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Lexical and Post-Lexical Phonological Representations in Spoken Production

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Abstract

Theories of spoken word production generally assume a distinction between at least two types of phonological processes and representations: lexical phonological processes that recover relatively arbitrary aspects of word forms from long-term memory and post-lexical phonological processes that specify the predictable aspects of phonological representations. In this work we examine the spoken production of two brain-damaged individuals. We use their differential patterns of accuracy across the tasks of spoken naming and repetition to establish that they suffer from distinct deficits originating fairly selectively within lexical or post-lexical processes. Independent and detailed analyses of their spoken productions reveal contrasting patterns that provide clear support for a distinction between two types of phonological representations: those that lack syllabic and featural information and are sensitive to lexical factors such as lexical frequency and neighborhood density, and those that include syllabic and featural information and are sensitive to detailed properties of phonological structure such as phoneme frequency and syllabic constituency.

Lexical and Post-Lexical Phonological Representations in Spoken Production

As famously noted by de Saussure (1910), certain aspects of the spoken form of words are relatively arbitrary. Within the confines of the possible sound sequences of a language, the link between sound sequences and concepts is close to random. This can be readily seen by comparing different languages—the concept “four legged furry canine” is associated with the sequence /dɒg/ in English, with a completely different sequence (/pero/) in Spanish and yet another one in French (/ʃjɛn/). In contrast, other aspects of word form are largely predictable from the structure of the sound sequence in which they occur. For example, in English, the plural morpheme’s form is predictable based on the voicing of the preceding context (compare cat/s/ and dog/z/). The contrast between largely arbitrary and largely predictable phonological structure has led most spoken production theories to postulate a distinction between what can be referred to as *lexical* and *post-lexical* phonological processes and representations.

It is generally assumed that the lexical phonological process (or processes) recovers largely arbitrary lexical phonological representations from long-term memory. In addition to their largely idiosyncratic relationship to meaning, these representations are most often assumed to be “abstract” in that they lack at least some of the predictable aspects of phonological structure (but see Bybee, 2001; Crompton, 1982; Pierrehumbert, 2001a). A subsequent post-lexical process (or processes) elaborates these lexical representations to produce (more) fully-specified post-lexical phonological representations that contain the information necessary to engage subsequent articulatory and motor processes¹.

¹ It is important to note that here “lexical” and “post-lexical” are not meant to refer to the distinctions of the theory of Lexical Phonology (Kiparsky, 1982, et seq.). Although there may be some similarities, the distinction we wish to focus on is not based on properties of phonological rules or constraints.

Despite a fairly broad consensus on a distinction of this general type, there is a great deal of disagreement regarding the specific content of lexical and post-lexical phonological representations and processes. The differences among theoretical positions largely concern three broad issues. One important dimension along which theories differ is the level at which detailed aspects of phonological representation are specified. Some theories posit an early specification of featural and syllabic information at the lexical level, others posit a later post-lexical or even articulatory specification of this information, and yet others propose that different aspects of phonological information are represented at different levels. Another dimension of difference concerns the level(s) at which lexical variables such as grammatical category, lexical frequency and neighborhood density are relevant, with some theories assuming fairly restricted early representation of lexical variables and others positing a more widespread representation or influence of lexical factors at post-lexical and even articulatory levels. Finally, theories differ in the extent to which processing is highly interactive or modular in this part of the spoken production system. This issue is orthogonal to the previous ones in that highly interactive theories may posit the distributed representation of lexical and phonological information across levels or they may posit representational distinctions at different levels. However, even in the latter case, in a highly interactive architecture the representational distinctions may not be discernable as the high degree of interactivity is likely to have the effect of propagating information from one level to the other, effectively distributing lexical and sublexical information throughout the production system. In this paper we will focus on the first two of these three questions. Essentially, we ask: How late in the process of speaking words are lexical factors represented? How early are phonological features represented? Given that lexical phonological representations and processes precede post-lexical ones, these questions, broadly

speaking, reduce to questions regarding the specific lexical and phonological content of lexical and post-lexical representations.

The proposals that have been put forward regarding these questions have typically made use of empirical effects that purportedly originate specifically at one level (lexical or post-lexical) in order to examine the content of the level at which the effect/s originate. However, given our relatively sparse understanding of the word production process, in order to localize the empirical effects to lexical or post-lexical levels investigators have generally had to make fairly substantive assumptions regarding the content of the very representations that are under investigation. As a result, the same empirical findings are often attributed by different researchers to different representational levels depending on the representational assumptions adopted. In this investigation we analyze the spoken production of two brain-damaged individuals by first identifying the primary locus of impairment for each of them; in contrast to other work, the identification of impairment locus is based only minimal assumptions regarding the content of lexical and post-lexical representations. We then go on to examine the specific characteristics of the errors that are generated from the affected levels of processing in order to elucidate the representational content of lexical and post-lexical phonological representations.

Our findings provide clear evidence for a distinction between two types of phonological representations: those which lack syllabic or featural information and are sensitive to lexical properties (e.g., lexical frequency and neighborhood density) and those that specify syllabic and featural structure and are sensitive to detailed properties of phonological structure (e.g., phoneme frequency, syllable constituency). On this basis we conclude in favor of a system with the following characteristics: the influence of lexical factors is restricted to a lexical phonological stage; featural and syllabic information is represented relatively late—at a post-lexical level; and

interactivity is at least sufficiently restricted that clear representational distinctions can be observed. We end with a discussion of the implications of our findings for theories of spoken word production as well as for the relationship between these and linguistic theories.

Lexical, featural and syllabic representation in spoken word production

In this section we review the different theoretical positions regarding the representation of lexical and detailed phonological information at lexical and/or post-lexical levels of phonological representation. Before doing so, we first clarify certain points.

First, while we assume a broad distinction between lexical and post-lexical phonological representations and processes, we also acknowledge that there is undoubtedly far greater differentiation than this within the spoken word production system. Our goal is simply to provide a somewhat more detailed understanding of the content of representations that fall generally within these two categories. Thus, for example, in addition to the components that map between lexical and post-lexical representations, the production system may also contain *buffering* processes that maintain the activity of representations while further processes are engaged (e.g., Caramazza, Miceli, and Villa, 1986). However, given our focus on the distinction between lexical and post-lexical representations, we postpone discussion of the role of the phonological buffer(s) to the General Discussion.

Second, some of the terminology we will use has previously been used in the literature, sometimes with multiple meanings. We will use the term *lemma* to refer to an amodal/modality-independent word or morpheme representation; *lexeme* will be used to refer to a word or morpheme representation that is modality specific (there are both phonological and orthographic lexemes). The phonological content of lexemes is retrieved or “unpacked” yielding *lexical phonological representations*; these, in turn, are subjected to phonological/phonetic processes

that generate *post-lexical phonological representations*. Finally, we will use the term *articulatory representations* to refer loosely to the motor processes and representations that drive the articulators (see Figure 1).

Lexical information

There is a general consensus that lexical factors such as word frequency and neighborhood density are represented or active at level/s of word or morpheme representation such as the lemma or lexeme. However, we are specifically concerned in understanding the extent to which these factors operate specifically at phonological (lexical or post-lexical) levels of representation. To this end we briefly review current arguments regarding the loci of lexical frequency and neighborhood density effects.

Lexical frequency. It is well documented that high frequency² words are produced more quickly and with fewer errors than low frequency words. For a number of reasons frequency effects are widely assumed to originate subsequent to semantic processing, yet prior to articulation. With regard to the post-semantic locus there is, first of all, the fact that word frequency effects are not found in tasks that do not require the retrieval of word forms (e.g., picture/word confirmation; see Jescheniak & Levelt, 1994, for experimental evidence and a review). Second, prior presentation of a picture name appears to prime post-semantic processing of picture naming; this repetition priming effect interacts with word frequency (Barry, Hirsh, Johnston, & Williams, 2001; La Heij, Puerta-Melguizo, van Oostrum, & Staareveld, 1999). Third, lexical frequency effects are observed in the speech errors of neurologically-impaired and -intact individuals that arise post-semantically (see Gordon, 2002, for a review). Finally, in

² Here, we do not distinguish word frequency from correlated measures such as age of acquisition (for recent reviews, see Bonin, Barry, Méot, and Chalard, 2004; Zevin and Seidenberg, 2002).

picture-word interference tasks, the frequency-dependent influence of distractor words is modulated by phonological, not semantic, similarity and follows the time course of phonological, not semantic, distractors (Miozzo & Caramazza, 2003). Evidence for a pre-articulatory locus for frequency effects includes the finding that frequency effects on naming latency are eliminated when a response delay is added to the naming task (see Jescheniak & Levelt, 1994, for experimental evidence and a review), indicating that the effects arise prior to the peripheral production processes involved in executing the articulation.

Given these constraints on the locus of word frequency effects, most theories assume that lexical frequency is, at a minimum, associated with the post-semantic processing of word-level representations³. However, many researchers have additionally assumed that word frequency also influences phonological processing—lexical and/or post-lexical. One proposal is that lexical frequency affects the strength or efficiency of processes by which word-level representations activate lexical phonological representations (Barry et al., 1997; MacKay, 1987). Another possibility is that frequency is encoded within word-level representations themselves (e.g., resting activation levels: Dell, 1990; Stemmer, 1985; selection thresholds: Jescheniak & Levelt, 1994; time required for representations to accumulate activation: Miozzo & Caramazza, 2003; verification time for binding representations to previous representational levels: Roelofs, 1997) and that it is via mechanisms such as cascading activation that the properties of word-level representations exert an influence on subsequent lexical phonological processes (e.g., see Dell 1990 and Goldrick, accepted, for a review).

³ One area of debate among these proposals is whether homophones (e.g., him/hymn) share these modality-specific frequency-sensitive representations (Dell, 1990; Jescheniak & Levelt, 1994; Jescheniak, Meyer, & Levelt, 2003; Levelt et al., 1999) or if they are associated with two distinct lexemes (Bonin & Fayol, 2002; Caramazza et al., 2001; Caramazza, Bi, Costa, & Miozzo, 2004). The research we report on here does not specifically analyze homophonic productions and, therefore, is not pertinent to this debate.

In sum, most current theoretical proposals posit that lexical frequency exerts an influence on lexical processes and representations at both word and phonological levels. Less clear is whether or not the influence frequency extends beyond these levels to post-lexical phonological processes and representations. Some have proposed (e.g., Dell, 1986; 1990) that activation from word-level representations cascades throughout the speech production system, allowing word frequency to extend its influence to articulatory representations (e.g., Munson, in press; Munson & Solomon, 2004; Whalen, 1991; but see Levelt et al., 1999)

Neighborhood density. Many theories assume that lexical phonological processing involves activating not only the phonological representation of the target word but also the representations of words that share the target's phonological structure (lexical neighbors; e.g., Dell, 1986). This is assumed to arise via the combined influence of cascading activation and feedback from phonological representations to lexemes (see Figure 1). The target word activates its lexical phonological representation; feedback then activates non-target words (formal neighbors) that share the target's phonological structure. Finally, cascading activation activates the lexical phonological representations of these formal neighbors. As discussed by Dell and Gordon (2003), the activation of formal lexical neighbors would be expected to facilitate the retrieval of the target's phonological representation⁴.

Empirical findings consistent with these proposals indicate that word production is facilitated by the number of a word's lexical phonological neighbors (neighborhood density) (Gordon, 2002; Stemberger, 2004; Vitevitch, 1997, 2002). These effects appear to arise

⁴ Activation of neighbors can also facilitate word-level selection process (e.g., L-level selection; see Figure 1). Feedback from lexical neighbors can serve to boost the activation of the target's word-level representation prior to selection (Dell & Gordon, 2003). See Goldrick (accepted) for discussion of why the density effects discussed here plausibly arise within lexical phonological processes rather than word-level selection.

specifically within lexical phonological processes. A pre-articulatory locus is supported by the fact that neighborhood density effects are found not only in production-based speech errors (Stemberger, 2004; Vitevitch, 1997, 2002), but also when responses are simple button presses (Vitevitch, 2002). Neighborhood density effects have been more specifically attributed to the lexical phonological level because they are still found when factors influencing post-lexical phonological processing are controlled (phonotactic probability; Vitevitch, 2002).

However, as with lexical frequency, systems with cascading activation predict that neighborhood density effects arising at a lexical phonological level should also exert an influence on post-lexical (and possibly articulatory) processing as well. Two sets of results are consistent with this claim. Recent studies suggest that vowels in words in high density neighborhoods are produced more distinctly (i.e., less centralized in F1/F2 space) than the same vowels in low density words (Munson, in press; Munson & Solomon, 2004; Wright, 2004). Scarborough (2003) reports that neighborhood density influences coarticulatory processes such that vowels exhibit greater anticipatory nasalization in words in high compared to low density neighborhoods. These findings suggest an influence of lexical neighborhood density on fairly low-level phonological processes.

In sum, the evidence indicates that lexical variables such as frequency and neighborhood density are represented fairly early in spoken word production: at word levels or lexical phonological levels. The extent to which these variables are represented at post-lexical levels is less clear. Clarification of this issue is complicated by the possibility that even if lexical variables are not represented at these levels, their effects may extend to later stages if the production system includes cascading activation.

Detailed phonological information

Detailed phonological information (e.g., featural and syllabic information) must certainly be specified prior to articulation. The question is: how early is it specified? Theories largely assume that lexemes or morphemes are linked to lexical phonological representations which (at a minimum) specify the identity and linear order of a word's segments. For example, if "cat" is being produced, its lexical phonological representation will at least specify that the word is composed of three segments arranged in a particular order: 1: /k/, 2: /æ/, 3: /t/. Beyond this, however, there is considerable disagreement regarding the specific content of either lexical or post-lexical phonological representations.

Featural information. A number of spoken production theories assume that there is no featural information at the level of lexical phonological representations (Butterworth, 1992; Dell, 1986, 1988; Garrett, 1980, 1984; Lecours & Lhermitte, 1969; Levelt, Roelofs, & Meyer, 1999; MacKay, 1987; Roelofs, 1997; Shattuck-Hufnagel, 1987, 1992; Stemberger, 1985), while others assume that all featural information is specified (Wheeler & Touretzky, 1997). Between these two extremes, there are those that claim that only non-redundant features are specified (Béland, Caplan, & Nespoulous, 1990; Caplan, 1987; Kohn & Smith, 1994; Levelt, 1989; Stemberger, 1991a, b). For example, since all nasals in English are voiced, the representation of nasal segments at the lexical phonological level would not specify their voicing. Other non-redundant (or contrastive) features would be specified. As an example of the latter, since in English nasals contrast in terms of place (velar /ŋ/, coronal /n/, labial /m/) the lexical phonological representations of these segments would include place specifications.

