Clements (2009) departs from previous accounts, relating sonority not to audibility but to the relative resonance of speech sounds. The acoustic correlates described in these accounts correspond to acoustic patterns. Tackling the issue from an opposite viewpoint, other proposals have attempted to describe the articulatory correlates of sonority. Examples of this approach include the proposal by Jespersen (1932), and Beckman, Edwards, and Fletcher (1992) that sonority relates to the degree of opening of the vocal tract. A detailed proposal was advanced in articulatory phonology (Chitoran, Goldstein, & Byrd, 2002). Although we have only cited a sample of phonetic accounts, it is clear that the question challenging a purely phonetic theory of sonority is to identify the correlates that best explain sonority. Our neuropsychological investigation does not address this question, focusing instead on the more preliminary question of whether sonority plays a role both at levels of phonetic processing and phonological processing.

1.2. Phonological vs. Phonetic deficits: The cases of DLE and HFL

The operational definition of phonology and phonetics we summarized above guided our characterization of what we refer to as phonological deficits and phonetic deficits, respectively. Specifically, phonological deficits affect abstract, context-independent elements, and reflect the computation of syllable structure. In contrast, phonetic deficits affect phonetic, context-specific features based in part on the previous computation of syllable structure. The defining features of phonological and phonetic deficits were shown by the deficits of DLE and HFL, two English speakers with post-stroke language impairments (Buchwald & Miozzo, 2011, 2012). Each individual presented with severe speech impairments that resulted in frequent errors affecting speech segments. Nevertheless, they produced clearly interpretable responses in repetition tasks where words were aurally presented one at a time by the experimenter. Their auditory word recognition was intact (see case description), indicating that their repetition errors reflected a speech production deficit rather than problems in the recognition of the verbal input. Although their errors were widespread, DLE and HFL found it particularly difficult to correctly repeat s-consonant onset clusters, as those in *star* and *smell*. Interestingly, their errors were typologically similar, consisting in the omission of the initial /s/ (*star* → star; *smell* → smell). Our prior investigations of DLE and HFL concentrated on the rate and nature of these omissions, and we used these errors to distinguish phonological from phonetic deficits. We reasoned that if the deficit is phonological, and the /s/ is deleted within the phonological representations, omissions would then reflect the features of a singleton consonant (since the input to the phonetic processes would have only one onset consonant). On the contrary, /s/ omissions caused by a phonetic impairment would result in forms that were generated based on the presence of a consonant cluster. These distinct hypotheses were tested in three experimental studies we describe below (see summary in Table 1).

a. *Allophonic variation*. The phonetic variants (allophones) of English voiceless stops (/p/, /t/, and /k/) are context specific (Klatt, 1975). When they occur as singleton onsets, these phonemes are produced with aspiration (i.e., their release is accompanied by a burst of air), and traditionally transcribed as [p^{h}], [t^{h}] and [k^{h}]. However, when voiceless stops are preceded in the onset by /s/ (/sp/, /st/, and /sk/), the unaspirated variant is produced which is – everything else being equal –phonetically equivalent to the corresponding voiced stops (/b/, /d/ and /g/). Thus, the stop in *spill* is phonetically realized as the voiced stop in *bill*. These allophonic variants are associated with measurable changes in voice-onset time (VOT), the duration from the release of the stop constriction to the onset of voicing (Lisker & Abramson, 1964). Specifically, aspirated voiceless stops have longer VOTs than their unaspirated counterparts and voiced stops. For the two individuals we discuss here, the VOTs of stops in s-omission errors (/p/ in spill) were compared to the VOTs of voiced and unvoiced stops in onset position ([b] in *bill*; [p^{h}] in *pill*) (Buchwald & Miozzo, 2011). A striking difference was found between DLE and HFL: for DLE, the consonants in omissions were aspirated voiceless stops (spill → p^{h}ill), but for HFL they were unaspirated stops (spill→bill). In other words, DLE's omissions reflected the context-specific phonetic features of a singleton rather than a consonant cluster, which suggests that omissions originated at a phonological level preceding phonetic encoding. However, the allophones produced by HFL only emerged in environments preceded by /s/, indicating that the deletion occurred after the specification of phonetic content.

b. *Segment duration*. The relative duration of a speech sound is a phonetic feature determined by various parameters, including the number of segments in the syllable or syllable part (e.g., onset). Typically, duration reduces if there are preceding elements (O'Shaughnessey, 1974), so that, for example, the nasal /m/ is normally shorter in *small* than *mall*. To examine the phonetic characteristics of the omissions, we compared nasal durations using minimal pairs like small/mall (Buchwald & Miozzo, 2012). Again, the findings differed markedly between participants: nasal durations were comparable between small and mall with DLE, but longer for small with HFL. These contrasting findings are consistent with the hypothesis that DLE's errors occur at a level of phonological representations that do not yet specify phonetic features like duration, while HFL's errors arise at a level where phonetic content is already encoded.

c. *Syllabification*. The sequence *a spill* can be optionally resyllabified assigning the /s/ in coda position ([əs.p^{h}ɪl]). This results in the elimination of the complex, multi-consonant onset cluster, which is replaced by a simpler singleton stop in the onset ([p^{h}ɪl]). As we mentioned above, it is generally assumed that syllabification is computed as part of phonological processing and that this syllabification serves as the input to phonetic processing. Consistent with this view, we anticipated sensitivity to possible changes of syllable structure in cases of phonological deficit. However, because syllabification is not one of the phonetic operations, the possibility of resyllabification might have negligible effects on phonetic deficits. These contrasting predictions were confirmed by the responses of DLE and HFL. DLE was significantly more accurate with than without articles (53% vs. 17%). Furthermore, VOT analyses revealed that the second onset consonant ([p] in *spill*) was generally realized as aspirated stops [p^{h}], the expected allophone in onset position. However, the presence of the article did not have noticeable effects on HFL's responses. Overall, the contrasting syllabification abilities demonstrated by DLH and HFL provide further evidence about the phonological and phonetic nature of their respective deficits.

Table 1
Summary of error types (DLE and HFL).

A. Voiceless stop allophones	s-Omission errors
DLE: spill → pʰill	(VOT of aspirated voiceless allophone)
HFL: spill → bill	(VOT of voiced stop)
B. Nasal duration	s-Omission errors
DLE: /m/ in small = /m/ in mall	
HFL: /m/ in small shorter than /m/ in mall	
C. Optional re-syllabification	Indefinite article + s-stop onset word (a spil)
Re-syllabification in DLE	(a spill → əs.pʰɪl)
No re-syllabification in HFL	(a spill → ə.bil)

In summary, the experimental evidence collected from DLE and HFL converge in showing impairments with different functional loci – phonological for DLE, phonetic for HFL.

1.3. The sonority profile of syllables

The position of phonemes within the syllable is in part determined by the sonority-based principle of dispersion, which states: sonority increases maximally and steadily from the onset to the vowel, and declines minimally from the vowel to the coda end (Clements, 1990). In the application of the principle, the sonority peak of the syllable corresponds to the nucleus (typically a vowel), and some syllable structures are more preferred (unmarked) than other syllable structures (marked). To illustrate this point we refer to the sonority scale shown in Table 2: Vowel > Glides > Liquids > Nasals > Fricatives > Stops (Broselow & Finer, 1991). While others have posited more fine-grained distinctions along the sonority scale (including differences between voiced and voiceless sounds), we use the distinctions in Table 2 which have widespread agreement. The syllable /ta/ is preferred to the syllable /la/, as the former implies a greater sonority increase from the onset to the peak than the latter. In contrast, given the syllables /at/ and /al/, /al/ is preferred as /l/ in the coda reflects a smaller sonority decline compared to /t/. For the present investigation, it is crucial to note that this principle also implies that some consonant clusters that involve a sharp rise in sonority from the margin to the peak (e.g., stop-liquid clusters, as in *plank*) are preferred to others with a less sharp rise (e.g., fricative-liquid clusters, as in *flank*). Other predictions based on this principle are discussed in Section 2. The dispersion principle also relates to the principle of Syllable Contact, which specifies the required decrease in sonority across syllable boundaries for each language. The application of this principle helps make syllable boundaries maximally salient in terms of sonority, possibly facilitating syllable recognition and the segmentation of speech into syllables.

Table 2
Sonority scale.

Sonority level	Sonority classes		Segments
High		Vowels	
		Glides	y, w
	Sonorants	Liquids	l, r
		Nasals	m, n
	Obstruents	Fricatives	f, v, s, z, θ, ʃ
Low		Stops	p, t, k, b, d, g

The principles of dispersion and syllable contact help define syllable markedness, and the larger concept of markedness has been widely argued to affect both the distribution of sounds within- and across-languages as well as the acquisition of sounds and their vulnerability to language loss (following Jakobson, 1941/1968). Both within languages and cross-linguistically, unmarked syllables tend to outnumber marked syllables (Blevins, 1995; Greenberg, 1978). Further, empirical studies of both language acquisition and language loss have also revealed that errors tend to concentrate on marked sequences (e.g., Bastiaanse, Gilbers, & van der Linde, 1994; Béland, Caplan, & Nespoulous, 1990; Buchwald, 2009; Buckingham, 1986; Christman, 1994; Ohala, 1999; Romani & Calabrese, 1998; Romani, Galluzzi, Bureca, & Olson, 2011). In addition, recognition has been reported to be more accurate for unmarked than marked syllables in experimental conditions hindering perception (e.g., by introducing of noise; Berent et al., 2008), although sonority does not account for all differences that were related to perceptual change (Davidson, 2011; Davidson & Shaw, 2012), indicating that sonority is one factor affecting sound structure processing.