Most theories of spoken production do assume that featural information is completely specified by the post-lexical level. As a consequence, those theories that lack featural

specification at the lexical phonological level must posit some process(es) that generates featural structure. However, at least one set of proposals that assumes that no featural information is accessed prior to articulatory representations (Levelt et al., 1999; Roelofs, 1997). These proposals assume that fully syllabified segmental representations are used to access pre-compiled articulatory representations of syllables (“gestural scores;” see also Browman & Goldstein, 1989). According to this view, features are not represented at any pre-articulatory phonological level.

Syllabic information. Some theories assume there is no representation of stress or syllable structure at the lexical phonological level (Béland et al., 1990; Wheeler & Touretzky, 1997). Others assume that a minimal amount of prosodic information (e.g., CV structure, number of syllables, position of stress) is present at the lexical level, but that it is not linked to segmental and/or featural information (Butterworth, 1992; Dell, 1986, 1988; Garrett, 1980, 1984; Levelt, 1989, Levelt et al., 1999; MacKay, 1987, Roelofs, 1997; Shattuck-Hufnagel, 1987, 1992; Stemberger, 1985). Yet others assume that prosodic and segmental information, as well as the link between the two, are specified in lexical phonological representations (Kohn & Smith, 1994).

All current proposals do assume that syllabic and segmental information are specified and linked within post-lexical phonological representations. For theories assuming that syllabic information is absent from lexical representations, this information must be generated on the basis of segmental and/or featural information (via rules as in Béland et al., 1990, or via constraint satisfaction as in Wheeler & Touretzky, 1997). Theories positing that syllabic information is present in lexical phonological representations but unlinked to segmental

information require processes that link the two types of information (for proposed mechanisms, see Dell, 1986; Levelt et al., 1999).

As indicated earlier, the mapping from lexical to post-lexical phonological representations may involve multiple intermediate processes and representations. For example, depending on the theory, there may be at least one intermediate representation where particular components of syllabic and/or featural structure are generated (e.g., Béland et al., 1990) or where syllabic and segmental information are linked prior to feature specification (e.g., Dell, 1986, 1988; Garrett, 1980, 1984; Shattuck-Hufnagel, 1987, 1992).

Summary

Most theories propose that spoken production processes distinguish between (relatively) abstract lexical phonological representations and more fully specified post-lexical ones. Lexical factors are typically assumed to be represented or to exert an influence on lexical phonological representations, while their influence beyond that level is in dispute. With regard to phonological information, depending on the particular theory lexical representations may lack some or all aspects of featural and/or syllabic information. Furthermore, while it is generally assumed that this information is fully specified at the post-lexical phonological level, there are certain theories that posit that features are specified only at the articulatory level.

Finally, we note that distinctions among phonological representational types are also found in many connectionist approaches to phonological processing. Some connectionist work explicitly assumes that phonological representations are stored in a relatively abstract form and are then elaborated prior to articulatory processing (e.g., Dell, Juliano, & Govindjee, 1993; Joanisse, 1999). Others, even though they make no such explicit assumptions (Nadeau, 2001; Plaut & Kello, 1999) do assume that multiple representations are required to mediate the

mapping from meaning to sound in both perception and production. Given this assumption, it is likely that such networks will develop distinctions between relative abstract and more fully specified phonological representations.

Paradigms used to elucidate the content of lexical and post-lexical representations

Given the degree of controversy regarding the representation of lexical and phonological information at the various levels of phonological representation and processing, it is worth briefly reviewing the various methods and paradigms that have been used to investigate these questions. The relevant evidence has largely come from studies of priming, spontaneous speech errors, and dissociations following neurological injury. As we indicated earlier, to localize the relevant empirical effects to certain levels of representation and processing these studies have typically relied heavily on representational assumptions regarding the very representations that are under investigation. As a result the available evidence severely under-constrains existing theories. We review some of the results that have been reported and briefly discuss some of the interpretative difficulties. These difficulties help motivate the approach we have taken in this paper.

Evidence from priming

Several studies indicate that while a phonological segment is susceptible to repetition or “priming” effects, these effects do not extend to highly similar segments (e.g., priming /t/ does not prime /d/). Roelofs (1999) used a form-preparation paradigm, where Dutch participants named blocks of pictures. If all the names of pictures in a block shared the same initial segment (e.g., book, bear), participants named the pictures more quickly than when pictures in a block had highly dissimilar initial segments (e.g., file, kite) . However, no form-overlap advantage was found when the pictures in a block had initial segments that were similar in their featural content

(e.g., book, pear), suggesting that priming was limited to identical segments⁵. Additional evidence suggest a similar priming effect in speech errors. Several studies of spontaneous (e.g., MacKay, 1970; Nootboom, 1969) and experimentally induced (Dell, 1984) speech errors have shown that when a segment is repeated, there is an increased likelihood of errors on nearby phonological material. For example, initial consonant errors (e.g., “time life” -> “lime tife”) are more likely to occur in a sequences like “time life,” where the vowel /ai/ is repeated, compared to sequences like “team laugh”, where there are two different vowels (/i/ and /ae/). Stemberger (1990) found that (in a spontaneous error corpus) that while repetition of an identical segment increased error rates above chance, repetition of highly similar segments did not.

These priming results support the notion that features are absent at some level of phonological representation. The question is: Which level? As indicated above, Roelofs (1997; see also Levelt et al., 1999) assumes that features are absent at both the lexical and post-lexical levels. As a consequence Roelofs can attribute the absence of features to either level. It is on the basis of additional theory internal considerations⁶ that Roelofs attributes the effect to the post-lexical level. In contrast, Stemberger (1990) assumes features are absent only at the lexical phonological level; and, therefore, he (not surprisingly) concludes that this type of effect must

⁵ Damian & Bowers (2003) demonstrated that the form-overlap advantage can be disrupted for reading aloud by pure orthographic differences between items (e.g., camel, kidney showed no advantage). This raises the possibility that Roelofs’ (1999) results do not reflect the absence of featural representation but disruption from competing orthographic representations. However, a recent study argues against this potential confound. Roelofs (in press) showed that no such orthographic disruptions are not found in object naming; as discussed above, Roelofs (1999) found no evidence of a featural similarity effect in this same task.

⁶ Previous studies (e.g., Roelofs & Meyer, 1998) have shown that the form-preparation paradigm is sensitive to prosodic structure (i.e., the syllable position of the primed segments). Within the framework assumed by Roelofs (Roelofs, 1997; Levelt et al., 1999), effects of prosodic structure are assumed to arise at the post-lexical level.

arise at the lexical level of representation. Without independent evidence regarding the effect locus, it is difficult to adjudicate between these contradictory claims.

Similar difficulties of interpretation arise with respect to the representation of prosodic information. There are a number of results indicating that phonological forms can prime one another solely on the basis of shared syllabic structure—with no segmental overlap. For example, Sevald, Dell, & Cole (1995) examined repetition speed for nonsense word pairs with no segmental overlap. Pairs with overlapping syllable structure (e.g., KARD PILT.NY) were repeated more quickly than those with differing structures (e.g., KARD PIL.TRY; for related results, see Costa & Sebastian-Gallés, 1998; Ferrand, Segui, & Humphreys, 1997; Ferrand & Segui, 1998, experiment 2; Ferrand, Segui, & Grainger, 1996; Meijer, 1996; Romani, 1992; but see Schiller, 1998, 2000; Roelofs & Meyer, 1998). These findings indicate that at some level of representation, syllabic information is represented independently of segmental information. Although current theories only posit this independence at the level of lexical phonological representations, it is logically possible that it could also occur at the post-lexical level (with prosodic and segmental information being linked only at the articulatory level).

Evidence from speech errors

Studies in a number of languages have reported that when segments shift in spontaneous speech errors, they surface with the featural specification appropriate to the “new” environment (e.g., Arabic: Abd-El-Jawad & Abu-Salim, 1987; English: Fromkin, 1971; Turkish: Wells-Jensen, 1999). Thus, when inflectional morphemes shift, the featural content is almost always appropriate to the phonological context (for exceptional situations, see Berg, 1987). For example, in the error “what that add/z/ up to” → “what that add up/s/ to” the inflectional morpheme /-s/ surfaces as [–voice] (the feature value appropriate to the context it surfaces in),

not [+voice] (the feature value appropriate to the target context; Garrett, 1984). Such “accommodation” is also found when single segments shift morpheme internally. For example, in “/k^h/orpus” → “/k^h/or/k/us,” the repeated /k/ surfaces with aspiration specification appropriate to its new prosodic environment (Stemberger, 1983).

To account for this type of result, researchers who assume that features are absent at the lexical level but specified at the post-lexical level (e.g., Dell, 1986; Garrett, 1984) posit that the same processes that generate the contextually correct allophones for non-errorful speech will also produce contextually correct allophones when an error arises at the lexical level. Alternatively, researchers assuming that features are absent at both lexical and post-lexical phonological levels (e.g., Roelofs, 1997) account for this by arguing that segmental post-lexical representations, unspecified for features, are used to generate *articulatory* representations that specify features. In other words, accommodation takes place during articulatory specification (see, e.g., Browman & Goldstein, 1992, for an articulatory-based proposal concerning the allophonic variation of aspiration in English). Once again, the challenge is to find independent reasons to prefer one set of assumptions over the other.

Evidence from acquired deficits

Extensive research has shown that brain damage can cause specific functional deficits which may be largely restricted to one stage of processing. If lexical phonological representations are distinct from post-lexical representations, we would expect that selective impairment at either representational level would lead to contrasting patterns of spoken production performance. However, in this area we also find contradictory interpretations of the evidence.

For example, Béland et al. (1990) assume that lexical phonological representations contain no specification of prosodic structure. They therefore attribute the errors sensitive to syllabic structure produced by a group of aphasic individuals to a deficit at the post-lexical level (and/or intermediate representations between lexical and post-lexical levels). In contrast, Kohn & Smith (1994) assume that syllabic information is specified at both levels. They therefore attribute the effects of syllabic complexity to both lexical and post-lexical levels. Thus, we see in cognitive neuropsychological work the same types of issues regarding the localization of effects of interest that we saw observed in priming and speech error paradigms.

Summary

Across a range of empirical paradigms, interpretative difficulties have stymied attempts to resolve theoretical debates concerning the nature of phonological representations. One way to address this problem would be to directly compare theoretical proposals by identifying their different predictions and seeking empirical evidence that would adjudicate among them. For a number of reasons, however, this has proven to be quite difficult. Another possibility, which we adopt in the work we report on here, is to make minimal representational assumptions and find an independent means of identifying the representational level or processing stage at which the relevant effects arise.

Identifying the functional locus of impairment

The representational distinctions between lexical and post-lexical processes (whatever they may be) presumably reflect the fact that the two levels play different functional roles in spoken word production. In that case, we might expect these processes to make different contributions to different spoken language tasks. If so, the patterns of performance on different tasks in a damaged system may serve to reveal the locus of a particular effect or deficit.

Specifically, we will argue that the tasks of repetition and object (or picture) naming can be used in this way.

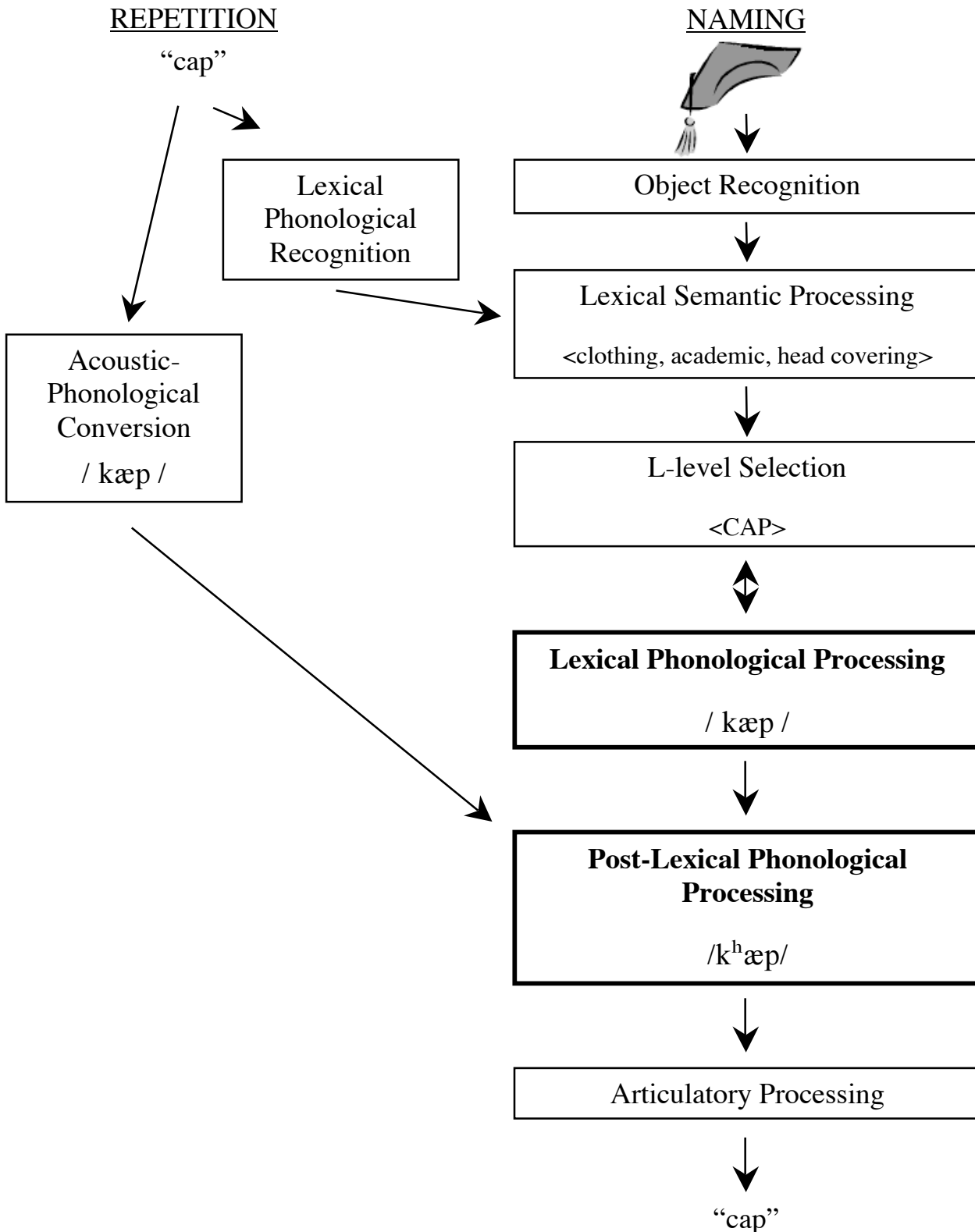


Figure 1. Functional framework (see text for details). Boxes depict processes (an example of the representation computed by a particular process are depicted below the process name). Information flow between processes is depicted by arrows. Note: the bidirectional arrow between L-level selection and lexical phonological processing is present to indicate feedback from the latter to the former (see Rapp & Goldrick (2000) for discussion).

We assume the fairly traditional functional framework for naming and repetition schematized in Figure 1. In object naming, visual input (e.g., a graduation cap) is processed by a variety of visual perceptual processes (subsumed here under “object recognition”) that activate the semantic representation of the lexical concept appropriate to the picture. Next, a word-level representation appropriate to the concept is selected (e.g., the node <CAP>). Following Rapp & Goldrick (2000), we remain neutral as to whether this representation is modality-independent (e.g., a lemma) or modality-dependent (e.g., a lexeme); hence, we use the term ‘L-level’ to refer to this representational type. On the basis of the L-level representation, a lexical phonological representation is retrieved from long-term memory (e.g., /k æ p/). This lexical phonological process corresponds to what is referred to as the phonological lexicon in most theories of spoken production. For illustrative purposes, Figure 1 depicts a lexical representation that does not specify redundant features (i.e., the initial /k/ in “cap” lacks aspiration). However, the content of phonological representations is not a crucial assumption. Critically, we simply assume that whatever their content, these representations serve as input to processes which generate more fully-specified post-lexical representations (e.g., /k^h æ p/). Post-lexical representations are then used to guide articulatory processes which, in turn, generate articulatory plans that are executed by motor systems.

In the proposed architecture, object naming requires various lexically-based processes (L-level selection, lexical phonological processing) to yield a phonological representation. Repetition can also take place via these processes (for discussion of the involvement of lexical processes in repetition, see Glosser, Kohn, Friedman, Sands, & Grugan, 1997; Martin, 1996). However, we assume that for repetition auditory input can also be processed by non-lexical acoustic-phonological conversion processes to yield a phonological representation. This

conversion system is non-lexical in the sense that it can map acoustic input to phonological output regardless of the lexical status—word or nonword—of the stimulus (e.g., either “blanch” or “blinch”). Importantly, we assume that the phonological output of this conversion process is the same as that of the lexical phonological processes, such that both types of output must be processed by post-lexical processes prior to production. Crucial for our purposes, these assumptions entail that while repetition does not require lexical phonological processes, it does require post-lexical ones; in contrast, naming requires both lexical and post-lexical processes.

Previous work supports this proposed differential recruitment of lexical and post-lexical processes by repetition and naming tasks. A number of individuals have been able to perform repetition tasks in spite of difficulty in a variety of lexically-based tasks (e.g., comprehension, object naming)—a pattern consistent with spared non-lexical conversion processes and damaged lexical processes. In addition, there are individuals with complementary deficits to non-lexical conversion processes who exhibit selective deficits in the repetition of nonwords (McCarthy & Warrington, 1984; see Hillis, 2001, for a review). Also relevant is the report by Hanley, Kay, & Edwards (2002) of two individuals with spoken production deficits (i.e., intact comprehension and articulation) who have comparable difficulty in picture naming but show different levels of performance in repetition. If the only means of accessing phonological information were lexical, the two individuals should have identical repetition performance. The pattern can be accounted for, however, by assuming non-lexical conversion processes differentially damaged in the two individuals (see also Hanley, Dell, Kay & Baron (2004) for computational support for this distinction).

In sum, this framework yields the prediction that two distinct patterns will emerge following selective deficits to lexical versus post-lexical processes. First, selective impairment

of lexical phonological processing will impair naming but not repetition. Second, since both naming and repetition require post-lexical processes, damage to these processes should result in comparable impairment in naming and repetition. On this basis, we can first use *accuracy in naming and repetition tasks* to identify the lexical versus post-lexical deficit locus for a given individual. If we can identify fairly selective deficits to these representational levels, we can then go on to address questions regarding the content of these representational levels by examining *error patterns and the effects of certain variables* on spoken production. For example, we can ask: Do the errors of an individual with a lexical but not a post-lexical impairment (or vice versa) show sensitivity to prosodic structure (e.g., the syllabic position of segments), phoneme frequency, lexical neighborhood density, etc.?

We describe two individuals with spoken production deficits whose differential patterns of accuracy in naming and repetition indicate fairly selective deficits to lexical versus post-lexical phonological processes. After establishing the loci of their impairments we carry out a detailed examination of the factors that influence a) performance accuracy and b) the nature of their errors. In this way our findings will contribute to our understanding of the content of lexical and post-lexical representations and processes.

Localization of Deficits

Case histories

CSS was a 62 year-old right handed man with three years of university education who was employed as a jet-testing engineer prior to suffering left parietal infarct as well as a lacunar infarct in the right basal ganglia. He also had an asymptomatic and stable left frontal lobe meningioma. CSS's spontaneous speech was marked by frequent hesitations and word-finding difficulties, as well as by semantic, morphological and phonological errors.

BON was a 62 year-old right handed woman who suffered a left hemisphere stroke affecting superior posterior frontal regions and the parietal lobe laterally and superiorly. Her spontaneous speech was halting and marked by phonological errors.

Localization of deficits to pre-articulatory, post-semantic processes

CSS's score at the 42nd percentile on the Peabody Picture Vocabulary Test indicated intact single word auditory comprehension. Consistent with this, he made no errors in several other auditory comprehension tasks: an auditory word/picture confirmation task (N = 774), the auditory comprehension subtest of the Boston Diagnostic Aphasia Exam, and a synonym-matching test with abstract and concrete nouns.

Results of various tasks indicate that BON's comprehension was also intact. Her auditory word discrimination was 97% accurate (N = 30), and her auditory lexical decision was 99% correct (N = 130). Barring 3 errors on one visual word/picture confirmation task (N = 20), she made no other errors in word comprehension. That is, she made no errors in a visual word/picture matching task from the Word-Visual, Word-Auditory, and Word-Semantic subtests of the Reading Comprehension Battery for Aphasia (N = 30; LaPointe & Horner, 1979), and no errors in an auditory word/picture confirmation task (N = 20). Furthermore, she was 100% correct on a picture/sentence matching task with reversible sentences (N = 16).

In addition to their intact auditory input processing and comprehension neither CSS nor BON showed any peripheral difficulties in spoken production. That is, their articulation of words was normal with neither of them suffering from dysarthria.

Their intact comprehension and articulation abilities indicate that CSS and BON's spoken production difficulties originate within post-semantic yet pre-articulatory processes. In the framework depicted in Figure 1, these correspond to lexical or post-lexical phonological

processes. Accuracy in naming and repetition were used to more precisely identify the deficit loci. As we indicated above, a deficit to lexical phonological processes predicts impaired naming in the face of intact repetition, while a deficit to post-lexical phonological processes predicts that naming and repetition should be comparably affected.

Naming and repetition. CSS was administered a set of 423 line drawings (consisting of 1976 phonemes) for spoken naming and was also asked (on another occasion) to repeat the names of these pictures aloud. His picture naming was clearly impaired (93.1% segments⁷ correct), while his repetition performance was relatively intact (98.6% correct). Consistent with a deficit to lexical phonological processing, his performance on picture naming was significantly worse than repetition ($\chi^2(1, N = 3962) = 72.83, p < .0001$; all statistical tests are corrected for continuity).

BON was administered a set of 165 line drawings (consisting of 598 phonemes) for naming and was also tested on her ability repeat the names of these pictures aloud. Her picture naming was clearly impaired (95.3% segments correct) as was her repetition (96.0% correct). Consistent with a deficit to post-lexical phonological processing, accuracy levels on these two tasks were not significantly different ($\chi^2(1, N = 1196) = 0.671, p > .181$).

CSS and BON exhibited a statistically significant interaction between their patterns of accuracy on naming and repetition (binomial test of difference in proportions⁸, $Z = 3.59, p < .001$), a pattern which allows us to localize CSS's deficit to lexical phonological processing and

⁷ Because we are examining the production system at the level of phonological processes, the unit of analysis used here is the phoneme. However, we have also carried out many of the analyses using words as the unit of analysis; these reveal essentially the same results.

⁸ Specifically, we compared across participants the size of the difference in accuracy between naming and repetition (e.g., asking if the 5.5% difference in accuracy for CSS is significantly different than the 0.7% difference for BON). See the section on statistical methods below for further discussion.

BON's deficit to post-lexical phonological processing. Note that this classification was made entirely and only on the basis of their accuracy on these tasks; the characteristics of their errors were not considered. Nonetheless, there were certain differences in their error distributions. Although form-based (phonological) errors (e.g., word errors: mitten → muffin; nonword errors: trumpet → /tʃɪrpet/) were the most prevalent error type for both individuals, and while virtually all of BON's errors in both naming and repetition were phonological⁹, CSS additionally produced a large number of semantic errors (e.g., owl → fox; 22% of his 55 errors), and compound word substitutions (snowman → snowhouse; 11% of his errors). These differences in error types provide additional confirmation of the contrasting deficits in these two individuals¹⁰.

Having identified the representational levels that are impaired in each individual, we proceed to a detailed examination of their performance in order to examine the nature of lexical

⁹ BON did produce one semantic error in picture naming, ant → bee (although this may be due to the high confusability of line drawings of insects). In addition, she produced a few inflectional morphological errors (e.g., sock → socks) but produced no phonologically distant morpheme substitution errors comparable to those produced by CSS (i.e., she produced no errors like snowman → snowhouse).

¹⁰ Although their reading performance was not extensively studied, the available data are also consistent with contrasting deficits. CSS was administered the same set of 423 words for reading. His accuracy (96.5% segments correct) was significantly lower than in repetition ($\chi^2(1, N = 3952) = 17.6, p < .001$) but significantly higher than naming ($\chi^2(1, N = 3952) = 21.6, p < .001$). This is expected, as reading aloud is intermediate between naming and repetition in terms of its reliance on lexical processes. It can partially be performed using non-lexical (graphemic-phonological) conversion procedures, but also requires use of lexical/semantic processes (see Rapp, Folk, & Tainturier, 2001, for a review). Furthermore, consistent with a deficit to lexical processes, CSS had particular difficulty with reading exception words (which are particularly reliant on lexical processes). On a separate list (with words matched for lexical frequency and letter length), his accuracy on exception words (85%; $N = 99$) was significantly lower than his regular word accuracy (97%; $N = 199$; $\chi^2(1, N = 298) = 14.9, p < .001$).

BON's accuracy data was also consistent with her hypothesized deficit. She was administered a subset (135 words) of the 165 words provided for naming and repetition. On this subset, her reading accuracy (95% segments correct; $N = 453$) was not significantly different from her naming (95% correct) or her repetition (96% correct; $\chi^2s < 1$). Since post-lexical processing is common to all three tasks, they are comparably affected by her deficit.

and post-lexical representations respectively. To this end, we will carry out two types of analyses: accuracy analyses that consider the factors that affect performance accuracy and error analyses that evaluate the factors that determine the specific characteristics of the errors.

Characterizing lexical and post-lexical representations/processes

Stimuli¹¹. Given that lexical phonological processing is required for picture naming but not repetition, for the upcoming analyses for CSS we consider only his picture naming performance on a larger set of picture stimuli (N = 2386 items). For BON, we consider data from both repetition and naming given that post-lexical processes are required for both tasks (N = 555). For BON, although we will present the results of analyses that combine data from the two tasks we note that data from the two tasks were also analyzed separately and in no case was the pattern of results different from the combined analysis, nor were there any statistically significant differences between the two tasks (results from the analyses are available from the authors upon request).

As noted above, CSS produced certain types of errors that were not produced by BON. He produced semantic errors (e.g., shirt → skirt) as well as errors in which one constituent of a compound was replaced with another morpheme (e.g., butterfly → butterflower). Including these errors in subsequent analyses could potentially skew the results in one of two ways. First, their inclusion might artificially inflate phonological differences between CSS and BON's error patterns, as semantic and compound constituent substitution errors are more likely to be phonologically distant from the target than non-semantically-related (typically form-related) word errors. Second, there is a possibility that these errors result from an additional deficit to L-

¹¹ Note that the set of items in each analysis below were constructed post-hoc from this overall set. This may increase the chance of Type II errors, as the same item may appear in multiple analyses (and alpha values are uncorrected).

level selection¹². Given these issues, we eliminated from subsequent analyses all compound word targets as well as all items which resulted in semantic errors (for further discussion of the properties of CSS's semantic errors, see Rapp & Goldrick, 2000; for compounds, see Badecker, 2001)¹³. This left a total of 1996 words in CSS' data set.

Scoring. In the analyses below, the number of target segments and syllables was determined based on transcriptions of the target word. For accuracy analyses, a target segment was counted as an error if it did not appear in the same prosodic position of its target syllable (i.e., all errors were considered position-specific substitutions or deletions). Intrusions (not included in the segment accuracy counts) were also scored in a position-specific manner. The production of any segment that did not appear in the same prosodic position in the target syllable was considered an intrusion.

Statistical methods. To examine the effect of each factor on a single individual's performance, we relied on the commonly-used chi-square test of association. After calculating within-participant chi-squares, we used the binomial test for difference in proportions to determine if a particular factor exerted a differential influence on each participant (i.e., to test for interactions). Note that both tests examine the fit between expected and observed 2-way distributions; for such distributions, the two tests are largely equivalent (Gravetter & Wallnau, 1991). The advantage of the binomial is that it allows us to test differences of differences—or

¹² In Rapp & Goldrick (2000) computer simulation analyses ruled out a unitary L-level selection deficit because damage restricted to this level could not reproduce his pattern of errors. On this basis we argued that CSS suffered either from a deficit to phonological encoding alone or from deficits to both phonological encoding and L-level selection.