One notable exception to the typology of syllable structure predicted by sonority relates to words with s-stop onsets (e.g., *stub*). These clusters violate the cardinal assumption of sonority-based theories of syllable structure that syllables increase in sonority from the margin to the peak, as /s/ is more sonorous than the following stops. Some proposals explaining the anomaly of s-stop onset confer /s/ the status of appendix, a segment that is not part of the syllable but instead occupies an extra-syllabic position (e.g., Clements & Keyser, 1983; Fujimura & Lovins, 1982; Gigerich, 1992; Goldsmith, 1990; Harris, 1994; Kiparsky, 2003: McCarthy, 2005).

This study focuses on the spoken production of individuals with acquired language impairment for whom words that normal speakers can produce effortlessly are not produced correctly. As mentioned, errors often concentrate on phonologically marked forms consistent with the claim that these forms are more difficult for the processing system (Jakobson, 1941/1968). The question addressed in the present investigation of DLE and HFL is whether difficulty with syllables with poor sonority profiles arises in deficits affecting phonology, phonetics, or both of these levels of processing. Specifically, we anticipate one of these three outcomes: (a) accuracy affected by sonority only appears in *phonological deficits*, a finding suggesting sonority encoding at phonological level; (b) accuracy affected by sonority only appears in *phonetic deficits*, an outcome indicating the existence of phonetic correlates of sonority; (c) accuracy affected by sonority is found in *both* types of deficits, a result favoring the conclusion that phonological *and* phonetic processing are both sensitive to aspects of sound structure processing that relate to sonority. Because we tested word production (using a spoken word repetition task) our results speak directly to the role of sonority-based distinctions at various levels in language production.

2. Methods

2.1. Participants

DLE (b. 1934) is a left-handed male with college degree who worked in engineering and business administration prior to retirement. In 2001, he suffered a left middle cerebral artery infarct. MRI scans revealed an extended left hemisphere lesion affecting the entire inferior frontal gyrus and insula, much of the pre-central gyrus, the inferior-parietal and superior-temporal regions, and the anterior and lateral portions of the thalamus. HFL (b. 1950) is a right-handed male who earned a medical doctorate and worked as a radiologist prior to his CVA. A neurologist's report indicated that he suffered a left MCA infarct in 2007 leaving him with right-sided hemiplegia. Each individual was diagnosed with nonfluent aphasia (mild in the case of DLE, moderate/severe in the case of HFL).

Spoken word production was impaired, very severely in HFL whose naming accuracy in the Boston Naming Test (Kaplan, Goodglass, & Weintraub, 1983) was 1/15 (short version), more moderately in DLE's who scored 33/60 in the same test (long version). The most common naming errors produced by DLE were phonologically related words (conventionally defined as errors sharing at least 50% of target phonemes, e.g., *cannon* → *gannon*; 47/130, 36%; other frequent errors produced by DLE were no responses, 23%, and perseverations, 20%). Phonologically related errors are considered a key feature of deficits affecting word form processing in production (Miceli, Capasso, & Caramazza, 2004). This type of deficits can be restricted to problems in the retrieval of word phonology or also affects further mechanisms involved in speech sound processing. Naming and repetition responses are compared to further characterize these deficits (e.g., Goldrick & Rapp, 2007). The finding that DLE and HFL were also impaired in word repetition suggests rather widespread deficits central to spoken word production. Each individual exhibited additional symptoms suggestive of apraxia of speech, including distortions and dysprosodic speech (Wambaugh, Duffy, McNeil, Robin, & Rogers, 2006). These symptoms were greater in severity and frequency with HFL. In addition, HFL frequently exhibited groping, a problem observed only infrequently in DLE. No dysarthrias were diagnosed for either participant.

Speech comprehension was tested using a picture-word matching task (Peabody Picture Vocabulary Test; Dunn & Dunn, 1981). While DLE's scores were within normal range (43rd percentile), HFL's revealed a mildly impairment (4th percentile). The spoken repetition task we used in the present investigation requires we assess the presence of difficulties in auditory speech recognition. Testing results from both participants ruled out difficulties of this sort. For example, they both performed within controls' range in an auditory task that demanded to discriminate between word pairs that were identical or differed by a single phoneme (PALPA 2; Kay, Lesser, & Coltheart, 1992). Furthermore, they both performed at ceiling in a series of auditory word discrimination tasks reported in Buchwald and Miozzo (2011).

2.2. Tasks

A repetition task was used with both participants to investigate onsets and codas varying in sonority. Words were orally presented one at the time and immediately repeated by the participants. The experimenter re-presented the word upon the participant's request. The production of codas was also tested with DLE using picture naming. To facilitate naming responses, pictures were presented along with brief descriptions underneath that were read out loud by the experimenter. The first phoneme was offered as cue whenever DLE experienced word-finding difficulties. Note that cues would aid name retrieval without specifically affecting the production of codas. The severity of HFL's naming made it impossible to test HFL using picture naming. In the repetition and naming tasks, the experimenter immediately transcribed the responses that were later checked against an audio recording for accuracy. In all tasks, only the first complete response was retained for analysis.

2.3. Materials

Although DLE and HFL were particularly accurate when words had onsets and codas formed by a single consonant (top, dot), their errors were especially frequent with two-consonant clusters (block, cost) (Buchwald & Miozzo, 2011). To increase error opportunities, we generated four word lists that contained words with two consonants in the onset ($C_1C_2V\ldots$) or the coda ($\ldots VC_1C_2$). Each list contained two types of monosyllabic words: those with a preferred, less complex syllable structure (*unmarked*), and those with a less preferred, more complex syllable structure (*marked*). Complexity was determined with reference to the sonority scale presented in Table 2. To ensure that differences on these lists could not arise due to difficulties with specific consonants, we verified that the individual consonants were produced with similar levels of accuracy as singletons. Specifically, we calculated the probabilities with which participants correctly produced these consonants as singleton onsets (e.g., the /b/ in *bake*) and report the averaged correct percentages of the phonemes examined in each list.

Lists 1 and 2. They included words varying for onset complexity and were presented in the repetition task. Words of List 1 had onsets formed by stop-liquids (*blow*) and fricative-liquids (*flow*). Specifically, the stop onset consonants were /b/, /k/, /g/ and /p/, whereas the fricative onset consonants were /f/, /ʃ/ and /θ/. Either the liquid /l/ or /r/ was part of the onsets. Because of their comparatively small sonority increase, fricative-liquid onsets are marked relative to stop-liquid onsets. When occurring as singletons, the stops and fricatives examined in List 1 were produced with similar accuracy by DLE (79% vs. 85%) as well as by HFL (79% vs. 79%). We restricted these lists to clusters with liquids as C_2 and did not include words with glides as C_2 for several reasons. In particular, there is some debate about whether clusters with glides as C_2 have a better or worse sonority profile than those with liquids (Eckman & Iverson, 1993), there are fewer words with glides as C_2

which compromised list creation, and there is debate about whether one of the English glides (/j/) is actually treated as a glide in these sequences (see Buchwald, 2009).

In List 2, s-liquid onsets (e.g., *slot*) were compared to s-nasal onsets (e.g., *snot*) that were characterized by a smaller sonority increase and therefore were relatively marked. List 2 also included words with s-stop onsets (e.g., *stub*), which are the most complex according to their sonority profile. We examined whether responses to s-stop onsets differed from those to other prevocalic consonants, a finding providing converging evidence of sensitivity to sonority-based syllable structures. Each individual was capable of accurately producing the stops, nasals and liquids of List 2 when they were administered as singletons (DLE: 87% stops, 98% nasals, and 99% liquids; HFL: 86% stops; 93% nasals; 96% liquids), with no statistically significant differences among these segments. Similar results held for the singleton /s/ (accuracy: DLE = 89%, HFL = 88%), which was the C_1 in the clusters in List 2.

Lists 3 and 4. They were designed to examine coda sonority with reference to the sonorant/obstruent distinction. Consonants can be grouped into the sonority classes of sonorants (nasals and liquids) and obstruents (stops and fricatives), with the former having higher sonority ranking than the latter (e.g., Gigerich, 1992). The words included in Lists 3 and 4 had codas formed either by sonorant–obstruent (SO; *milk*) or two obstruents (OO; *past*). As sonority should ideally decreases minimally from vowels to word ends, OO codas are more complex relative to SO codas. Lists 3 and 4 were used in repetition and picture naming, respectively. Importantly, the consonants compared in Lists 3 and 4 were produced as singletons with comparable levels of accuracy (OO vs. SO: DLE = 88% vs. 92%; HFL = 78% vs. 78%).