¹³ Note that exclusion of these errors does not alter the localization of CSS's deficit. Excluding semantic and morphological errors, his accuracy in naming (96.3% of 1869 segments correct) was still significantly worse than in repetition (99.1% of 1942 segments correct; $\chi^2(1, N = 3811) = 33.0, p < .001$).

interactions. For example, we can evaluate if the differences in accuracy for high and low frequency phonemes are significantly different for CSS (0.1%) and BON's (4.3%).

One concern with certain of the analyses we will report is that they involve a relatively small number of items for BON. However, despite legitimate concerns about power, the overall differences in the patterns exhibited by the two individuals cannot be attributed to lack of power. As we will show, across a series of analyses CSS' performance shows no sensitivity to a number of phonological factors despite a large N while BON shows large effects of these variables despite a small N; furthermore interaction tests show significant differences between BON's and CSS' accuracy patterns.

Accuracy analyses: Indexing processing difficulty

To determine the characteristics of particular representations we examined the factors that affected the accuracy with which these representations are processed. We assumed that if, for example, higher frequency words are more robustly encoded at a particular level of phonological representation, then it should be harder to activate phonological representations that have a lower lexical frequency and, as a result, segments in low frequency words will be produced less accurately than segments in high frequency words.

Lexical factors

Lexical frequency of the target. From the total set of stimuli administered to each subject we compiled matched subsets of high frequency (greater than 20 per million in CELEX [Baayen, Piepenbrock, & Gulikers, 1995]) and low frequency (≤ 20) target words. Lists were controlled for length (only 3 and 4 phoneme words were used) and markedness of place of articulation (words contained no dorsal segments /k,g,ŋ/; see below for the rationale for this control).

As shown in Table 1, CSS's accuracy on segments in high frequency words (98%) was greater than on low frequency words (96.2%; $\chi^2(1, N = 1940) = 6.0, p < .02$). In contrast, BON showed no significant difference in accuracy for segments in low (95.3%) and high frequency words (95.5%) ($\chi^2(1, N = 501) < 1$). Although the individual statistical tests resulted in different outcomes, the interaction test was not significant ($Z = 0.8$).

One interpretative concern was that although high and low frequency items were restricted to a length of 3-4 phonemes, the number of 3 and 4 phoneme length target words was not equal across frequency levels. To control for a possible contribution of length, we repeated the analysis separately for words of each length. The pattern of results observed for the complete data set was found once again, although due to the reduction in the number of items the statistical tests failed to reach significance. In summary, CSS showed a consistent effect of lexical frequency on accuracy, while BON did not.

Table 1. Segment accuracy as a function of lexical frequency (deficit locus indicated in parentheses).

| | High Frequency Words | Low Frequency Words |
|----------------------------|----------------------|---------------------|
| * CSS (lexical deficit) | 98% (N = 917) | 96% (N = 1023) |
| BON (post-lexical deficit) | 96% (N = 309) | 95% (N = 192) |

Note: * = significant difference at $p < .05$.

Lexical neighborhood density. As noted in the Introduction, a number of studies have indicated that lexical phonological processing involves activating not only the phonological representation of the target word, but also the representations of words that share the word's phonological structure—its lexical neighbors. Activation of these neighbors appears to facilitate

processing such that words with many neighbors (high neighborhood density) are processed more quickly and accurately than words with few neighbors (low density) (Dell & Gordon, 2003; Gordon, 2002; Stemberger, 2004; Vitevitch, 1997, 2002).

To evaluate the role of neighborhood density we created a categorical neighborhood density measure by assuming that each target's strongly activated ("close") neighbors are those words that: share at least 70% of the target's phonemes in any position, are higher in frequency than the target, and share the target's grammatical category, first phoneme, and phoneme length (+/- 1 phoneme; see Goldrick & Rapp, 2001, for discussion of these criteria). We categorized words as high-density targets if they had four or more of these close neighbors; words with no neighbors with these characteristics were categorized as low-density targets.

High and low density stimuli were matched for phoneme length (all items had 4-6 phonemes¹⁴). In addition, given CSS's (but not BON's) sensitivity to lexical frequency, for CSS the two sets were matched for lexical frequency (all items less than 10/million; low density, average frequency= 3.9; high density= 4.2). For BON, items were matched in terms of dorsal segments (see below for effects of place of articulation) such that all words contained 1 dorsal segment.

Table 2 shows accuracy for target words in high and low density neighborhoods. CSS was significantly less accurate in producing the phonemes of words in low as compared to high density neighborhoods ($\chi^2(1, N = 1933) = 8.5, p < .005$), while BON's performance was not significantly affected by density ($\chi^2(1, N = 160) < 1$). The interaction test was marginally significant ($Z = 1.4, \text{one-tailed } p < .08$).

¹⁴ The high and low density items were slightly imbalanced for length. The same effects were revealed when the analysis was repeated, restricting it to words of length 4 (BON: high density 92.9% correct, low density 95.5% correct, $\chi^2(1, N = 72) < 1$; CSS: high density 100% correct, low density 95.2% correct, $\chi^2(1, N = 344) = 2.4, p < .14$).

Table 2. Segment accuracy as a function of neighborhood density (deficit locus indicated in parentheses).

| | High Density Words | Low Density Words |
|----------------------------|--------------------|---------------------|
| * CSS (lexical deficit) | 100% (N = 188) | 95.1% (N = 1745) |
| BON (post-lexical deficit) | 92.9% (N = 28) | 95.5% (N = 132) |

Note: * = significant difference at $p < .05$.

Lexicality and repetition. According to the functional architecture presented in Figure 1, neither individual's repetition accuracy should have been influenced by lexical status—whether the stimulus is a word or a nonword. That is, if CSS suffers only from a deficit affecting lexical phonological processing neither word nor nonword repetition should be affected. For BON, the post-lexical deficit should affect both words and nonwords comparably.

However, in contrast to these predictions, both individuals showed superior repetition performance for words compared to nonwords. Although CSS's word repetition was intact, his nonword repetition was significantly impaired (words : 98.6% segments correct, N = 1976; nonwords: 94.3% correct, N = 582; $\chi^2(1, N = 2558) = 33.1, p < .001$). BON's nonword repetition was significantly more impaired than her word repetition (words: 96% correct, N = 598; nonwords: 92% correct, N = 212; $\chi^2(1, N = 810) = 4.4, p < .04$). The interaction of lexicality and participant was not significant ($Z = 0.1, p > .90$). For both individuals, error types in nonword repetition included both word (CSS: /ʃɑrt/ → “short;” BON: /trɑn/ → “brawn”) and nonword (CSS: /spɪn/ → /spɪŋ/; BON: /klɛd/ → /glɛd/) responses. We discuss a possible account of these results in a later section.

Phonological factors

Phoneme frequency. Relative consonantal token frequency in spontaneous speech was calculated from Carterette & Jones (1974) and used to assign consonants to low and high frequency categories. Low frequency consonants were those with relative frequencies of less than 3% (i.e., those that made up fewer than 3% of the consonantal tokens in Carterette & Jones); high frequency consonants were those with relative frequencies greater than or equal to 3%.

As indicated in Table 3, BON was significantly less accurate with low than high frequency segments ($\chi^2(1, N = 1467) = 7.6, p < .01$). In contrast, CSS showed no significant difference in accuracy ($\chi^2(1, N = 6005) = 0.003, p > .9$). Furthermore, the effect of phoneme frequency was significantly stronger for BON compared to CSS ($Z = 2.5, p < .02$).

Table 3. Consonant accuracy as a function of relative consonant frequency for each individual (hypothesized deficit indicated in parentheses).

| | High Frequency Consonants | Low Frequency Consonants |
|------------------------------|------------------------------|-----------------------------|
| CSS (lexical deficit) | 98% (N = 4549) | 98% (N = 1456) |
| * BON (post-lexical deficit) | 95% (N = 1134) | 91% (N = 333) |

Note: * = significant difference at $p < .05$.

Markedness of syllable position. One indication of the complexity of a phonological structure is the distribution of the structure across the world's languages; those structures that are found in fewer languages are assumed to be more complex. Typological distributions have contributed importantly to a number of linguistic theories (e.g., Chomsky & Halle, 1968, chapter 9; Jakobson, 1941; Prince & Smolensky, 1993; Trubetzkoy, 1939; see Battistella, 1996, for a

review) and we follow these theories in referring to typologically rare structures as cross-linguistically marked and typologically common structures as cross-linguistically unmarked. In terms of processing, we might expect that, at some level of processing, marked phonological structures might be less robustly encoded and thus more difficult to process than unmarked ones.. Typological data suggest that the final portion of syllables (the coda—in English, the consonants following the vowel) is marked relative to the initial portion of syllables (the onset—in English, the consonants preceding the vowel). Specifically, these data show that languages that have syllables with codas always have syllables with onsets, while many languages that make use of onset position fail to use coda position (Bell, 1971; but see Breen & Pensalfini, 1999). To examine the influence of the markedness of syllabic structure on processing, we examined BON and CSS's accuracy on segments in these two syllable positions.

Targets and errors were syllabified as follows. Syllable onsets were maximized such that the onset consisted of all consonants that could “legally” co-occur in onset position (Kahn, 1976). For example, “apply” was syllabified /ə.plaɪ./ not /əp.laɪ./.. Intervocalic consonants (e.g., the /m/ in “lemon”) were not counted for either onset or coda positions, due to their potential ambisyllabic status (Kahn, 1976; Treiman & Danis, 1988). Table 4 reports segment accuracy as a function of a syllable position in one and two syllable words. CSS' performance showed no significant effect of syllable position ($\chi^2(1, N = 4344) = 3.6, p > .05$). In contrast, BON was significantly less accurate in coda position ($\chi^2(1, N = 1253) = 10.2, p < .001$). Furthermore, the effect of syllable position was significantly larger for BON compared to CSS ($Z = 2.5, p < .02$).

Table 4. Consonant accuracy as a function of syllable position for each individual (hypothesized deficit indicated in parentheses).

| | Onset Consonants | Coda Consonants |
|------------------------------|-------------------|-------------------|
| CSS (lexical deficit) | 98% (N = 2264) | 97% (N = 2080) |
| * BON (post-lexical deficit) | 96% (N = 654) | 91% (N = 599) |

Note: * = significant difference at $p < .05$.

It is important to note that phoneme frequency cannot account for the syllable position effect in BON's data as the percentage of low frequency phoneme targets was actually significantly higher in onset than in coda position (Onset: 25% low frequency [N = 654]; Coda: 19% [N = 599]; $\chi^2(1, N = 1253) = 5.8, p < .02$). In addition, the onset-coda asymmetry is not attributable to different concentrations of singleton consonants vs. clusters (see below) given that the percentage of singletons was comparable for onsets (68%) and codas (72%) ($\chi^2(1, N = 1253) = 1.9, p > .16$). Furthermore, the same onset superiority is found both for singletons and clusters (singletons: 96% correct in onset vs. 93% in coda; clusters: 96% correct in onset vs. 86% in coda). Thus, the effect appears to derive from the complexity of the syllable position itself, not from the properties of the segments within it.

Furthermore, the syllable position effect also does not appear to be attributable to the frequency of these prosodic positions themselves. In the CELEX database, by either type or token frequency measures, fewer words have word-initial onsets than word-final codas (token: 67% vs. 69%; type: 82% vs. 88%). BON's accuracy patterns in the opposite direction with 97% accuracy on word-initial onsets (N = 598) vs. 92% on word-final codas (N = 562; $\chi^2(1, N = 1160) = 8.7, p < .005$).

Markedness of place of articulation. Typologically, coronal consonants (those involving the tongue tip such as /t/) are unmarked relative to dorsals (those produced using the tongue body such as /k/). Furthermore, languages tend to make more distinctions among coronal consonants than dorsals, and dorsal phonemes tend to be more restricted to particular environments (e.g., onset) within particular languages (Paradis & Prunet, 1991). Again, assuming that typologically rare structures are more difficult to process, we would expect that dorsal consonants may be more error-prone than coronal consonants.

Table 5 reports BON and CSS' accuracy on coronal (/t,d/) and dorsal (/k,g/) stops. CSS' accuracy on these segments was not influenced by place of articulation ($\chi^2(1, N = 1537) = 1.5, p > .2$). This contrasts with BON, whose performance was significantly influenced by this factor ($\chi^2(1, N = 392) = 4.4, p < .04$). These effects were significantly different across these two individuals ($Z = 2.6, p < .02$), indicating that the markedness of place features influences processing difficulty at the level of post-lexical processing only.

Table 5. Consonant accuracy as a function place of articulation for each individual (hypothesized deficit indicated in parentheses).

| | Coronal Oral Stops /t,d/ | Dorsal Oral Stops /k,g/ |
|------------------------------|-----------------------------|----------------------------|
| CSS (lexical deficit) | 98% (N = 850) | 99% (N = 687) |
| * BON (post-lexical deficit) | 93% (N = 194) | 86% (N = 198) |

Note: * = significant difference at $p < .05$.

We were, however, unable to rule out the possibility that the effect of place of articulation is an artifact of phoneme frequency. That is because the sum of the relative token

frequencies of the coronal stops in English is 15%, while dorsal segments have a total frequency in English of only 7% (frequencies calculated using CELEX). We discuss the problem of contrasting markedness and frequency in the General Discussion. Note, however, that although we cannot rule out a phoneme frequency account of the place of articulation effect, we can rule out that it is due to a general effect of syllable position because the onset/coda distribution of the coronal and dorsal stops would have predicted results contrary to those we observed (38% of the 198 dorsal stops were in coda position compared to 46% of the 194 coronal stops).

Summary: Accuracy analyses

If our assumptions regarding the differential recruitment of lexical and post-lexical phonological processes by the tasks of naming and repetition are correct and BON and CSS do indeed suffer from deficits to distinct representational levels, we would expect their performance to differ along a number of dimensions that were not considered in determining their deficit loci. As shown in Table 6, the accuracy analyses confirm these predictions. CSS's naming accuracy was consistently influenced by word-level properties of targets—lexical frequency and neighborhood density—but was uninfluenced by the fine-grained aspects of their phonological structure. In contrast, BON's accuracy was consistently influenced by the frequency/complexity of phonological structure (frequency of phonemes, markedness of syllable position and place of articulation), but uninfluenced by word-level properties of target words. These contrasting patterns were confirmed by the finding of statistically significant interactions.

Table 6. Summary of segment accuracy analyses.

| Factors influencing processing difficulty (accuracy) | | CSS (lexical deficit) | BON (post-lexical deficit) |
|---|--|-----------------------------|----------------------------------|
| Lexical frequency: | | | |
| | High frequency > Low frequency | + | - |
| Neighborhood density: | | | |
| Lexical | Dense neighborhoods > Sparse neighborhoods | + | - |
| Lexicality: | | | |
| | Word repetition > Nonword Repetition | + | + |
| Phoneme frequency: | | | |
| | High frequency > low frequency | - | + |
| Syllable position: | | | |
| Phonological | Unmarked onset > Marked coda | - | + |
| Place of articulation: | | | |
| | Unmarked coronal > Marked dorsal | - | + |

Note: > = significantly higher accuracy at $p < .05$.

However, there was one dimension along which CSS and BON did not differ. Both individuals showed an influence of lexicality (a word-level variable) on repetition, with words being repeated more accurately than nonwords. This difference suggests an additional deficit in both cases. One possibility is that both individuals suffer from a mild deficit to acoustic-phonological conversion. In that case, word repetition would have an advantage over nonword repetition because while words can be processed by either the lexical or the nonlexical (acoustic-phonological conversion) routes, nonwords rely on the acoustic-phonological route alone. Another possibility is suggested by the fact that lexicality effects have also been reported in the literature for a number of individuals with deficits to the phonological output buffer, a process maintaining the activation of phonological representations during speech production (Caramazza et al., 1986; we return to these cases in the General Discussion). Distinguishing between these possibilities would require considerably further testing both with matched sets of words and nonwords and sets which would allow the manipulation of relevant variables, something which we did not do.

Setting aside (for now) the potential source of the nonword repetition results, the findings presented thus far not only indicate that the deficit loci differ in these two cases but, importantly, also provide evidence concerning the content of representations at the implicated levels of representation/processing. The lack of influence of featural and prosodic factors on CSS' performance is an indication that lexical phonological representations are phonologically abstract. In contrast, BON's sensitivity to these variables reveals that post-lexical processes manipulate phonological representations that are specified for featural and syllabic structure. In addition, the absence of lexical frequency and neighborhood density effects in BON's case but not CSS's indicates that while these lexical factors do influence phonological processing, their

influence is limited. In sum, the findings confirm those proposals that posit a relatively early and limited influence of lexical factors and the relatively late specification of detailed phonological features. Additionally, as has been already stated, what is particularly novel about this set of findings is that the evidence used to determine the deficit loci was independent of the evidence used to draw inferences regarding the characteristics of a particular representational/processing stage. The ability to independently establish the loci of the effects of interest reduces the interpretative difficulties involved in attributing the observed effects to specific levels of representation.

Analysis of error characteristics

The following analyses are based on the assumption that the factors that influence performance accuracy should also influence the types of errors that will be produced. For example, if post-lexical phonological processing is disrupted, then we might expect that the relatively inaccessible low-frequency phonemes are likely to be replaced by the higher frequency phonemes that they are in competition with. That is, not only will more weakly encoded structures be more susceptible to disruption; when disruption occurs, they will be replaced by more strongly encoded structures. On this reasoning, the likelihood of a particular error outcome can provide information regarding the representational variables that are operative at specific levels of processing.

Unlike in the previous section, the following analyses do not analyze both CSS and BON's errors for all variables of interest. Instead for CSS we consider the effect of lexical variables (lexicality and lexical frequency) on error outcomes and for BON we consider the effect of the complexity of phonological structure (phoneme frequency and markedness). We

proceeded in this manner because of the difficulty involved in simultaneously controlling lexical and phonological variables given the limited amount of data available for each individual.

It is important to note that each of the subsequent analyses requires a determination of the extent to which an error pattern would occur by chance in a system insensitive to the variable of interest. For example, to determine if a frequency bias is present, it is not enough to determine that lexical errors are typically more frequent than their targets. It is also necessary to evaluate the extent to which lexical errors would, by chance, be more frequent than their targets in a system lacking a frequency bias. In previous reports this type of analysis has not always been carried out, although Gagnon, Schwartz, Martin, Dell, & Saffran (1997) provide one example of such an analysis that involve the explicit calculation of chance probabilities.

Characteristics of lexical phonological errors

Lexicality. Although the function of lexical phonological processing is to yield phonological representations that correspond to lexical items, failures in the course of lexical phonological processing can result in the production of nonwords. This is because the representational units are phonological. For example, when attempting to activate /kæp/ a disruption in the processing of the initial phoneme may result in the production of the nonword /fæp/. If, however, (as we discussed in the Introduction) the activation of lexical phonological representations is influenced by cascading activation and feedback (Dell, 1986) then phoneme sequences corresponding to lexical neighbors (e.g., /mæp/) should be more strongly activated than nonword sequences (e.g., /fæp/). That is, if lexical phonological processing is generally sensitive to lexical encoding strength, then (all other things being equal) word errors should be more likely than nonword errors. This prediction is what is referred to as the “lexical bias effect” (Dell & Reich, 1981; Gagnon et al., 1997).

Of CSS's 151 errors that were neither semantically nor morphologically related to the target, 40% were words. To determine if this represents a true lexical bias we need to compare this rate to the chance likelihood of word outcomes. Specifically, the observed rate of word errors must be compared to the likelihood of word outcomes in a system unbiased towards word outcomes. Dell et al. (1997) calculated that the random substitution of a single phoneme would produce a word 26% of the time (note that Dell et al. assumed substitutions were phonotactically constrained, as were CSS' errors). CSS's observed rate of 40% was significantly greater than this (binomial test, $Z=3.9$, $p < .001$), indicating that his error responses were significantly biased towards word outcomes.

Lexical frequency. Given that (as we reported earlier) lexical frequency contributes to encoding strength at the lexical phonological level, we would expect that errors should be higher in frequency than their targets—an effect we will refer to as a “lexical frequency bias”. To evaluate this prediction we must first determine what would be observed by a system in which frequency is not encoded and error outcomes are not biased by lexical frequency. To do so, we relied on the assumption that lexical phonological processing involves activating not only the target word but also phonologically related words (giving rise to neighborhood density effects; see above). Since neighbors have already been activated, they are more likely to occur as errors than non-neighbors. Given this, the critical question becomes: How likely is it that (in a system in which lexical frequency is not encoded) a higher frequency neighbor will, by chance, be produced as an error?

To illustrate the calculation for a single word, consider CSS's word error “bolt” → “boat.” We found that 25 words in the CELEX database shared approximately the same percentage (within 10%) of the phonemes of “bolt” as “boat” does. This is our best estimate of

the words that are just as activate as “boat” during lexical phonological processing of “bolt.” Three of these 25 words are higher in frequency than “bolt.” If lexical phonological processes were sensitive only to phonological overlap (and were not biased by lexical frequency), word errors for “bolt” should result in higher frequency words 12% of the time. Similar calculations were performed for each of CSS’ targets that led to word substitutions. Collapsing across all of the targets, the analysis indicates that higher frequency words would be produced by chance 30% of the time (standard error: 5%).

In contrast, 56% of CSS’s 61 errors were higher in frequency than their targets. This is significantly greater than the chance rate ($Z=5.5$, $p < .001$), indicating that errors in lexical phonological processing were indeed more likely to result in words of higher frequency than the target—a true lexical frequency bias.

Featural similarity. As we have indicated, many theories of lexical phonological processing claim that either some or all features are unspecified within lexical phonological representations. If features are not represented at this level, then segmental substitutions should not be influenced by featural similarity. To test this prediction, we considered CSS’ word errors involving initial singleton consonant substitutions (e.g., beaver→weaver; $N = 9^{15}$). One-third of these substitution involved consonants that differed by either one or two features (based on 13 consonantal features adapted from O’Grady, Dobrovolsky, & Aronoff (1997)). The question is: is 33% different than what would be predicted by chance?

¹⁵ The small number of errors in this analysis (for both CSS and BON) is due to two factors. First, for this analysis the error outcomes must be words, eliminating a substantial portion (> 60%) of the errors. Second, for positions other than the word-initial position, matching segments across words requires making substantial assumptions regarding the representation of a given position. The analysis is also restricted to singleton consonants for a similar reason.

We assumed that for CSS consonant substitutions would have their source in non-target words activated during production. We therefore used a similar method to calculate chance as in the analysis for lexical frequency bias. For each target, we found those words in CELEX that shared approximately the same percentage of phonemes with the target as the error. We then calculated the featural overlap between each initial singleton consonant in these words and the target word's initial consonant. These overlap values allowed us to determine the likelihood that a substitution of a singleton consonant in word initial position would, by chance, differ by two features or less from the target. Collapsing across all targets, the predicted rate of such substitutions was 13% (standard 10%). The observed value of 33% does not significantly differ from this chance rate ($Z = 1.4$, $p > .16$), suggesting that featural similarity does not influence CSS' consonant substitutions.

Given the small number of errors available for analysis, the failure to find a significant effect might simply stem from a lack of power. To test this, we repeated the analysis with BON's word errors involving word-final singleton consonant substitutions (e.g., pig → pick; $N = 7$). (Note: word final position was used because BON makes very few word-initial errors.) In contrast to CSS, 86% of BON's substitutions differed by one or two features. When we carried out a chance analysis based on BON's responses, we found that the observed value of 86% was significantly greater than the chance rate of 33% (standard error 16%; $Z = 2.3$, $p < .01$). Even though fewer errors were available for BON than for CSS a significant effect is found with same analysis method. This certainly increases our confidence that the absence of an effect for CSS actually indicates the absence of the influence of featural similarity on his consonants substitutions.

Length: Segmental and syllabic. As noted in the Introduction, a number of theories claim that lexical phonological representations consist of a linear string of unprosodified segments. We might therefore expect errors arising at this level to be sensitive to segmental length but not syllabic length. To test this prediction, we used an analysis similar to those described above examining words in CELEX that are similar in phonological overlap to the actual error. The full set of CSS' lexical substitutions (N=61) was used to estimate the rate at which syllabic and segmental length will be preserved by chance. We found that that, collapsing across all the targets, the chance estimate for preserving segmental length (+/- 1 phoneme) was 24% (standard error: 4.5%), significantly lower than the observed rate of 89% (N = 61 word errors; $Z = 14.2$, $p < .001$). Importantly, this tendency to preserve phoneme length did not appear to derive from preservation of syllable number. If we exclude errors on which syllable number was preserved, phoneme number was still preserved at a level numerically greater than chance (observed: 45% (N = 11); chance: 25% (standard error = 11%); $Z = 1.4$, $p < .18$). In contrast, after excluding errors on which phoneme number was preserved, syllable number was preserved at a rate *lower* than chance (observed: 14% (N = 7); chance: 28% (standard error = 16%); $Z = -.5$, $p > .5$)¹⁶.

Characteristics of post-lexical phonological errors

Phoneme frequency. The accuracy data suggest that at a post-lexical level the representations of high frequency phonemes tend to be more robustly encoded than those of low frequency phonemes. On this basis we might expect that failures in post-lexical phonological processing would be more likely to yield high frequency than low frequency phonemes—a

¹⁶ The analysis was also repeated for BON's word errors. All of her 32 word errors preserved both segmental and syllabic length; this was significantly greater than expected by chance (calculated based on neighbors in CELEX, chance preservation of segmental length: 28%, s.e. 6%; $Z = 11.4$, $p < .001$; chance preservation of syllabic length: 59%, s.e.: 8%; $Z = 5.3$, $p < .001$). This is consistent with the specification of both segmental and syllabic structure within post-lexical representations.

“phoneme frequency bias.” In order to determine if such a bias is present, we need to compare the observed rate of higher-frequency-phoneme substitutions to the rate expected by chance in an unbiased system (i.e., one in which phoneme frequency is not represented or does not influence error outcomes).

In order to calculate the chance likelihood that a consonant substitution would result in a higher frequency consonant we made two assumptions. The first was that the post-lexical system is sensitive to the constraints on the possible sound sequences of English. Many studies have shown that spontaneous speech errors rarely result in forms violating these phonotactic constraints (e.g., Stemberger, 1983). This was true of BON as well; only one of her errors violated the phonotactic constraints of English (“cheese” → /stʃiz/). We therefore considered that for each of BON’s consonant errors the most active competitor phonemes would have been those consonants that did not violate phonotactic constraints in the environment in which the error occurred. The second assumption was that errors would be constrained by featural similarity—that errors changing only a single feature (e.g., voicing as in /k/ → /g/) would be more likely than errors changing multiple target features (e.g., voicing and place as in /k/ → /d/). To incorporate this constraint into the analysis, we considered as possible competitors only the subset of the consonants that differed from the target consonant in a single feature (involving a change in one of place, manner or voicing) and which would, when substituted, result in a phonotactically legal sequence.

Using this method we identified the set of likely competitors for each BON’s consonant substitution errors in coda position ($N = 16^{17}$) and determined how many of them were of higher

¹⁷ Unlike the featural similarity analyses above, both words and nonword outcomes were included here.

frequency than the target phoneme. Combining the values across the target phonemes, we found that on average a single feature error would, by chance, result in a higher frequency, phonotactically legal consonant 58% of the time (standard error: 11%). BON actually produced a higher frequency phoneme for 88% of the errors, a rate significantly greater than chance ($Z=2.5$, $p < .02$). This suggests that post-lexical phonological processes may be “phoneme-frequency biased.” Note, however that since phoneme frequency and markedness are almost completely confounded, we cannot rule out the possibility that these results could be due to the markedness of the consonants. We return to this issue in the General Discussion.

Clusters vs. singleton consonants. The fact that the languages of the world tend to avoid clusters (Greenberg, 1978) suggests that clusters are more difficult to process than singletons and are therefore likely to be less robustly encoded than singletons. To investigate the potential influence of this factor, we compared the likelihood that clusters would be mis-produced as singleton consonants to the probability that singletons would be mis-produced as clusters.