The words included in each list were matched for length (number of phonemes) and log-transformed lemma and syllable frequencies (norms from CELEX; Baayen, Piepenbrock, & Van Rijin, 1993), variables that could potentially affect our participants' responses. The ANOVAs carried out to compare these variables yielded results with $p > 0.15$. Information about the words included in each list is presented in Table 3. The words in the lists described above were tested together with filler words bearing other syllable structures (e.g., CVC or VCC), a few of which were inflected. Filler words were introduced to diversify word types in the attempt to prevent participants from forming strong expectations about the syllabic and morphological structure of the tested words. Lists 1–3 were included, along with filler words, in an omnibus list administered for repetition during several testing sections, and lists were repeated to obtain a larger number of response tokens.

2.4. Accuracy analyses

We scored the accuracy of the words produced by DLE and HFL on several dimensions. In addition to whole word accuracy, given the focus of the present investigation on onsets and codas, specific accuracy analyses were conducted that concentrated on prevocalic and postvocalic consonants. Onsets and codas were rated as correct if *both* of their consonants were produced correctly. Furthermore, we controlled whether the remaining of the word could have affected the production of the segments analyzed in each list. For example, we examined whether onset accuracy depended on rhyme (vowel + coda) accuracy. Comparisons were carried out using chi-squares ($\alpha = .05$). Scoring reliability was controlled asking a second rater to independently score 920 of DLE's responses and 100% of HFL's responses. Raters' agreement was almost unanimous (98.5% and 98%).

3. Results

3.1. Onset accuracy

Relatively unmarked stop-liquid onsets (*blow*) were produced significantly more accurately than marked fricative-liquid onsets (*flow*) by DLE (82% vs. 39%; $\chi^2 = 85.7$,

Table 3
Features controlled for marked and unmarked onsets and codas.

	Examples	N items	Phoneme number mean (sd)	Word frequency mean (sd)	Syllable frequency mean (sd)
List 1					
Consonant-liquid Onsets					
Stop-liquid	*blow*	230	4.1 (0.5)	7.7 (1.7)	0.8 (0.5)
Fricative-liquid	*flow*	230	4.1 (0.5)	7.6 (1.9)	0.9 (0.6)
List 2					
S-consonant Onsets					
s-Liquid	*slit*	114	4.0 (0.3)	7.4 (1.6)	0.7 (0.5)
s-Nasal	*snot*	114	4.0 (0.3)	7.5 (1.6)	0.8 (0.6)
s-Stop	*stub*	114	4.0 (0.3)	7.8 (1.7)	0.9 (0.7)
List 3					
Codas					
SO	*milk*	60	4.2 (0.7)	2.2 (0.8)	1.0 (0.7)
OO	*past*	60	4.1 (0.8)	2.4 (0.8)	1.1 (0.6)
List 4 (picture-naming)					
Codas					
SO	*corn*	69	4.2 (0.8)	9.0 (1.4)	1.1 (0.7)
OO	*desk*	64	4.3 (0.7)	8.8 (1.8)	1.1 (0.7)

p<.0001) as well as HFL (87% vs. 61%; $\chi^2 = 30.89$, $p < .001$). Whole-word accuracy was significantly greater for words with stop-liquid onsets for DLE (63% vs. 32%, $\chi^2 = 43.94$, $p < .0001$) but not HFL (46% vs. 41%, $\chi^2 = 0.49$, *ns*). Critically, as illustrated in Fig. 1 (top panel), no significant differences appeared in the remaining segments of the word (rhyme; vowel + coda) for either participant, a finding that suggests an effect circumscribed to word onsets.

A sonority effect was also found with List 2; for DLE, onset accuracy was greater for s-liquid onsets (*slot*) relative to the comparatively marked s-nasal onsets (*snot*; 37% vs. 15%, $\chi^2 = 11.97$, $p = .0005$) as was whole-word accuracy (32% vs. 14%, $\chi^2 = 9.97$, $p = .001$). DLE's accuracy was also particularly low for s-stop onsets (13%). HFL showed a broadly similar pattern. Although the numerical difference between s-liquid and s-nasal clusters (72% vs. 57%) was not significant, accuracy was especially low with s-stop clusters (42%). As shown in Fig. 1 (middle panel), the response differences observed with the onsets did not extend to other word segments in List 2. As noted in Section 2.3, the differences that emerged with each of the onset lists cannot be accounted for by difficulties in producing specific phonemes as singletons.

3.2. Coda accuracy

The unmarked SO codas (*milk*) were repeated more accurately than the marked OO codas (*past*) by DLE (78% vs. 51%; $\chi^2 = 8.15$, $p = .004$) and HFL (55% vs. 6%; $\chi^2 = 84.91$, $p < .001$). Whole-word accuracy was also significantly greater for words with SO codas relative to OO codas (DLE: 61% vs. 42%, $\chi^2 = 4.81$, $p = .02$; HFL: 41% vs. 2%, $\chi^2 = 69.29$, $p = .001$). As illustrated in Fig. 1 (bottom panel), accuracy rates were comparable for the other word segments (onsets + vowel), a finding confirming selective effects of coda sonority. As with onsets, the sonority effects in coda clusters do not reflect difficulties with specific phonemes. DLE was also better at producing SO codas relative to OO codas in picture naming (90% vs. 73%; $\chi^2 = 6.05$, $p = .01$). Unsurprisingly, given DLE's naming deficit, pic-

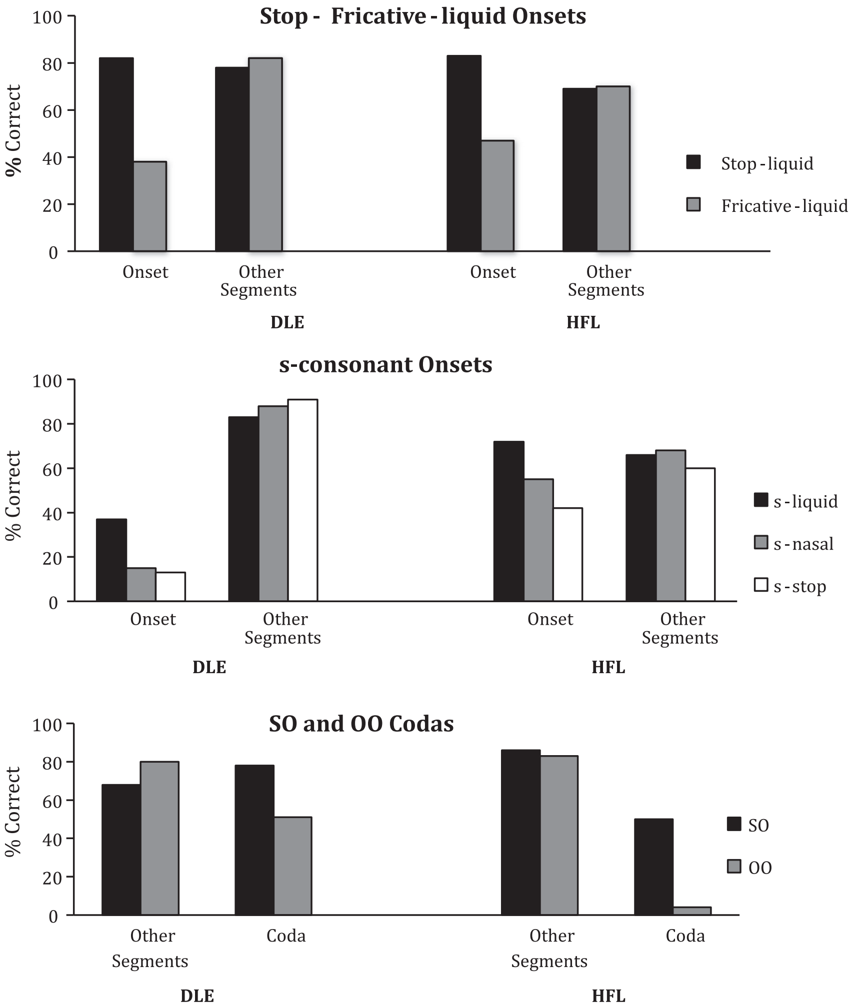

Fig. 1. % Onsets, codas, and other segments correctly repeated by DLE and HFL. *Top*: (unmarked) stop-liquid onsets (*blow*) vs. (marked) fricative-liquid onsets (*flow*). Middle: (unmarked) s-liquid onsets (*slot*) vs. (marked) s-nasal onsets (*snot*) and (marked) s-stop onsets (*stub*). Bottom: (unmarked) SO codas (*milk*) vs. (marked) OO codas (*past*). In top and middle panels other segments correspond to rhymes.

tures were often named correctly only when the onset phoneme had been provided as cue (31/133, 23%), an event that occurred a comparable number of time with words ending in SO and OO clusters. (As mentioned above, the severity of HFL's naming deficit prevented us from administering this participant the picture-naming task).

3.3. Error analyses

To include more responses in our error analyses, we examined larger response sets than those used to assess accuracy, examining each of the critical errors produced in repetition by DLE ($N = 1436$) and HFL ($N = 1382$) over more than 1 year of testing. The errors of both participants consisted of phoneme omissions (*flow* → low; *past* → pas) or phoneme substitutions (*flow* 8 klow; *past* → pask). Errors were scored separately for each of the prevocalic consonants (C_1C_2V), as well as for each of the postvocalic consonants (VC_1C_2).

3.3.1. DLE's errors

As illustrated in Fig. 2 (top panel), the errors observed with onsets formed by stop-liquid and fricative-liquid sequences demonstrated a remarkably similar distribution, generally concentrating on prevocalic C_1 (>90%) and leaving the prevocalic C_2 intact. To gain further insight on the errors overwhelmingly affecting the prevocalic C_1, we examined the relative incidence of C_1 omissions and C_1 substitutions (Fig. 2, top panel). It was the nature of the resilient C_2 consonant that determined whether C_1 errors surfaced as omissions or substitutions: when C_2 was a liquid, C_1 was either omitted (*flow* → low) or substituted (*flow* → klow); however, when C_2 was a nasal, C_1 was preferentially omitted (*smell* → mell). Interestingly, compared to the other onsets, s-stop onsets demonstrated a markedly different error pattern, eliciting fewer C_1 errors (50%) and more C_2 errors, either in isolation (19%) or jointly with C_1 (31%). Furthermore, errors affecting s-stop onsets demonstrated a clear-cut distribution: omissions were the predominant errors with both C_1 (99%; *sport* → port) and C_2 (92%; *stop* → sop). It is worth noting that the two cluster types where C_1 was frequently deleted corresponds to the clusters with the less sonorous C_2, which are preferred as singleton onsets to the more sonorous liquid consonants.

DLE's errors differed noticeably between SO and OO codas (Fig. 3). In SO codas, errors concentrated on the postvocalic C_2 (85%) and typically consisted of omissions (*milk* → mil; 75%). In OO codas, errors were more evenly distributed between C_1 (37%) and C_2 (51%), and frequently resulted in the substitution of C_1 (*past* → paft; 32%) or C_2 (*past* → pask; 44%).

3.3.2. HFL's errors

The patterns from HFL are remarkably similar to those detailed above for DLE. As illustrated in Fig. 2 (top panel), when errors observed with onsets containing either a nasal or liquid C_2 affected a single onset consonant, the prevocalic C_1 was affected much more frequently than C_2 (∼70% vs. 10%). As with DLE, the type of error affecting C_1 was determined by C_2: substitution rates were higher than deletion rates when C_2 was a liquid (>70% substitutions), but deletions outnumbered substitutions when C_2 was a nasal (83% vs. 17%; Fig. 2, bottom panel). Compared to the other onsets, s-stop onsets demonstrated a markedly different error pattern, eliciting fewer C_1 errors (31%) and more C_2 errors (61%). Furthermore, errors affecting the C_1 were primarily deletions (97%).

HFL also exhibited differences between SO and OO codas (Fig. 3). In SO codas, errors concentrated on the postvocalic C_2 (81%) and typically consisted of substitutions (*milk* → milt; 71%). In OO codas, errors typically affected C_2 (45%) or both consonants (46%), and errors affecting only one segment typically resulted in the deletion of C_1 (*past* → pat; 75%).

3.3.3. Do errors generate better sonority profiles?

Prior investigations assessed whether errors improved the sonority profiles, as was assumed that impaired systems tolerating low degree of complexity would demonstrate a 'preference' for errors reducing complexity (e.g., Romani & Galluzzi, 2005; Romani et al., 2011). Compared to targets, errors would result in onsets with steeper transitions from consonants to vowels (*flan* → plan) and would show the mirror-pattern of shallower transitions from vowels to consonants in codas (*cast* → cart). However, DLE and HFL's errors revealed that other factors in addition to sonority constraint the nature of their errors. For example, the effects of DLE's errors affecting onsets and codas on sonority were mixed, with some errors improving the sonority profile (44%), other worsening it (41%), and other still leaving it unchanged (15%). To illustrate the factors determining the observed error patterns, we focus on several patterns in DLE's errors.

A first consideration concerns what errors could emerge in the context of DLE's deficit. For example, DLE's errors involving s-nasal onsets were largely due to C_1 omissions (96%) and thus consistently led to a worse sonority profile (*smack* → mack). As we observed earlier, prevocalic C_2 was generally preserved in DLE's onset errors. To the extent that onset errors must concentrate on prevocalic C_1, and that substitutions of /s/ with other consonants in s-nasal onsets would generate phonotactic illegal onsets in English (Fudge, 1987; Gigerich, 1992; Selkirk, 1984), /s/ omissions represented the only possible error. Thus, while this error generated a worse sonority profile than C_2 deletion would have, this error does not reflect in this case a lack of sensitivity to sonority but rather the effect of other constraints. As noted in Section 3.3.1, the increased likelihood of C_1 deletion when C_2 was a less sonorous consonant may reflect the complicated relationship among various constraints (including those based on sonority) that governed DLE's errors. A second illustrative example is provided by substitutions, which can either improve the sonority profile (*flock* → block) or worsen it (*bliss* → fliss). These errors are informative only if baseline probabilities are known, which is difficult to determine in part because pre- and postvocalic C_1–C_2 sequences that improve or worsen sonority profiles are unevenly distributed in English onsets and codas. To adequately address this issue, it will be crucial for future work to carry out well-controlled and circumscribed error analyses to provide an isolated test of possible sonority effects.

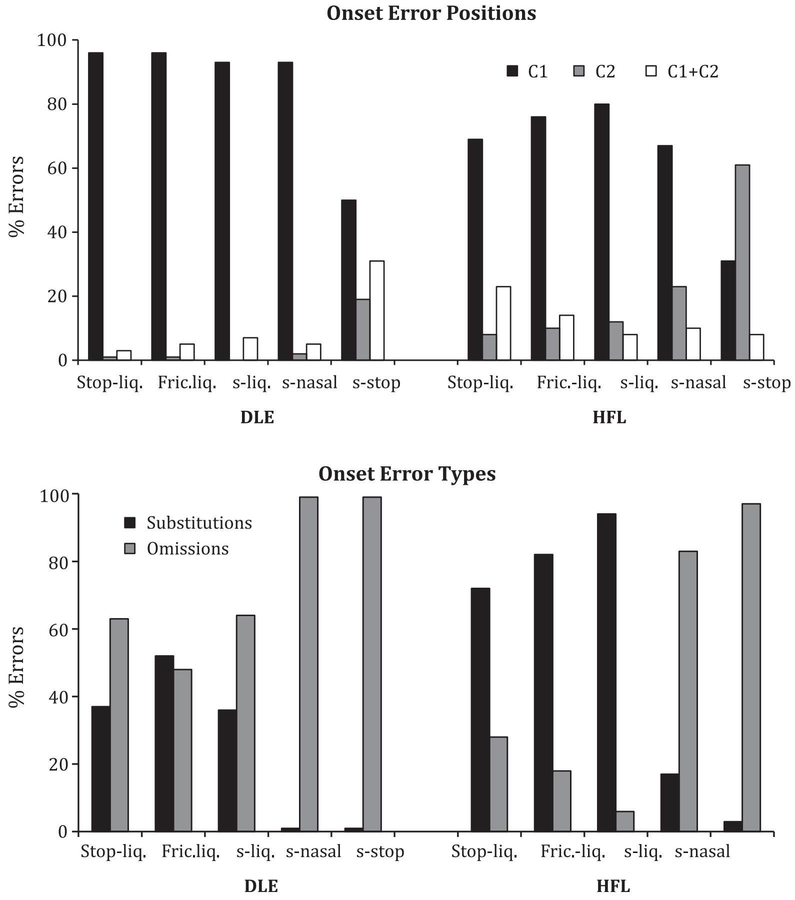

Fig. 2. Characteristics of onset errors recorded from DLE and HFL while they repeated words with onsets formed by stop-liquid (*blow*), fricative-liquid (*flow*), s-liquid (*slit*), s-nasal (*snot*) and s-stop (*stub*). Top:% errors affecting only the first onset consonant (C_1), only the second onset consonant (C2), or both consonants (C1 + C2); Bottom:% C1 errors resulting in substitutions (*flow* → klow) and omissions (*flow* → low). Total number of errors analyzed: stop-liquid onsets, DLE = 149, HFL = 147; fricative-liquid onsets, DLE = 164, HFL = 173; s-liquid onsets, DLE = 135, HFL = 75; s-nasal onsets, DLE = 337, HFL = 133; s-stop onsets, DLE = 339, HFL = 636. Fic. = Fricative; Liq. = Liquid.

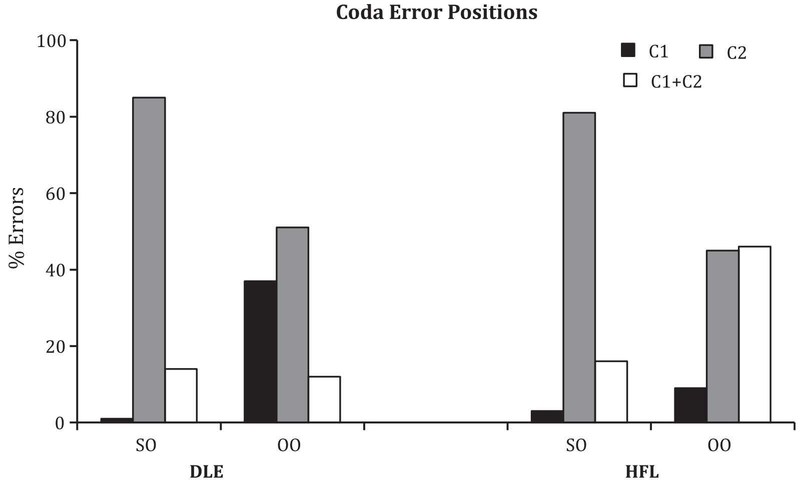

Fig. 3. % Errors affecting only the first coda consonant (C1), only the second coda consonant (C2), or both consonants (C1 + C2) recorded from DLE and HFL. Sonorant–obstruent (SO) codas (*milk*) vs. obstruent–obstruent (OO) codas (*past*). Total number of errors analyzed: SO codas, DLE = 162, HFL = 72; OO codas, DLE = 150, HFL = 146.