Because we again assumed that it was unlikely that errors would violate phonotactic constraints, we excluded from the analysis all words with singleton consonant targets that do not participate in any legal clusters in the syllable position in which they were found. For example, /z/ was excluded from the onset singleton counts, as there are no legal onset clusters containing /z/ that could have been produced as errors; it was, however, included in the coda counts, as /nz/ is a legal coda cluster. (Note that this issue does not arise with regard to clusters, as all singleton constituents of clusters are phonotactically legal; e.g., for /nz/, both /n/ and /z/ are legal codas; therefore no clusters were excluded).

BON produced singleton consonants for 9% of the 203 cluster targets in her corpus. In contrast, she produced clusters for only 2% of the 815 singleton targets. This difference was

significant ($\chi^2(1, N = 1018) = 23.4$ $p < .001$), revealing that post-lexical phonological processes are biased to produce the unmarked outcome, singletons. Note, however, that we cannot rule out the possibility that these effects are due to overall singleton and cluster frequency. Using CELEX token frequencies, we find that 83% of word-initial onsets and word-final codas are single consonants, while only 15% are clusters (using type counts, 70% are singletons and 26% two segment clusters). Thus, it is unclear whether these results reflect a markedness bias or syllable constituent frequency bias.

Summary of the error analyses

The error analyses have the merit that each involved the comparison of observed rates of some event to the rate at which it would be expected to occur by chance in a system in which the feature of interest was not represented or was not active. This allows for a strong test of the hypothesis that a particular feature is indeed exerting an influence on the participant's errors and, therefore, active at a given level of representation. The results provide strong and clear confirmation of the findings of the accuracy analyses. Once again, we see that lexical phonological processes are sensitive to word-level properties (i.e., lexicality, lexical frequency). Furthermore, lexical phonological processing appears to be selectively sensitive to segmental structure. Errors arising at this level preserve segmental, not syllabic length, and are unaffected by featural similarity. Post-lexical processing, in contrast, is sensitive to the fine-grained properties of phonological structure and complexity. Errors arising at this level were biased towards frequent (unmarked) phonological structures. In sum, we find striking convergence across all the analyses that have been performed with regard to the content and nature of lexical and post-lexical phonological representations and processing.

General Discussion

On the basis of contrasting patterns of accuracy in naming and repetition tasks, we localized the spoken production deficits of two individuals—CSS and BON—to lexical and post-lexical phonological processes, respectively. In order to investigate the content of these representational levels, we then evaluated the effect of different lexical and phonological factors on production accuracy as well as on the characteristics of the spoken errors. Consistent with the claim that lexical and post-lexical representations differ in their sensitivity to lexical variables and their degree of phonological specification, we found that the performance of the two individuals was affected by a nearly complementary set of factors. Specifically, CSS's naming performance was affected only by word-level variables (lexical frequency and neighborhood density), while BON's was consistently sensitive only to phonological complexity (syllable position, place of articulation, cluster/singleton, phoneme frequency). A very important aspect of these findings is that we are able to ascribe these complementary sensitivities to different representational levels on the basis of information independent and distinct from the data used to characterize the affected representations/processes.

These findings significantly advance our understanding of the questions posed in the Introduction: How late in the process of speaking words are lexical factors represented? How early are phonological features represented? The results we have reported reveal that the influence of lexical factors is restricted to a lexical phonological stage and that featural and syllabic information is represented relatively late—at a post-lexical level. Furthermore, the fact that we are able to document such distinctive patterns of performance at all indicates that interactivity among representational levels and processes is at least sufficiently restricted that clear representational distinctions can be observed.

Related cases

There are at least three reported cases that are generally consistent with our findings regarding lexical phonological deficits. Kay & Ellis (1987) described the case of EST, whose naming and repetition accuracies were significantly different from one another, consistent with a lexical phonological deficit. Like CSS, EST produced phonological as well as some semantic errors in naming, but his repetition performance was relatively intact. Analysis of EST's errors revealed that, also like CSS, in picture naming EST produced many more errors for low versus high frequency words¹⁸. Similarly DPI (Bachoud-Lévi & Dupoux, 2003), also had higher rates of errors on naming tasks compared to repetition. Furthermore, like EST and CSS, DPI's performance was influenced by word-level variables (e.g., lexical frequency). However, unlike CSS, DPI showed no significant lexical bias effect. Finally, LKK (Law, 2004) was more impaired in naming compared to repetition. Like the previous cases, his performance was also influenced by lexical variables (e.g., a marginally significant effect of lexical frequency). Furthermore, like CSS, his performance was largely unaffected by phonological variables.

With respect to the post-lexical level, Romani & Calabrese (1998; see also Romani, Olson, Semenza, & Grana, 2002), reported the case of DB, an individual whose accuracy across tasks was consistent with a post-lexical phonological deficit. Although Romani and colleagues focused on his repetition performance, they also reported that "DB made the same types of errors in reading, spontaneous speech and picture naming (Romani et al., p. 546)." As was the case for BON, DB's errors were sensitive to phonological complexity. For example, DB was less accurate on complex syllabic structures, and his errors tended to reduce syllable structure

¹⁸ Furthermore, in reading, he was less accurate on irregular words (which require lexical processing) compared to regular words (which can be read via non-lexical conversion processes; Kay & Patterson, 1985; see also footnote 10 for regularity effects on CSS' reading performance).

complexity¹⁹. These cases provide further evidence of the differential importance of word-level variables for lexical phonological processing and phonological complexity for post-lexical processing.

Implications for lexical and post-lexical phonological representations

The content of lexical phonological representations

As discussed in the Introduction, it has been claimed that prosodic information is underspecified in some manner (either completely absent or unlinked to segmental structure) at the level of lexical phonological representation. Consistent with this, we found that CSS' performance is insensitive to syllable-position markedness and his errors fail to preserve syllabic length. Similarly, with respect to featural structure, two observations are most consistent with theories claiming that features are not represented at the lexical phonological level. First, place of articulation does not affect CSS' errors; second, his initial consonant substitutions were insensitive to featural similarity. If, at this level, segments were fully specified with respect to features, we would have expected some influence of features on errors. Furthermore, the data are even problematic for the view that only contrastive features are specified. In English, place of articulation is a contrastive feature for oral and nasal stops (e.g., /t/ and /k/ differ solely in terms of place specification); thus, even theories claiming specification only of contrastive features would predict an effect of place of articulation. The fact that CSS performed similarly with dorsal and coronal segments is best accounted for within a framework in which lexical phonological representations lack featural specification.

¹⁹ Romani & Calabrese (1998) also report that DB's accuracy was affected by lexical frequency; however, it is unclear if the high and low frequency words are matched for phonological complexity. To address this concern, recall that for BON we compared high and low frequency words matched for length and which lacked (marked) dorsal segments.

If lexical phonological representations lack featural and prosodic structure, what information do they specify? As reviewed in the introduction, a number of theories have posited that these representations specify only the linear order of abstract segments. Three observations from this investigation are consistent with such a claim. First, as we have discussed, there is no evidence of featural specification at this level. Second, many of CSS' errors involved single phoneme substitutions (e.g., "beaver" → "weaver"). Third, as shown above, CSS's errors preserve the phoneme length of the target. This pattern is readily understood within a segment-based account, but is inconsistent with a representational scheme using larger units such as syllables.

In summary, the absence of featural and syllabic effects, combined with significant effects of segmental structure, all point to a lexical phonological representation consisting of a string of abstract segments representing the identity of constituent phonemes. Note that this conclusion also allows us to readily understand the priming effects reviewed in the Introduction. If we attribute the priming effects reported by Roelofs (1999) and the repeated-phoneme effects reported by Stemberger (1990) to the lexical phonological level, then given that featural information is unspecified at this level it is understandable that effects are limited to identical segments.

The content of post-lexical phonological representations

Our finding that BON's performance is clearly influenced by prosodic and featural factors provides support for the widespread claim that syllabic and featural information is present and linked at the level of post-lexical representation.

However, with regard to featural information, it should be noted that segmental and featural markedness are highly confounded—frequent phonemes tend to consist of unmarked

features. For example the fact that dorsal phonemes are less frequent than coronal phonemes, makes it unclear whether it is featural markedness or segmental frequency that is responsible for BON's lower accuracy on dorsal segments. Thus, a system lacking features at the post-lexical level could account for this aspect of BON's data if it included frequency sensitive segmental representations. However, our finding that BON's consonant substitution errors (unlike CSS's) are more likely than would be expected by chance to involve segments that differ by one or two features from the target segments cannot be accounted for without positing featural specification. Thus, the preponderance of the evidence favors the more parsimonious view that featural information is specified at the post-lexical level.

Furthermore, the claim of featural specification at the post-lexical level is consistent with a number of observations from speech errors, including the findings that: 1) featural similarity influences the likelihood of two segments interacting in spontaneous speech errors (e.g., Arabic: Abd-El-Jawad & Abu-Salim, 1987; Dutch: Nootboom, 1969; English: Frisch, 1997; German: MacKay, 1970; Spanish: García-Albea, del Viso, & Igoa, 1989; Swedish: Söderpalm, 1979); 2) speech errors involving single features can be experimentally induced (Guest, 2001), and 3) the spoken production system can encode phonotactic constraints at the level of features (Goldrick, 2004).

Finally, the assumption that features are specified at the post-lexical level but not at the lexical not only provides a natural explanation for CSS and BON's contrasting patterns, but it also provides a means to reconcile the absence of a featural similarity effect in the priming studies of Roelofs (1999) and Stemberger (1990) with the presence of featural similarity effects in the studies of spontaneous speech errors (e.g., Frisch, 1997; see above). By attributing

priming effects to the lexical level and assuming that at least some spontaneous speech errors arise at the post-lexical level we can understand the differential influence of featural similarity.

Lexical influences on phonological processing

As discussed in the Introduction, many studies have shown that lexical frequency exerts an influence within the broad area of post-semantic, pre-articulatory spoken production processes. CSS' higher accuracy on high frequency words as well as his tendency to produce higher frequency words in errors suggests that these effects can occur specifically within lexical phonological processing. This is generally consistent with the two classes of proposals that have been put forward to account for lexical frequency effects. Theories that have attributed these effects to frequency-dependent differences in the strength of connections between word-level representations and lexical phonological representations transparently account for these results by directly attribute lexical frequency effects to lexical phonological processes. Proposals that instead attribute lexical frequency effects to word-level representations specifically can also account for these results by including a mechanism (such as cascading activation) that allows word-level properties to exert an influence on subsequent processing stages.

Theories which posit cascading activation and feedback between word-level and lexical phonological processes predict a facilitatory effect of neighborhood density on production (see Dell & Gordon, 2003). This effect has been reported in previous studies and was reported here in the analysis of CSS' performance. One point of contrast is that other studies have defined a word's neighborhood as consisting of all words created by substitution, deletion, or addition of a single phoneme from the target. In contrast, our definition included grammatical category, phoneme length, lexical frequency, and overlap in initial position (Goldrick & Rapp, 2001).

Characterizing phonological complexity

One issue for theories of post-lexical processing is how best to characterize the basis for phonological processing difficulty. The two most broadly invoked accounts are language-specific frequency and cross-linguistic markedness. Since both factors index some aspect of linguistic complexity, it is not surprising that these two frequency measures are, in general, very highly correlated (Berg, 1998; Frisch, 1996; Greenberg, 1966; Trubetzkoy, 1939/1969; Zipf, 1935), making it difficult to determine their specific and independent contributions to processing difficulty. Importantly, however, these two measures are not always perfectly correlated. BON showed a strong sensitivity to the prosodic position of consonants; she was much more likely to produce an error in coda as compared to onset position. As we indicated, however, this pattern is not attributable to the frequency in English of segments in these positions (low frequency segments are in fact more likely to be found in onset), nor is attributable to the frequency of these prosodic positions (word-initial onsets are less frequent than word-final codas, yet BON is more accurate on segments in word-initial onsets). This suggests that the processing difficulty of prosodic positions is based on cross-linguistic markedness, not within-language frequency. Certainly, further work to identify the respective contributions of these factors would be of considerable value.

Linguistic theory and the processes of spoken word production

Evidence of effects of cross-linguistic markedness in spoken production suggests a relation between generative linguistics and theories of spoken production. Not only is it the case that linguistic research on typologies can provide input for future studies of phonological processing; these results also suggest a connection between theoretical concepts in linguistics and spoken production processing.

Generative linguistic theory has traditionally distinguished two components of phonological knowledge. One is the phonological lexicon—knowledge of the particular lexical items used by a language, assumed by many theories to include only non-redundant, abstract phonological information (Chomsky & Halle, 1968, chapter 8; but see Bybee, 2001; Pierrehumbert, 2001a). The second is the phonological component of the grammar, which generates fully-specified surface forms on the basis of the abstract stored forms (e.g., the grammar generates /k^hæp/ on the basis of /kæp/; Chomsky & Halle, 1968). These characterizations correspond reasonably directly to the proposed lexical/post-lexical processing distinction, whereby lexical phonological processing generates abstract lexical representations which, in turn, are used to generate more fully-specified post-lexical representations.

Furthermore, the internal structure of the grammatical component appears to be somewhat similar to that of post-lexical processing. Many linguistic theories propose that grammars prefer to generate unmarked surface forms (e.g., Chomsky & Halle, 1968, chapter 9; Prince & Smolensky, 1993). A similar distinction was found within post-lexical processes; errors were more likely to result in unmarked than marked forms, suggesting at least certain basic similarities between the organization of the phonological grammar and post-lexical phonological processing.

However, one should not assume that spoken production processes share every feature of the proposed components of linguistic theories. First, phonological grammars are typically assumed to be deterministic (e.g., Chomsky & Halle, 1968; Prince & Smolensky, 1993); a grammar always produces the same output for a given input (but see Pierrehumbert, 2001b, for a recent review of alternative proposals). Under this assumption the grammar would not predict the probabilistic effects we have reported. That is, although BON was more likely to produce an

unmarked output than a marked output, marked outputs were certainly produced with non-zero probability. The crucial observation is that grammatical principles (i.e., markedness) stochastically influence BON's behavior. A second difference is in the characterization of the phonological lexicon; most phonological theories tend to see it as a static list of items (but see Burzio, 2002; Bybee, 2001). The data reported here seem more consistent with interactive lexical phonological processes. During retrieval, not only is the target word activated, but the representations of related words are also activated giving rise to lexicality effects, frequency effects, and neighborhood effects.