In light of these issues, one well-suited test of sonority is provided by the comparison of C_2 omissions in SO codas (*camp* → cam) vs. OO codas (*task* → tas). These sequences are useful because both types of errors involve the same consonants (obstruents) and result in permissible codas in English, but a sonority improvement only occurs when C2 is deleted in SO codas. Thus, if sonority is a factor affecting constrains errors on these sequences, we expect more C_2 omissions among errors affecting SO codas compared to OO codas. This pattern was observed for both DLE and HFL (DLE: 72% vs. 7%, $\chi^2 = 135.54$, $p < .0001$; HFL: 63% vs. 28%, $\chi^2 = 14.81$, $p < .001$).

3.4. Results summary

The accuracy with which DLE and HFL produced onsets and codas varied predictably as a function of the sonority profiles of these clusters. Further evidence suggesting an effect of sonority emerged with words bearing s-stop onsets (*spot*, *still*, *scarf*) that violate well-formedness for having a sonority peak in the onset. Most of the errors of DLE (98%) and HFL (97%) resulted in the elimination of the onset sonority peak, a finding demonstrating sensitivity to sonority structures. Evidence suggesting an effect of sonority also appeared with the coda errors produced by DLE and HFL. C_2 omissions were exceedingly more frequent in SO codas than OO codas, a discrepancy explainable by the fact that C_2 omissions improved sonority in SO codas. A close scrutiny of the errors produced by our participants revealed that other factors in addition to sonority were likely to determine the nature and position of their errors, including phonotactic constraints, avoidance of two-consonant ($C_1 + C_2$) errors, variations in error opportunities, and error susceptibility of prevocalic consonants ($C_1 > C_2$).

Our results underscore the need of detailed error analyses to understand the effects of sonority. The conclusion that sonority is one of many factors influencing error rates and types converges with the one reached in developmental studies where it has been noted that not all children produce errors conforming to sonority patterns and several mechanisms have been proposed to interact with sonority (Barlow, 2001; Goad & Rose, 2004; Pater & Barlow, 2003). Individuals with acquired speech deficits show similar variability to the one reported in developmental studies. However, we also note that in some previously reported neuropsychological studies, errors resulted in rather consistent improvement of sonority profiles (Béland et al., 1990; Den Ouden & Bastiaanse, 2005; Romani & Galluzzi, 2005; Romani et al., 2011). It is presently unclear why the effects of sonority in aphasic errors varies in strengths and in what circumstances other mechanisms would interact with sonority in determining the forms that error would take (see Goldrick & Daland, 2009 for more general discussion of grammatically-based variation in aphasic errors). This is certainly a topic that deserves additional attention, and requires systematic investigations to understand the extent to which differences in participants' deficits and languages as well as in the tests used can be responsible for the variability in the findings.

Two lines of evidence make it unlikely that problems with specific phonemes – rather than sonority – affected the responses of DLE and HFL. First, as we have pointed out above, changes in the responses were observed with phoneme combinations varying for sonority not when phonemes occurred as singletons. Were the results reflecting difficulties with phonemes rather than changes in sonority profiles, similar problems would have extended to singleton phonemes. Second,

it is noteworthy that it is syllable position (onset vs. coda) that made particular phonemes problematic rather than specific phonological and phonetic characteristics, as clearly illustrated by stops, nasals and liquids. For example, /l/ was associated with lower accuracy rates in the *marked* onset cluster /fl/ compared to the *unmarked* coda cluster /lf/. These asymmetries rule out problems with specific phonemes as the primary cause of the errors recorded from DLE and HFL. Nevertheless, they point to sonority as a plausible explanation of the findings observed with our participants.

Sonority-based markedness generalizations are largely mirrored by language-internal frequency, so that those phoneme sequences that are preferred from a sonority standpoint typically occur quite commonly in the language. The close relationship between sonority and phoneme-sequence frequencies introduces a possible confounding and demands we clarify whether the effects we attributed to sonority would instead reflect the frequency of phoneme sequences. A frequency control was conducted in a post-hoc analysis using position-specific biphone frequencies obtained from Vitevitch and Luce (2004). This is a token-based estimate of the probability with which a sequence of two phonemes (/bl/) occurs in specific word positions across English words (e.g., in first and second positions as in *black*). Position-specific biphone frequencies could be matched only with a set of the words of List 1, which comprised words with marked fricative-liquid onsets (*flow*) and unmarked stop-liquid onsets (*blow*) administered in the repetition task. Marked and unmarked words were equally represented in this set ($N = 177$), had onset consonants of comparable position-specific biphone frequencies (means =.006; $t(352) < 1$), and were matched for the variables controlled in the other lists (fricative-liquid vs. stop-liquid onsets, means: word frequency, 7.7 vs. 7.9; syllable frequency, 0.9 vs. 0.8; phoneme number, 4.1 vs. 4.1; *t*s with *p*s > .44). Even when position-specific biphone frequencies were controlled, stop-liquid onsets were produced significantly more accurately than the comparatively more marked fricative-liquid onsets by DLE (83.0% vs. 44.6%; $\chi^2 = 56.58$, $p < .0001$) as well as HFL (49.1% vs. 34.4%; $\chi^2 = 7.84$, $p = .005$). These results make it unlikely that the effects of sonority were primarily due to the frequency with which phoneme sequences varying for sonority occur in English.

4. General discussion

The most relevant findings of our investigation relates to the remarkable similarities of the apparent sonority effects demonstrated by DLE and HFL, despite results showing that their speech deficits arise from impairment to phonological vs. phonetic processing, respectively. First, their response accuracy was predicted by the relative sonority of the stimuli in each of the lists we tested involving different phoneme sequences in both onset position and coda position. In contrast to the homogeneity of the accuracy data, errors varied considerably across phoneme sequences, a result revealing that other variables in addition to sonority must determine the output of impaired word production systems. Taken together, the accuracy and error analysis data have several implications for understanding sonority and the representation of speech sounds accessed in speaking, issues that we will examine in the remaining of Section 4.

4.1. Multi-level sonority encoding

The primary question addressed in the present investigation concerned the locus of sonority effects, specifically whether the underlying principles governing sound structure that form the concept of sonority play a role at the phonological and/or phonetic level of processing. The finding that variations in sonority had highly similar effects on the performance of DLE and HFL invites the conclusion that sonority – in some form – is encoded at both phonological and phonetic levels. In this section, we consider both alternative explanations of these data and what the implications of these findings are for accounts of spoken production.

One clear alternative explanation of the data is that the similarities of the sonority effects demonstrated by DLE and HFL relate to deficits affecting a common level of processing. Pointing to the fact that our participants share articulatory problems (albeit fairly mild in DLE), it could be proposed that the similarities of sonority effects stem from these common problems. We doubt this is a valid account for reasons related to the nature of DLE's errors. The experimental evidence showed incontrovertibly that a low tolerance to sonority-marked onsets was the root of DLE's onset errors, some of which surfaced as omissions of prevocalic C_1 (e.g., *s̲port* → port or *s̲mell* → mell). Crucially, there is evidence that these omissions occur at a phonological level (Buchwald & Miozzo, 2011, 2012). As described in detail in the Introduction, these errors bore characteristics of abstract phonological representations rather than context-specific phonetic representations. In essence, the characteristics of DLE's errors make it unlikely that sonority effects derived from articulatory problems.

The sonority effects we observed with DLE, an individual with clear phonological impairment, are in apparent contrast with the findings of Romani et al. (2011) who reported sonority effects with participants suffering from articulatory planning deficits but not with those showing phonological deficits (see also Romani & Calabrese, 1998; Romani & Galluzzi, 2005; Romani et al., 2002). These contrasting findings will need to be addressed in future work. In considering these differences, we have several possible explanations that may reflect the need for consistency in how sonority effects are assessed. In particular, these studies critically differed in the ways deficits were defined and sonority was tested. Their diagnostic criteria to assign individual participants to a group were based on phonetic errors, defined as words with phonemes produced in a slurred, mumbled, or imprecise way. They used a cut-off of phonetic error rates (above 10% for articulatory planning deficits, lower than 5% for phonological deficits). Based on this way of separating individuals, their two groups of patients differed crucially in the incidence of what they referred to as *syllabic simplifications* – that is, errors in which the consonant-vowel templates or the sonority profiles of target syllables were simplified. Syllabic simplifications outnumbered errors that complicated syllable templates and sonority profiles with participants suffering from articulatory planning deficits but not with those affected by phonological deficits. It remains possible that the group differences that were reported by Romani et al. (2011) reflect variability in the number/type of factors affecting error typology. We also note that there could be genuine differences in the phonological deficits of DLE and the individuals tested in Romani et al. (2011). If it is reasonable to assume that multiple processes occur between accessing stored phonological representations of lexical items and computing representations to serve as input to the articulatory system, then these processes can break in a variety of ways giving rise to marked variations in phonological deficits, as argued on the basis of empirical findings by Goldrick and Rapp (2007) and Nozari, Kittredge, Dell, and Schwartz (2010). It is worth restating here that DLE does show some mild impairment on tasks used to assess motor planning (see case report), but on the basis of the detailed work contrasting these individuals described in the introduction, we are confident that our characterization of DLE as having errors arising due to a phonological disturbance is an accurate description.

If we are correct in associating the sonority effects observed with DLE and HFL with phonological and phonetic deficits, respectively, then the straightforward implication of our findings for models of word production is that principles governing sound structure captured by the notion of sonority are active in both phonological and phonetic processing. This conclusion raises the important questions of what is the nature and function of sonority at each of these levels and whether this constitutes a redundant representation of the same principles. Combining the mainstream idea that sonority is key to syllable structure (Clements, 1990; Gigerich, 1992; Selkirk, 1984; Zec, 1995) with the idea that phonology is the domain of syllabification (Dell, 1986; Levelt et al., 1999; Prince & Smolensky, 1993), a reasonable proposal is that the phonological encoding of sonority is associated with syllable formation. As reviewed in the Introduction, several accounts argue in favor of acoustic and/or articulatory correlates of sonority that allegedly provide independently motivated explanations of the sonority ranking. Although the definition of these correlates is an issue far from resolved, one may speculate that these correlations could also serve as blueprints for generating sonority-based constraints operating at phonological levels of processing. This 'sonority isomorphism' between phonology and phonetics can have important ramifications from a processing perspective. One is that sonority acts as a filter favoring phonological representations that already incorporate some desirable articulatory/acoustic features.

As many have observed, an important consequence of sonority relates to frequency, therefore phoneme sequences with preferable sonority profiles tend to occur rather frequently in a language. Several lines of evidence from word production demonstrate that frequency not only affects access to word forms (Jescheniak & Levelt, 1994; Miozzo & Caramazza, 2003) but also processes occurring more downstream, including syllable computation (Cholin, Levelt, & Schiller, 2006; Laganaro, 2005; Laganaro & Alario, 2006) and articulation (Gahl, 2008). Furthermore, individuals whose acquired deficits selectively affect the production of word sounds typically show an advantage for high-frequency forms (Cholin, Rapp, & Miozzo, 2010; Kohn & Goodglass, 1985; Laganaro, 2008; Nozari et al., 2010). Such widespread sensitivity to frequency raises the question of whether the similarly widespread effects of sonority observed with DLE an HFL could in part be a manifestation of frequency. A frequency account does not find support from our data. In fact, effects of sonority were observed even when we tightly controlled for syllable frequency and the frequency of occurrence of phoneme pairs in word-specific positions (biphone frequency; Vitevitch & Luce, 2004). While our results suggest that different mechanisms underlie the effects of sonority and frequency in speech production, they provide some hints about the relationship between sonority and frequency. The mechanisms involved in spoken production (and comprehension) that favor forms with ideal sonority patterns function as forces pushing those forms so to determine, diachronically, the appearance and preservation in the language of desirable forms at the expense of those with marked patterns. Under this view, sonority contributes to the frequency of a given form (both language internally and cross-linguistically) while sonority and frequency reflect the functioning of partially different cognitive mechanisms. Although the data from DLE and HFL seem to rule out effects of frequency in disguise, further evidence is needed before reaching firmer conclusions on the relationship between sonority and frequency, not only because it is desirable to obtain additional converging evidence but also because the complexity of such relationship requires a systematic investigation.

In sum, we have shown that both phonological and phonetic processing are affected by differences in sonority sequencing. We have considered various accounts for this, including: that there is a single set of sonority principles governing phonological and phonetic processing that is represented redundantly; that the notion of sonority correlates to different principles within phonology and within phonetics; and that both are the result of a correlation with additional factors that affect processing such as frequency. By having established that sonority is associated with both phonological and phonetic processes, our data allow us to go beyond the issue of where sonority plays a role and focus instead on questions concerning how sonority plays a role at each of these levels of processing.

4.2. The appendix

Prevocalic s-stop clusters (*spell*, *stop*, *skull*) violate the sonority sequencing principle of syllable formation by containing a reverse sonority cluster (with sonority lowering before it rises). To the extent that the anomaly of s-stop onsets is rooted in sonority, a reasonable prediction is that conditions reducing the tolerance to sonority-marked forms would make s-stop onsets particularly problematic. This prediction was confirmed by DLE and HFL, whose errors were especially common with prevocalic s-stop sequences. Note that although these errors often resulted in /s/ omission, they did not arise from problems with the realization of /s/. The fact that in other onsets /s/ accuracy rates were higher and very comparable to those of other fricatives, points instead to problems with the clusters themselves.

Many linguistic accounts have endorsed the idea that the /s/ of s-stop onsets occupies an extra-syllabic position, commonly referred to as *appendix* (Blevins, 1995; Clements & Keyser, 1983; Fujimura & Lovins, 1982; Gigerich, 1992; Goldsmith, 1990; Green, 2003; Harris, 1994; Kiparsky, 2003: McCarthy, 2005; Vaux & Wolfe, 2009). Accounts of the appendix differ in architecture and a point of debate is whether the appendix is linked to the foot (Kiparsky, 2003), the prosodic word (e.g., Goldsmith, 1990; Harris, 1994), the prosodic phrase (Vaux, 1998) or multiple loci (e.g., Green, 2003; Rialland, 1994; Vaux & Wolfe, 2009). These differences aside, all of these accounts view appendixes as typologically distinct from other prevocalic constituents and attempt to explain a wide range of linguistic phenomena – reviewed by Kiparsky (2003) and Vaux and Wolfe (2009) – that demonstrate the uniqueness of appendixes. Converging evidence confirming the anomaly of appendixes has emerged from behavioral studies reporting on speech errors of young speakers (Goad & Rose, 2004), vowel reduction (Fudge, 1984; Hayes, 1985), language games (Pierrehumbert & Nair, 1995), and oral syllabification of words (Treiman & Zukowski, 1990) and nonwords (Treiman, Gross, & Cwikiel-Glavin, 1992). The results obtained from DLE and HFL add to this evidence. In their responses, both prevocalic consonants were susceptible to errors in s-stop clusters (C_1: *spell* → pell; C_2: *spell* → sell), unlike in the other prevocalic clusters where C_1 errors (*slope* → lope) largely outnumbered C_2 errors (*slope* → sope). Interestingly, a relative preservation of /s/ in s-stop clusters was also observed with patient DB (Romani & Calabrese, 1998). Although the causes of these discrepant error distributions in conditions of language impairment are currently unclear and demand further investigation, our neuropsychological findings appear to be generally consistent with linguistic accounts that confer the appendix a special representational status.

4.3. Concluding comments on syllable organization

Once we exclude s-stop onsets and concentrate to the remaining phoneme sequences tested with DLE and HFL, a striking asymmetry appears: in onsets, C_2 were far less vulnerable than C_1, a low degree of error susceptibility demonstrated by neither of the postvocalic consonants. These patterns bear some resemblance with well-established facts about cross-linguistic preferences and empirical observations about phonological development. The CV sequence that is generally left intact in our participants' responses is also the most preferred cross-linguistically (Clements, 1990; Clements & Keyser, 1983) and the earliest to appear developmentally (e.g., Becker & Tessier, 2011; Goad & Rose, 2004; Ohala, 1999; Pater, 2009; Salidis & Johson, 1997). Why do these differences arise across syllable components? A promising framework for addressing this question is provided by articulatory phonology and the dynamical system theory in which it is grounded (Browman & Goldstein, 1992; Browman and Goldstein, 1995; Goldstein, Byrd, & Saltzman, 2006; Nam, Goldstein, & Saltzman, 2010; Salztamn & Byrd, 2000).