Issues for future research

Interactions between lexical and post-lexical processes

The findings reported here suggest that lexical and post-lexical processes are not strongly interactive. If there were strong interactions, we would predict effects of word-level properties on BON's performance and effects of phonological complexity on CSS' performance. However, limiting interaction between processes does not entail eliminating it. For example, in previous work (Rapp & Goldrick, 2000; Goldrick, accepted) we have found evidence that the processing relationships between lexical semantic, L-level, and lexical phonological processes are neither completely discrete nor completely interactive; rather, interaction is present, but restricted in important and specific ways.

We suspect a similar situation may be the case at the level of lexical and post-lexical phonological processing. CSS' and BON's patterns of performance suggest limits on interactivity, but there is other evidence of its presence. First, as we will discuss below, the performance of individuals with phonological output buffer deficits suggests that interactivity may be revealed by certain forms of impairment. Second, as discussed in the Introduction,

certain studies have suggested that lexical frequency and neighborhood density may exert an influence on aspects of phonological structure which are presumably not represented at the level of lexical phonological representations (e.g., duration, precise realization of vowels). For example, Goldrick & Blumstein (in press) report that lexicality influences the magnitude of sub-phonemic “traces” of targets in experimentally induced speech errors; Bell, Jurafsky, Fosler-Lussier, Girand, Gregory, & Gildea (2003) report that function words (e.g., ‘in’) exhibit variation in their phonological form as a function of their lexical context; Pierrehumbert (2001a, 2002) reviews evidence showing that certain phonological processes involving features (such as /t/ allophony) are sensitive to lexical frequency. Future research will explore the possibility that limited interactivity between lexical and post-lexical phonological representations and processes could account for these data as well as the differential patterns performance we have reported for BON and CSS.

The role of the phonological output buffer

As noted in the Introduction, many theories propose that the speech production system includes a phonological output buffer that maintains the activity of phonological representations so that they can be converted into more detailed phonological (Caplan, Vanier, & Baker, 1986) or articulatory (Caramazza et al., 1986) representations. One important question concerns the nature of the representations that are buffered. If the buffer supports conversion to other phonological representations, it can be assumed to buffer lexical phonological representations. If it supports conversion to articulation, it is likely to buffering of post-lexical phonological representations.

The primary neuropsychological evidence for the existence of such a buffer has been the neurologically-impaired individuals who exhibit very similar error patterns in repeating, reading

aloud, and writing nonword stimuli to dictation—tasks which, arguably, require phonological representations to be held in working memory while being manipulated by different conversion processes (Bisiacchi, Ciolotti, & Denes, 1989; Bub, Black, Howell, & Kertesz, 1987; Caramazza et al., 1986; Shallice, Rumati, & Zadini, 2000). In all of these tasks, these individuals produce phonologically related errors, and several studies (e.g., Bisiacchi et al., 1989; Caramazza et al., 1986; Shallice et al., 2000) report that the relative distribution of substitution, addition, deletion and transposition errors is remarkably similar across each task. Furthermore, the segments involved in errors exhibit a high degree of feature similarity (Caramazza et al., 1986; Shallice et al., 2000). The similarity of performance across multiple tasks and the involvement of featural representations would seem to argue for associating this buffer with maintaining post-lexical representations. However, the fact that nonwords are affected more than words does not accord with the hypothesized non-lexical nature of post-lexical processes (e.g., the insensitivity of post-lexical processes to lexical variables such as frequency and density and, presumably, lexicality). Furthermore at least some of these individuals exhibit lexical frequency effects (e.g., Bub et al., 1987; Shallice et al., 2000).

One possible way to reconcile these findings is to assume that when the buffer is damaged and post-lexical representations are weakly activated their activity is maintained through re-activation. In that case, words would have the advantage over nonwords of having lexical representations which can serve as the basis for the reactivation or “refresh”. As a result, nonwords would be most affected by this damage; similarly, low-frequency words may provide less support to a damaged buffer and thus are also more affected by damage (see Caplan, 1992; Caplan et al., 1986, for similar proposals).

Given that BON and CSS also had greater difficulty in nonword versus word repetition they may suffer from an additional deficit to these buffering processes. However, identifying the source of their nonword repetition difficulties would require additional testing that was not carried out in this investigation. It is clear that the functional architecture in Figure 1 must be extended to include a role for the phonological output buffer; future work will be required to understand its operation and contributions to the multiple processes that may be recruited.

Relationship between perception and production

The discussion regarding a buffer that is shared by a number of spoken language processes brings us naturally to the long-standing issue regarding the relationship between perception and production. Although the research in this area is too extensive to be reviewed here, it is worth pointing out that Vitevitch and Luce (1998, 1999) have proposed a distinction between two phonological representations in speech perception, suggesting that incoming speech is processed at both lexical and sub-lexical levels. The perceptual distinction they have proposed is intriguingly similar to the lexical/post-lexical distinction we have discussed here for production. At a gross level, then, phonological processes involved in the perception and production of speech appear to use similar organizational structures. An important avenue for future research is to determine how intimate the connection between these processes might actually be. The study of neurologically impaired individuals may provide an important avenue for research on this question²⁰.

²⁰ The apparently intact perceptual processing of both CSS and BON suggests two possibilities for this relationship: one, that there are independent systems dedicated to perception and production; or two, that perception and production tasks place differential demands on a common system.

Conclusion

Distinguishing lexical and post-lexical representations on the basis of their functional roles in the spoken production system has provided an independent means of supporting the claim that lexical representations are considerably more abstract, in terms of featural and prosodic structure, than post-lexical representations. This work reveals a phonological processing system with clearly distinct representational types in which the influence of lexical properties and detailed phonological structure are fairly restricted. These findings make contact with and contribute to integrating a wide range of studies, including those of lexical access in spoken production, linguistic theories of phonology, and studies of speech perception, revealing fertile terrain for future investigation.

References

- Abd-El-Jawad, H. & Abu-Salim, I. (1987). Slips of the tongue in Arabic and their theoretical implications. Language Sciences, *9*, 145-171.
- Baayen, R.H., Piepenbrock, R., & Gulikers, L. (1995). The CELEX Lexical Database (Release 2) [CD-ROM]. Philadelphia: Linguistics Data Consortium.
- Bachoud-Lévi, A.-C., & Dupoux, E. (2003). An influence of syntactic and semantic variables on word form retrieval. Cognitive Neuropsychology, *20*, 163-188.
- Badecker, W. (2001). Lexical composition and the production of compounds: Evidence from errors in naming. Language and Cognitive Processes, *16*, 337-366.
- Barry, C., Hirsch, K. W., Johnston, R. A., & Williams, C. L. (2001). Age of acquisition, word frequency, and the locus of repetition priming of picture naming. Journal of Memory and Language, *44*, 350-375.
- Battistella, E. L. (1996). The logic of markedness. Oxford: Oxford University Press.
- Béland, R., Caplan, D., & Nespoulous, J.-L. (1990). The role of abstract phonological representations in word production: Evidence from phonemic paraphasias. Journal of Neurolinguistics, *5*, 125-164.
- Bell, A. (1971). Some patterns of occurrence and formation of syllable structures. In Working papers on language universal (vol. 6, pp. 23-137). Palo Alto: Language Universals Project, Stanford University.
- Bell, A., Jurafsky, D., Fosler-Lussier, E., Girand, C., Gregory, M., & Gildea, D. (2003). Effects of disfluencies, predictability, and utterance position on word form variation in English conversational speech. Journal of the Acoustical Society of America, *113*, 1001-1024.
- Berg, T. (1987). The case against accommodation: Evidence from German speech error data. Journal of Memory and Language, *26*, 277-299.

- Berg, T. (1998). Linguistic structure and change: An explanation from language processing. Oxford: Clarendon Press.
- Bisiachi, P. S., Cipolotti, L., & Denes, G. (1989). Impairment in processing meaningless verbal material in several modalities: The relationship between short-term memory and phonological skills. Quarterly Journal of Experimental Psychology, 41A, 293-319.
- Bonin, P., Barry, C., Méot, A., & Chalard, M. (2004). The influence of age of acquisition in word reading and other tasks: A never ending story? Journal of Memory and Language, 50, 456-476.
- Bonin, P., & Fayol, M. (2002). Frequency effects in the written and spoken production of homophonic picture names. European Journal of Cognitive Psychology, 14, 289-313.
- Breen, G., & Pensalfini, R. (1999). Arrernte: A language with no syllable onsets. Linguistic Inquiry, 30, 1-26.
- Browman, C. P., & Goldstein, L. (1989). Articulatory gestures as phonological units. Phonology, 6, 201-251.
- Browman, C. P., & Goldstein, L. (1992). Articulatory phonology: An overview. Phonetica, 49, 155-180.
- Bub, D., Black, S., Howell, J., & Kertesz, A. (1987). Speech output processes and reading. In M. Coltheart, G. Sartori, & R. Job (Eds.) The cognitive neuropsychology of language (pp. 79-110). Hillsdale, NJ: Lawrence Erlbaum.
- Burzio, L. (2002). Surface-to-surface morphology: When your representations turn into constraints. In P. Boucher (Ed.) Many morphologies (pp. 142-177). Cascadilla Press.
- Butterworth, B. (1992). Disorders of phonological encoding. Cognition, 42, 261-286.
- Bybee, J. L. (2001). Phonology and language use. Cambridge: Cambridge University Press.

- Caplan, D. (1987). Phonological representations in word production. In E. Keller & M. Gopnik (Eds.), Motor and sensory processes of language (pp. 111-124). Hillsdale, NJ: Lawrence Erlbaum Associates.
- Caplan, D. (1992). Language: Structure, processing, and disorders. Cambridge, MA: MIT Press.
- Caplan, D., Vanier, M., & Baker, C. (1986). A case study of reproduction conduction aphasia I: Word production. Cognitive Neuropsychology, *3*, 99-128.
- Caramazza, A., Bi, Y. Costa, A., Miozzo, M. (2004). What determines the speed of lexical access: Homophone or specific-word frequency? A reply to Jescheniak et al. (2003). Journal of Experimental Psychology: Learning, Memory, and Cognition, *30*, 278-282.
- Caramazza, A., Costa, A., Miozzo, M., & Bi, Y. (2001). The specific-word frequency effect: Implications for the representation of homophones in speech production. Journal of Experimental Psychology: Learning, Memory, and Cognition, *27*, 1430-1450.
- Caramazza, A., Miceli, G., & Villa, G. (1986). The role of the (output) phonological buffer in reading, writing, and repetition. Cognitive Neuropsychology, *3*, 37-76.
- Carterette, E. C., & Jones, M. H. (1974). Informal speech. Berkeley: University of California Press.
- Chomsky, N., & Halle, M. (1968). The sound pattern of English. New York: Harper & Row.
- Costa, A., & Sebastian-Gallés, N. (1998). Abstract phonological structure in language production: Evidence from Spanish. Journal of Experimental Psychology: Learning, Memory, and Cognition, *24*, 886-903.
- Crompton, A. (1982). Syllables and segments in speech production. In A. Cutler (Ed.) Slips of the tongue and language production (pp.109-162). Berlin: Mouton.
- Damian, M. F., Bowers, J. S., (2003). Effects of orthography on speech production in a form-preparation paradigm. Journal of Memory and Language, *49*, 119-132.

- de Saussure, F. (1910/1993). Third course of lectures on general linguistics. (E. Komatsu, Ed.; R. Harris, Trans.) Oxford: Pergamon Press.
- Dell, G. S., (1984). Representation of serial order in speech: Evidence from the repeated phoneme effect in speech errors. Journal of Experimental Psychology: Learning, Memory, and Cognition, *10*, 222-233.
- Dell, G. S. (1986). A spreading activation theory of retrieval in sentence production. Psychological Review, *93*, 283-321.
- Dell, G. S. (1988). The retrieval of phonological forms in production: Tests of predictions from a connectionist model. Journal of Memory and Language, *27*, 124-142.
- Dell, G. S. (1990). Effects of frequency and vocabulary type on phonological speech errors. Language and Cognitive Processes, *4*, 313-349.
- Dell, G. S., & Gordon, J. K. (2003). Neighbors in the lexicon: Friends or foes? In N. O. Schiller & A. S. Meyer (Eds.) Phonetics and phonology in language comprehension and production: Differences and similarities. New York: Mouton de Gruyter.
- Dell, G. S., Juliano, C., & Govindjee, A. (1993). Structure and content in language production: A theory of frame constraints in phonological speech errors. Cognitive Science, *17*, 149-195.
- Dell, G. S., Schwartz, M. F., Martin, N., Saffran, E. M., & Gagnon, D. A. (1997). Lexical access in aphasic and nonaphasic speakers. Psychological Review, *104*, 801-838.
- Ferrand, L., & Segui, J. (1998). The syllable's role in speech production: Are syllables chunks, schemas, or both? Psychonomic Bulletin and Review, *5*, 253-298.
- Ferrand, L., Segui, J., & Grainger, J. (1996). Masked priming of word and picture naming: The role of syllabic units. Journal of Memory and Language, *35*, 708-723.

- Ferrand, L., Segui, J., & Humphreys, G. W. (1997). The syllable's role in word naming. Memory and Cognition, *25*, 458-470.
- Frisch, S. (1996). Similarity and frequency in phonology. Doctoral dissertation, Northwestern University. ROA-198-0597, Rutgers Optimality Archive, <http://roa.rutgers.edu/>.
- Frisch, S. (1997). Against underspecification in speech errors. Studies in the Linguistic Sciences, *27*, 79-97.
- Fromkin, V. A. (1971). The non-anomalous nature of anomalous utterances. Language, *47*, 27-52.
- Gagnon, D. A., Schwartz, M. F., Martin, N., Dell, G. S., & Saffran, E. M. (1997). The origins of formal paraphasias in aphasics' picture naming. Brain and Language, *59*, 450-472.
- García-Albea, J. E., del Viso, S., & Igoa, J. M. (1989). Movement errors and levels of processing in sentence production. Journal of Psycholinguistic Research, *18*, 145-161.
- Garrett, M. F. (1980). Levels of processing in sentence production. In B. Butterworth (Ed). Language production (vol. 1, pp. 177-220). New York: Academic Press.
- Garrett, M. F. (1984). The organization of processing structure for language production: Applications to aphasic speech. In D. Caplan, A. R. Lecours & A. Smith (Eds.) Biological perspectives on language (pp.172-193). Cambridge, MA: MIT Press.
- Glosser, G., Kohn, S. E., Friedman, R. B., Sands, L., & Grugan, P. (1997). Repetition of single words and nonwords in Alzheimer's disease. Cortex, *33*, 653-666.
- Goldrick, M. (2004). Phonological features and phonotactic constraints in speech production. Journal of Memory and Language, *51*, 586-603.
- Goldrick, M. (accepted pending revision). Limited interaction in speech production: Chronometric, speech error, and neuropsychological evidence. Language and Cognitive Processes.