In the articulatory phonology framework, sound structure is decomposable into discrete articulatory gestures consisting of a constriction degree at a specific constriction location (e.g., labial closure, palatal wide); furthermore, each gesture is characterized by specific activation timing and is associated with a planning oscillator. The coordination of speech gestures and their relative timing depend on the coupling of their corresponding oscillators during speech planning. Once the oscillators settle in a stable pattern of relative phasing, gestures are triggered with proper activation timing. There are two basic modes of coupling, each corresponding to a distinct temporal relationship between speech gestures: in-phase coupling triggering synchronous activation, and anti-phase coupling generating temporally separated forms of activation. An intrinsic characteristic of oscillators is that their in-phase coupling results in a more stable coordination pattern than the anti-phase coupling (Salztamn & Byrd, 2000; Turvey, 1990). This characteristic of oscillators, along with kinematic data on the timing of speech gestures (Löfqvist & Gracco, 1999), led Goldstein et al. (2006) to propose the coupling hypothesis of syllable structure according to which CV sequences results from in-phase coupling, while VC sequences stem from anti-phase coupling. To the extent that the coupling hypothesis of syllable structure presupposes more stable and stronger binding in CV sequences, it contributes to explain a variety of phenomena, including the preference of CV sequences observed at the level of cross-linguistic distributions and phonological acquisition (Nam et al., 2010). Kinematic data were also key to extend the hypothesis to CC sequences in onsets and codas. The inclusion of an additional C in CC onsets produces a shift of both consonants, thereby C_2 is pushed 'rightward' and thus overlapping even more in time with the nuclear V, whereas C_1 is moved 'leftward,' that is further away from C_2 and V (Browman & Goldstein, 1988; Byrd, 1995). Similar shifts are not observed with CC in codas (Byrd, 1995). These differences were modeled assuming anti-phase coupling for the CC sequences in onsets (Browman & Goldstein, 2000). As revealed by computer simulations conducted by Nam et al. (2010), the weakest couplings were those involving the prevocalic C_1, while the strongest coupling appeared in C_2V position. If we make the reasonable assumption that stronger coupling corresponds to greater resistance to damage, the syllable structure proposed within articulatory phonology mirrors closely the error distributions observed with DLE and HFL. In fact, prevocalic C_1, associated with the weakest coupling, was the most vulnerable consonant, whereas prevocalic C_2, associated with the most stable coupling, was the most preserved consonant. It is noteworthy that articulatory phonology provides an account of DLE and HFL's errors for which evidence strongly indicates a phonological deficit. This is entirely compatible with articulatory phonology, where speech gestures are conceptualized both as units of phonological information and units of speech production.

We set out our investigation with clear predictions on the accuracy of the repetition responses of DLE and HFL. The distribution of their errors was a serendipitous finding. Nevertheless, it is encouraging that this finding receives a comprehensive account under articulatory phonology, a theory that proved successful in explaining a wide range of data from normal and impaired speakers, but even more importantly that this finding is consistent with previous results concerning cross-linguistic distribution, phonological acquisition and kinematic observations. This should make us more confident about the strength of the data aligning with our predictions and of their implications for sonority accounts.

Acknowledgments

The present investigation was supported by NIH Grant DC006242. Cristina Sanchez, Jennifer O'Shea, Julia Wadolowska and Julianne Remus contributed to testing and data analyses. We thank D.L.E. and H.F.L. for their participation in the study.

References

Anderson, S. (1982). The analysis of French schwa, or how to get something for nothing. *Language, 58*, 534–573.

Baayen, R., Piepenbrock, R., & Van Rijin, H. (1993). *The CELEX lexical database*. Philadelphia, PA: Linguistic Data Consortium, University of Pennsylvania.

Barlow, J. A. (2001). The structure of /s/-sequences: Evidence from a disordered system. *Journal of Child Language, 28*, 291–324.

Bastiaanse, R., Gilbers, D., & van der Linde, K. (1994). Sonority substitutions in Broca's and conduction aphasia. *Journal of Neurolinguistics, 8*, 247–255.

Becker, M., & Tessier, A.-M. (2011). Trajectories of faithfulness in child-specific phonology. *Phonology, 28*, 163–196.

Beckman, M., Edwards, J., & Fletcher, J. (1992). Prosodic structure and tempo in a sonority model of articulatory dynamics. In G. J. Docherty & R. D. Ladd (Eds.), *Papers in laboratory phonology II: Gesture, segments, prosody* (pp. 68–86). Cambridge: Cambridge University Press.

Béland, R., Caplan, D., & Nespoulous, J. L. (1990). The role of abstract phonological representation in word production: Evidence from phonemic paraphasias. *Journal of Neurolinguistics, 5*, 125–164.

Berent, I., Lennertz, T., Jun, J., Moreno, M. A., & Smolensky, P. (2008). Language universal in human brains. *Proceedings of the National Academy of Sciences, 105*, 5321–5325.

Blevins, J. (1995). The syllable in phonological theory. In J. Golsmith (Ed.), *The handbook of phonological theory*. Cambridge, Mass: Blackwell.

Broselow, E., & Finer, D. (1991). Parameter setting in second language phonology and syntax. *Second Language Research, 7*, 35–59.

Browman, C. P., & Goldstein, L. (1988). Some notes on syllable structure in articulatory phonology. *Phonetica, 45*, 140–155.

Browman, C. P., & Goldstein, L. (1992). Articulatory phonology: An overview. *Phonetica, 49*, 155–180.

Browman, C. P., & Goldstein, L. (2000). Competing constraints on intergestural coordination and self-organization of phonological structures. *Les Cahiers de l'ICP, Bulletin de la Communication Parlée, 5*, 25–34.

Browman, C. P., & Goldstein, L. (1995). Gestural syllable position effects in American English. In F. Bell-Berti & L. Raphael (Eds.), *Producing speech contemporary issues* (pp. 19–33). New York, NY: American Institute of Physics.

Buchwald, A. (2009). Minimizing and optimizing structure in phonology: Evidence from aphasia. *Lingua, 119*, 1380–1395.

Buchwald, A., & Miozzo, M. (2011). Finding levels of abstraction in speech production: Evidence from sound-production impairment. *Psychological Science, 22*, 1113–1119.

Buchwald, A., & Miozzo, M. (2012). Phonological and motor errors in individuals with acquired sound production impairment. *Journal of Speech, Language, and Hearing Research, 55*, 1573–1586.

Buckingham, H. W. (1986). The scan-copier mechanisms and the positional level of language production: Evidence from phonemic paraphasia. *Cognitive Science, 10*, 195–217.

Byrd, D. (1995). C-centers revisited. *Phonetica, 52*, 263–282.

Chitoran, I., Goldstein, L., & Byrd, D. (2002). Gestural overlap and recoverability: Articulatory evidence from Georgian. In C. Gussenhoven & N. Warner (Eds.). *Laboratory phonology 7* (pp. 419–447). Berlin, New York: Mouton de Gruyter.

Cholin, J., Levelt, W. J. M., & Schiller, N. O. (2006). Effects of syllable frequency in speech production. *Cognition, 99*, 205–235.

Cholin, J., Rapp, B., & Miozzo, M. (2010). Under what circumstances do inflectional rules apply? *Cognitive Neuropsychology, 27*, 334–359.

Christman, S. S. (1994). Target-related neologism formation in jargonaphasia. *Brain and Language, 46*, 109–128.

Clements, G. N. (1990). The role of the sonority cycle in core syllabification. In M. Beckman & J. Kingston (Eds.), *Papers in laboratory phonology 1*. Cambridge, MA: Cambridge University Press.

Clements, G. N., & Keyser, S. J. (1983). *CV phonology*. Cambridge, MA: MIT Press.

Clements, G. N. (2009). Does sonority have a phonetic basis? Comments on the chapter by Bert Vaux. In E. Raimy & C. E. Cairms (Eds.), *Contemporary views on architecture and representations in phonology*. Cambridge, MA: MIT Press.

Crowley, T., & Bowern, C. (2010). *An introduction to historical linguistics*. New York, NY: Oxford University Press.

Daland, R., Hayes, B., White, J., Garellek, M., Davis, A., & Norrmann, I. (2011). Explaining sonority projection effects. *Phonology, 28*, 197–234.

Davidson, L. (2011). Phonetic and phonological factors in the second language production of phonemes and phonotactics. *Language and Linguistics Compass, 5*, 126–139.

Davidson, L., & Shaw, J. (2012). Sources of illusion in consonant cluster perception. *Journal of Phonetics, 40*, 234–248.

Dell, G. S. (1986). A spreading-activation theory of retrieval in sentence production. *Psychological Review, 93*, 283–321.

Den Ouden, D.B., & Bastiaanse, R. (2005). Phonological encoding and conduction aphasia. In R. J. Hartsuiker, R. Bastiaanse, A. Postma, & F. Wijne (Eds.), *Phonological encoding and monitoring in normal and pathological speech* (pp. 86–101). Psychology Press.

Dunn, L. M., & Dunn, L. M. (1981). *Peabody picture vocabulary test*. Circle Pines, MN: American Guidance Service.

Eckman, F. R., & Iverson, G. K. (1993). Sonority and markedness among onset clusters in the interlanguage of ESL learners. *Second Language Research, 9*, 234–252.

Fudge, E. (1984). *English word stress*. London: Allen & Unwin.

Fudge, E. (1987). Branching structures within the syllable. *Journal of Linguistics, 23*, 359–377.

Fujimura, O., & Lovins, J. (1982). *Syllables as concatenative phonetic units*. Bloomington, IN: Indiana University Linguistics Club.

Gahl, S. (2008). "Thyme" and "time" are not homophones. The effect of lemma frequency on word durations in spontaneous speech. *Language, 84*, 474–496.

Gigerich, H. J. (1992). *English phonology*. Cambridge: Cambridge University Press.

Goad, H. (in press). Phonological processes in child speech. In J. Lidz, W. Snyder & J. Pater (Eds.), *The Oxford handbook of developmental linguistics.* Oxford: Oxford University Press.

Goad, H., & Rose, Y. (2004). Input elaboration, head faithfulness and evidence for representation in the acquisition of left-edge clusters. In R. Kager, J. Pater, & W. Zonneweld (Eds.), *Fixing priorities: Constraints in phonological acquisition* (pp. 109–157). Cambridge: Cambridge University Press.

Goldrick, M., & Daland, R. (2009). Linking speech errors and phonological grammars: Insights from Harmonic Grammar networks. *Phonology, 26*, 147–185.

Goldrick, M., & Rapp, B. (2007). Lexical and post-lexical phonological representations in spoken production. *Cognition, 102*, 219–260.

Goldsmith, J. (1990). *Autosegmental and metrical phonology*. Oxford: Blackwell.

Goldstein, L., Byrd, D., & Saltzman, E. (2006). The role of vocal tract gestural action units in understanding the evolution of phonology. In M. Arbib (Ed.), *From action to language: The mirror neuron system* (pp. 215–249). Cambridge: Cambridge University Press.

Green, A. (2003). Extrasyllabic consonants and onset well-formedness. In C. Féry & R. van de Vijver (Eds.), *The syllable in optimality theory* (pp. 238–253). Cambridge: Cambridge University Press.

Greenberg, J. H (1978). Some generalizations concerning initial and final consonant clusters. In *Universals of human language*. In J. H. Greenberg (Ed.). *Phonology* (Vol. 2). Stanford, CA: Stanford University Press.

Harris, J. (1994). *English sound structure*. Oxford: Blackwell.

Hayes, B. (1985). *A metrical theory of stress rules*. New York, NY: Garland.

Heffner, R.-M. S. (1950). *General phonetics*. Madison: The University of Wisconsin Press.

Indefrey, P. (2011). The spatial and temporal signatures of word production components: A critical update. *Frontiers in Psychology, 2*, 255. http://dx.doi.org/10.3389/fpsyg.2011.00255.

Jakobson, R. (1941/1968). *Child language, aphasia, and phonological universals*. The Hague: Mouton.

Jescheniak, J., & Levelt, W. J. M. (1994). Word frequency effects in speech production: Retrieval of syntactic information and of phonological form. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 20*, 824–843.

Jespersen, O. (1932). *Lehrbuch der Phonetik*. Leipzig & Berlin: B.G. Tuebner.

Kaplan, E., Goodglass, H., & Weintraub, S. (1983). *The Boston naming test*. Philadelphia: Lea & Febiger.

Kay Lesser, R., & Coltheart, M. (1992). *Psycholinguistic assessment of language processing in aphasia*. Hove: Erlbaum.

Kiparsky, P. (2003). Syllables and moras in Arabic. In C. Féry & R. van de Vijver (Eds.), *The syllable in optimality theory* (pp. 147–182). Cambridge: Cambridge University Press.

Klatt, D. H. (1975). Voice onset time, frication, and aspiration in word-initial consonant clusters. *Journal of Speech and Hearing Research, 18*, 686–706.

Kohn, S. E., & Goodglass, H. (1985). Picture naming in aphasia. *Brain and Language, 24*, 266–283.

Ladefoged, P. (1993). *A course in phonetics* (3rd ed.). Orlando: Harcourt Brace & Company.

Laganaro, M. (2005). Syllable frequency effect in speech production: evidence from aphasia. *Journal of Neurolinguistics, 18*, 221–235.

Laganaro, M. (2008). Is there a syllable frequency effect in aphasia or in apraxia of speech or both? *Aphasiology, 22*, 1191–1200.

Laganaro, M., & Alario, F.-X. (2006). On the locus of the syllable frequency effect in speech production. *Journal of Memory and Language, 55*, 178–196.

Levelt, W. J. M., Roelofs, A., & Meyer, A. (1999). A theory of lexical access in speech production. *Behavioral and Brain Sciences, 22*, 1–75.

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

Locke, J. L. (1983). *Phonological acquisition and change*. New York: Academic Press.

Löfqvist, A., & Gracco, V. L. (1999). Interarticulatory programming in VCV sequences: Lip and tongue movements. *Journal of the Acoustic Society of America, 105*, 1854–1876.

McCarthy, J. (2005). Optimal paradigms. In L. Downing, T. A. Hall, & R. Raffelsiefen (Eds.), *Paradigms in phonological theory* (pp. 170–210). Oxford: Oxford University Press.

Miceli, G., Capasso, R., & Caramazza, A. (2004). The relationship between morphological and phonological errors in aphasic speech: Data from a word repetition task. *Neuropsychologia, 42*, 273–287.

Miozzo, M., & Caramazza, A. (2003). When more is less: A counterintuitive effect of distractor frequency in the picture-word interference paradigm. *Journal of Experimental Psychology: General, 132*, 228–258.

Nam, H., Goldstein, L., & Saltzman, E. (2010). Self-organization of syllable structure: A coupled oscillator model. In F. Pellegrino, E. Marisco, & I. Chitoran (Eds.), *Approaches to phonological complexity*. Berlin, New York: Mouton de Gruyter.

Nozari, N., Kittredge, A. K., Dell, G. S., & Schwartz, M. F. (2010). Naming and repetition in aphasia: Steps, routes, and frequency effects. *Journal of Language and Memory, 63*, 541–559.

Ohala, D. K. (1999). The influence of sonority on children's clusters reductions. *Journal of Communication Disorders, 32*, 397–422.

O'Shaughnessy, D. (1974). Consonant durations in clusters. *IEEE Transactions on Acoustics, Speech and Signal Processing, ASSP-22*(4), 282–295.

Pater, J. (2009). Weighted constraints in generative linguistics. *Cognitive Science, 33*, 1–37.

Pater, J., & Barlow, J. A. (2003). Constrain conflict in cluster reduction. *Journal of Child Language, 30*, 487–526.

Pierrehumbert, J., & Nair, R. (1995). Word games and syllable structure. *Language and Speech, 38*, 78–114.

Prince, A., & Smolensky, P. (1993). *Optimality theory: Constraint interaction in generative grammar*. Rutgers: Technical Reports TR-2.

Rialland, A. (1994). The phonology and phonetics of extrasyllabicity in French. In P. Keating (Ed.), *The phonological structure and phonetic form: Papers in laboratory phonology III*. Cambridge: Cambridge University Press.

Romani, C., & Calabrese, A. (1998). Syllabic constraints in phonological errors of an aphasic patient. *Brain and Language, 64*, 83–121.

Romani, C., & Galluzzi, C. (2005). Effects of syllabic complexity in predicting accuracy of repetition and direction of errors in patients with articulatory and phonological difficulties. *Cognitive Neuropsychology, 22*, 817–850.

Romani, C., Galluzzi, C., Bureca, I., & Olson, A. (2011). Effects of syllable structure in aphasic errors: Implications for a new model of speech production. *Cognitive Psychology, 62*, 151–192.

Romani, C., Olson, A., Semenza, C., & Granà, A. (2002). Patterns of phonological errors as a function of a phonological versus articulatory locus of impairment. *Cortex, 38*, 541–567.

Salidis, J., & Johson, J. S. (1997). The production of minimal words: A longitudinal case study of phonological development. *Language Acquisition, 6*, 1–36.

Salztamn, E., & Byrd, D. (2000). Task-dynamics of gestural timing: Phase windows and multifrequency rhythms. *Human Movement Science, 19*, 449–526.

Selkirk, E. (1984). On the major class features and syllable theory. In M. Aranoff & R. T. Oehrle (Eds.), *Language sound structure: studies in phonology presented to Harris Halle by his teacher and students* (pp. 107–136). Cambridge, MA: MIT Press.

Selkirk, E. (1982). The syllable. In H. van der Hulst & N. Smith (Eds.), *The structure of phonological representations*. Dordrecht: Foris.

Sievers, E. (1881). *Grundzüge der Phonetik*. Leipzig: Breitkopf und Hartel.

Stenneken, P., Bastiaanse, R., Huber, W., & Jacobs, A. M. (2005). Syllable structure and sonority in language inventory and aphasic neologisms. *Brain and Language, 95*, 280–292.

Treiman, R., Gross, J., & Cwikiel-Glavin, A. (1992). The syllabification of /s/ clusters in English. *Journal of Phonetics, 20*, 383–402.

Treiman, R., & Zukowski, A. (1990). Toward an understanding of English syllabification. *Journal of Memory and Language, 29*, 66–85.

Turvey, M. (1990). Coordination. *American Psychologist, 45*, 938–953.

Vaux, B. (1998). *The phonology of Armenian*. Oxford: Clarendon Press.

Vaux, B., & Wolfe, A. (2009). The appendix. In E. Raimy & C. E. Cairms (Eds.), *Contemporary views on architecture and representations in phonology*. Cambridge, MA: MIT Press.

Vitevitch, M. S., & Luce, P. (2004). A web-based interface to calculate phonotactic probability for words and nonwords in English. *Behavior Research Methods, Instruments, & Computers, 36*, 481–487.

Wambaugh, J. L., Duffy, J. R., McNeil, M. R., Robin, D. A., & Rogers, M. A. (2006). Treatment guidelines for acquired apraxia of speech: Treatment descriptions and recommendations. *Journal of Medical Speech Language Pathology, 14*, 33–67.

Whitney, W. D. (1865). The relation of vowel and consonant. *Journal of the American Oriental Society, 8*, 357–373.

Zec, D. (1995). Sonority constraints on syllable structure. *Phonology, 12*, 85–129.