- Goldrick, M., & Blumstein, S. E. (in press). Cascading activation from phonological planning to articulatory processes: Evidence from tongue twisters. Language and Cognitive Processes.
- Goldrick, M., & Rapp, B. (2001, November). Mrs. Malaprop's neighborhood: Using word errors to reveal neighborhood structure. Poster presented at the Psychonomic Society annual meeting, Orlando, FL.
- Gordon, J. K. (2002). Phonological neighborhood effects in aphasic speech: Spontaneous and structured contexts. Brain and Language, 82, 113-145.
- Gravetter, F. J., & Wallnau, L. B. (1991). Statistics for the behavioral sciences (3rd edition). St. Paul, Minnesota: West Publishing.
- Greenberg, J. H. (1966). Language universals. The Hague: Mouton.
- Greenberg, J. H. (1978). Some generalizations concerning initial and final consonant clusters. In J. H. Greenberg (Ed.) Universals of human language (Vol. 2, pp. 243-279). Stanford, CA: Stanford University Press.
- Guest, D. J. (2001). Phonetic features in language production: An experimental examination of phonetic feature errors. Doctoral dissertation, University of Illinois at Urbana-Champaign, Champaign, IL.
- Hanley, J. R., Dell, G. S., Kay, J., & Baron, R. (2004). Evidence for the involvement of a nonlexical route in the repetition of familiar words: A comparison of single and dual route models of auditory repetition. Cognitive Neuropsychology, 21, 147-158.
- Hanley, J. R., Kay, J., & Edwards, M. (2002). Imageability effects, phonological errors, and the relationship between auditory repetition and picture naming: Implications for models of auditory repetition. Cognitive Neuropsychology, 19, 193-206.

- Hillis, A. E. (2001). The organization of the lexical system. In B. Rapp (Ed.) The handbook of cognitive neuropsychology: What deficits reveal about the human mind (pp. 185-210). Philadelphia: Psychology Press.
- Jakobson, R. (1941/1968). Child language aphasia and phonological universals. (A. R. Keiler, Trans.) The Hague: Mouton.
- Jescheniak, J. D., & Levelt, W. J. M. (1994). Word frequency effects in spoken production: Retrieval of syntactic information and phonological form. Journal of Experimental Psychology: Learning, Memory, and Cognition, *20*, 824-843.
- Jescheniak, J. D., Meyer, A. S., & Levelt, W. J. M. (2003). Specific-word frequency is not all that counts in speech production: Comments on Caramazza, Costa, et al. (2001) and new experimental data. Journal of Experimental Psychology: Learning, Memory, and Cognition, *29*, 432-438.
- Joanisse, M. F. (1999). Exploring syllable structure in connectionist networks. In Proceedings of the XIVth international congress of phonetic sciences (pp. 731-734).
- Kahn, D. (1976/1980). Syllable based generalizations in English phonology. Doctoral dissertation, Massachusetts Institute of Technology. Published 1980. New York: Garland.
- Kay, J., & Ellis, A. (1987). A cognitive neuropsychological case study of anomia. Brain, *110*, 613-629.
- Kay, J., & Patterson, K. E. (1986). Routes to meaning in surface dyslexia. In K. E. Patterson, J. C. Marshall, & M. Coltheart (Eds.) Surface dyslexia: Neuropsychological and cognitive studies of phonological reading (pp. 79-104). Hillsdale, NJ: Lawrence Erlbaum Associates.
- Kiparsky, P. (1982). Lexical morphology and phonology. In I.-S. Yang (Ed.) Linguistics in the morning calm (pp.3-91). Seoul: Hanshin.

- Kohn, S. E., & Smith, K. L. (1994). Distinctions between two phonological output deficits. Applied Psycholinguistics, *15*, 75-95.
- La Heij, W., Puerta-Melguizo, M. C., van Oostrum, M., & Starreveld, P. A. (1999). Picture naming: Identical priming and word frequency interact. Acta Psychologica, *102*, 77-95.
- LaPointe, L. L. & Horner, J. (1979). Reading comprehension battery for aphasia. Tigard, OR: C.C. Publications.
- Law, S.-P. (2004). Impairment to phonological processes in a Cantonese-speaking brain-damaged patient. Aphasiology, *18*, 373-388.
- Lecours, A. R., & Lhermitte, F. (1969). Phonemic paraphasias: Linguistic structures and tentative hypothesis. Cortex, *5*, 193-228.
- Levelt, W. J. M. (1989). Speaking: From intention to articulation. Cambridge, MA: MIT Press.
- Levelt, W. J. M., Roelofs, A., & Meyer, A. S. (1999). A theory of lexical access in speech production. Behavioral and Brain Sciences, *22*, 1-75.
- MacKay, D. G. (1970) Spoonerisms: The structure of errors in the serial order of speech. Neuropsychologia, *8*, 323-350.
- MacKay, D. G. (1987). The organization of perception and action: A theory for language and other cognitive skills. New York: Springer-Verlag.
- Martin, N. (1996). Models of deep dysphasia. Neurocase, *2*, 73-80.
- McCarthy, R., & Warrington, E. K. (1984). A two-route model of speech production: Evidence from aphasia. Brain, *107*, 463-485.
- Meijer, P. J. A. (1996). Suprasegmental structures in phonological encoding: The CV structure. Journal of Memory and Language, *35*, 840-853.

- 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*, 228-252.
- Munson, B. (in press). Lexical access, lexical representation, and vowel articulation. In J. S. Cole & J. I. Hualde (Eds.) Papers in laboratory phonology 9: Change in phonology. New York: Mouton de Gruyter.
- Munson, B., & Solomon, N. P. (2004). The effect of phonological neighborhood density on vowel articulation. Journal of Speech, Language, and Hearing Research, *47*, 1048-1058.
- Nadeau, S. (2001). Phonology: A review and proposals from a connectionist perspective. Brain and Language, *79*, 511-579.
- Nooteboom, S. G. (1969). The tongue slips into patterns. In A. G. Sciarone, A. J. van Essen, & A. van Raad (Eds.) Leyden studies in linguistics and phonetics (pp. 114-132). The Hague: Mouton. [Reprinted in V. A. Fromkin (Ed.) (1973) Speech errors as linguistic evidence (pp. 144-156). The Hague: Mouton.]
- O' Grady, W., Dobrovolsky, M., & Aronoff, M. (1997). Contemporary linguistics: An introduction (3rd edition). New York: St. Martin's.
- Paradis, C., & Prunet, J.-F., eds. (1991). Phonetics and phonology, vol. 2: The special status of coronals. San Diego: Academic Press.
- Peterson, R. R. & Savoy, P. (1998). Lexical selection and phonological encoding during language production: Evidence for cascaded processing. Journal of Experimental Psychology: Learning, Memory, and Cognition, *24*, 539-557.

- Pierrehumbert, J. (2001a). Exemplar dynamics: Word frequency, lenition, and contrast . In J. Bybee & P. Hopper (Eds.) Frequency effects and the emergence of linguistic structure (pp. 137-157). Amsterdam: John Benjamins.
- Pierrehumbert, J. (2001b). Stochastic phonology. Glott International, 5(6), 195-207.
- Pierrehumbert, J. (2002) Word-specific phonetics. In C. Gussenhoven & N. Warner (Eds.) Papers in Laboratory Phonology VII (pp. 101-140). Berlin: Mouton de Gruyter.
- Plaut, D. C., & Kello, C. T. (1999). The emergence of phonology from the interplay of speech perception and comprehension: A distributed connectionist approach. In B. MacWhinney (Ed.) The emergence of language (pp. 381-415). Mahweh, NJ: Erlbaum.
- Prince, A., & Smolensky, P. (1993/2002). Optimality theory: Constraint interaction in generative grammar. Technical report TR-2, Rutgers Center for Cognitive Science, Rutgers University, New Brunswick, NJ. Technical report CU-CS-696-93, Department of Computer Science, University of Colorado, Boulder. Revised version, 2002: ROA-537-0802, Rutgers Optimality Archive, <http://roa.rutgers.edu/>.
- Rapp, B., Folk, J., & Tainturier, M.-J. (2001). Word reading. In B. Rapp (Ed.) The handbook of cognitive neuropsychology: What deficits reveal about the human mind (pp. 233-262). Philadelphia: Psychology Press.
- Rapp, B., & Goldrick, M. (2000). Discreteness and interactivity in spoken word production. Psychological Review, 107, 460-499.
- Roelofs, A. (1997). The WEAVER model of word-form encoding in speech production. Cognition, 64, 249-284.
- Roelofs, A. (1999). Phonological segments and features as planning units in speech production. Language and Cognitive Processes, 14, 173-200.

- Roelofs, A. (in press). The influence of spelling on phonological encoding in word reading, object naming, and word generation. Psychonomic Bulletin & Review.
- Roelofs, A., & Meyer, A. S. (1998). Metrical structure in planning the production of spoken words. Journal of Experimental Psychology: Learning, Memory, and Cognition, 24, 922-939.
- Romani, C. (1992). The representation of prosodic and syllabic structure in speech production. Doctoral dissertation, Johns Hopkins University, Baltimore, MD.
- Romani, C., & Calabrese, A. (1998). Syllabic constraints on the phonological errors of an aphasic patient. Brain and Language, 64, 83-121.
- Romani, C., Olson, A., Semenza, C., & Granà, A. (2002). Patterns of phonological errors as a function of a phonological versus an articulatory locus of impairment. Cortex, 38, 541-567.
- Scarborough, R. A. (2003). Lexical confusability and degree of coarticulation. In P. M. Nowak, C. Yoquelet, & D. Mortensen (Eds.) Proceedings of the 29th annual meeting of the Berkeley Linguistics Society.
- Schiller, N. O. (1998). The effect of visually masked syllable primes on the naming latencies of words and pictures. Journal of Memory and Language, 39, 484-507.
- Schiller, N. O. (2000). Single word production in English: The role of subsyllabic units during phonological encoding. Journal of Experimental Psychology: Learning, Memory, and Cognition, 26, 512-528.
- Sevold, C. A., Dell, G. S., & Cole, J. S. (1995). Syllable structure in speech production: Are syllables chunks or schemas? Journal of Memory and Language, 34, 807-820.
- Shallice, T., Rumiat, R. I., & Zadini, A. (2000). The selective impairment of the phonological output buffer. Cognitive Neuropsychology, 17, 517-546.

- Shattuck-Hufnagel, S. (1987). The role of word-onset consonants in speech production planning: New evidence from speech error patterns. In E. Keller & M. Gopnik (Eds.) Motor and sensory processes of language (pp.17-51). Hillsdale, NJ: Lawrence Erlbaum Associates.
- Shattuck-Hufnagel, S. (1992). The role of word structure in segmental serial ordering. Cognition, 42, 213-259.
- Snodgrass, J. G. & Vanderwart, M. A. (1980). A standardized set of 260 pictures: Norms for name agreement, image agreement, familiarity, and visual complexity. Journal of Experimental Psychology: Human Learning and Memory, 6, 174-215.
- Söderpalm, E. (1979). Speech errors in normal and pathological speech. Travaux de l'Institute de Linguistique de Lund, 14. Lund: CWK Gleerup.
- Stemberger, J. P. (1983). Speech errors and theoretical phonology: A review. Unpublished manuscript, Carnegie-Mellon University. Distributed by the Indiana University Linguistics Club, Bloomington, IN.
- Stemberger, J. P. (1985). An interactive activation model of language production. In A. W. Ellis (Ed.) Progress in the psychology of language (Vol.1, pp. 143-186). Hillsdale, NJ: Lawrence Erlbaum Associates.
- Stemberger, J. P. (1990). Wordshape errors in language production. Cognition, 35, 123-157.
- Stemberger, J. P. (1991a). Radical underspecification in language production. Phonology, 8, 73-112.
- Stemberger, J. P. (1991b). Apparent anti-frequency effects in language production: The addition bias and phonological underspecification. Journal of Memory and Language, 30, 161-185.
- Stemberger, J. P. (2004). Neighbourhood effects on error rates in speech production. Brain and Language, 90, 413-422.

- Treiman, R., & Danis, C. (1988). Syllabification of intervocalic consonants. Journal of Memory and Language, 27, 87-104.
- Trubetzkoy, N.S. (1939/1969). Principles of phonology. (C. A. M. Baltaxe, Trans.) Berkeley, CA: University of California Press.
- Vitevitch, M. S. (1997). The neighborhood characteristics of malapropisms. Language and Speech, 40, 211-228.
- Vitevitch, M.S. (2002). The influence of phonological similarity neighborhoods on speech production. Journal of Experimental Psychology: Learning, Memory and Cognition, 28, 735-747.
- Vitevitch, M. S., & Luce, P. A. (1998). When words compete: Levels of processing in spoken word recognition. Psychological Science, 9, 325-329.
- Vitevitch, M. S., & Luce, P. A. (1999). Probabilistic phonotactics and neighborhood activation in spoken word recognition. Journal of Memory and Language, 40, 374-408.
- Wells-Jensen, S. (1999). Cognitive correlates of linguistic complexity: A cross-linguistic comparison of errors in speech. Doctoral dissertation, State University of New York at Buffalo, Buffalo, NY.
- Whalen, D. H. (1991). Infrequent words are longer in duration than frequent words. Journal of the Acoustical Society of America, 91, 2339-2340.
- Wheeler, D. W., & Touretzky, D. S. (1997). A parallel licensing model of normal slips and phonemic paraphasias. Brain and Language, 59, 147-201.
- Wright, R. (2004). Factors of lexical competition in vowel articulation. In J. Local, R. Ogden, & R. Temple (Eds.) Phonetic interpretation: Papers in Laboratory Phonology VI (pp. 26-50). Cambridge: Cambridge University Press.

Zevin, J. D., & Seidenberg, M. S. (2002). Age of acquisition effects in word reading and other tasks. Journal of Memory and Language, 47, 1-29.

Zipf, G. K. (1935). The psycho-biology of language: An introduction to dynamic philology. Boston: Houghton Mifflin.

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