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Linking speech errors and generative phonological theory

Matthew Goldrick

Department of Linguistics
Northwestern University

Address for Correspondence:
Matthew Goldrick
Department of Linguistics
Northwestern University
2016 Sheridan Rd.
Evanston, IL 60208 USA
Phone: (847) 491-8053
Fax: (847) 491-3770
Email: matt-goldrick@northwestern.edu

Abstract

Speech errors are a critical source of data on the tacit knowledge that underlies our creative use of language. Studies of errors in spontaneous speech, in experimental paradigms such as tongue twisters, and those produced by aphasic individuals reveal the influence of linguistic principles on the production of speech. Linguistic representations from distinctive features and gestures to prosodic structure shape speech error distributions. Speech errors respect allophonic and allomorphic relationships between linguistic forms. Phonological well-formedness—as measured by cross-linguistic markedness and within-language frequency—influences which structures are (mis)produced in errors. Recent advances in constraint-based generative phonological theories (Optimality Theory, Harmonic Grammar, and Maximum Entropy Grammars) may provide insight into these patterns. Formal models of variation and computational models of constraint satisfaction may provide the means to quantitatively link phonological principles and speech error distributions.

1. Introduction

Our creative linguistic abilities reflect our tacit or implicit knowledge of the structure of our language (Chomsky 1986). Speech errors are a quintessential expression of these design features of the human language faculty. As unintentional deviations from what we attempt to produce, they provide a window into the tacit knowledge underlying speech. Errors also provide insight into the creative possibilities this knowledge offers (Dell 1995). Drawing on an attested error (Fromkin 1971), suppose someone refers to "Chomsky and *Challe's* (/tʃɑleɪz/) seminal work on English sound structure"—knowing full well that the second author's name is in fact *Halle*. *Challe's* is a novel, creative combination of English sounds. But critically this creativity is constrained by the sound patterns of English. Although it is not a real word, *Challe's* is a possible sequence of English sounds.

Following a preliminary discussion of the nature of speech error data, evidence linking phonological speech errors distributions to the principles of linguistic theory is reviewed. The final section considers how constraint-based generative grammars could be used to develop formal, quantitative models of speech error data.

2. Preliminaries: The Nature of Speech Error Data

This discussion focuses on cases where a speaker knows the correct form (e.g., *Halle*). This sense of error is distinct from cases where speakers are not aware of the "correct" normative form (Zwicky 1979). This review therefore focuses on speakers with full competence of their linguistic system—i.e., errors produced by adult speakers in their native language (for reviews of production deviations in children, see Dinnsen and Gierut

2008; Jaeger 2005; for studies of second language acquisition, see Broselow, Chen and Wang 1998; Flege 2003; Davidson 2010 for recent reviews).

Speech errors can arise spontaneously due to normal variation in cognitive functioning (e.g., fatigue; Garnham, Shillcock, Brown, Mill and Cutler 1981 report errors occur at roughly once every thousand words). Neurological traumas can induce much greater rates of errors; this review focuses on evidence from aphasia (Jakobson 1941; Blumstein 1973; see Ziegler 2009 for a recent review of evidence from apraxia of speech). Evidence from experimental error-induction tasks (e.g., tongue twisters) is also considered (see Baars 1992 for a review of various paradigms).

The opportunistic nature of spontaneous speech errors means such data is practically limited to transcription-based observation. (n.b.: Results from these studies largely agree with systematic transcription analyses of recorded speech errors: Pérez, Santiago, Palma and O'Seaghdha 2007; Stemberger 1992.) Detailed acoustic (Laver 1980) and articulatory (Mowrey and MacKay 1990) analyses have been limited to laboratory studies.

3. Linguistic Principles and Speech Errors

Utilizing the principles of linguistic theory provides insight into the nature of speech error distributions. Appealing to linguistic representations, the relationships between allomorphs and allophones, and phonological well-formedness has helped researchers characterize a wide range of empirical data.

3.1 REPRESENTATIONAL STRUCTURE

Speech errors are influenced by representational structures across the prosodic hierarchy. Individual sub-segmental representations such as distinctive features (Chomsky and Halle 1968) or gestures (Browman and Goldstein 1989) can be misproduced. For example, Goldstein, Pouplier, Chen, Saltzmann and Byrd (2007) document errors on sequences involving /t/ and /k/ targets where the tongue dorsum (but not tongue tip) is produced with the incorrect constriction. Transcription studies have reported similar effects in experimental paradigms (Guest 2001) but not in spontaneous errors (Shattuck-Hufnagel and Klatt 1979).

Sounds with similar sub-segmental structure (e.g., /m/ and /n/) are more likely to interact in errors than less similar sounds (e.g., /m/ and /k/). This has been documented in spontaneous speech errors in a number of languages (Arabic: Abd-El-Jawad and Abu-Salim 1987; Dutch: Nooteboom 1969; Van den Broecke and Goldstein 1980; English: Boomer and Laver 1968; Frisch 1997; Fromkin 1971; Garrett 1975; Levitt and Healy 1985; MacKay 1970; Shattuck-Hufnagel and Klatt 1979; Stemberger 1991b; Van den Broecke and Goldstein 1980; Vousden Brown and Harley 2000; Finnish: Hokkanen 2001; German: Berg 1991a; MacKay 1970; Van den Broecke and Goldstein 1980; Taiwanese Mandarin: Wan and Jaeger 2003; Spanish: García-Albea del Viso and Igoa 1989; Swedish: Söderpalm 1979). Such effects have also been observed in experimentally-induced speech errors (English: Acheson and MacDonald 2009; Frisch 2000; Kupin 1982; Levitt and Healy 1985; Stemberger 1991a, b; Walker 2007; Wiltshire 1998, 1999; Hindi, Japanese, Spanish, Turkish: Wells-Jensen 2007) and in studies of individuals with acquired language disorders (Blumstein 1998). Recent work suggests similarity influences not just categorical error outcomes but also the subphonemic articulatory properties of errors (McMillan and Corley in press). Note that analysis of both spontaneous (English: Frisch 1997; German: Berg 1991a) and experimentally induced errors (Stemberger 1991a, b; Walker 2007) suggest that similarity is not a linear function of the number of shared features/gestures but reflects the structure of segmental inventories (see Frisch, Pierrehumbert and Broe 2004 for further discussion).

Distinctive features or gestures are typically assumed to be linked together, from relatively small subgroups (e.g., nodes in feature geometry—Sagey 1986; phasing relations between gestures—Browman and Goldstein 1989) to units roughly equivalent to traditional phonological segments (e.g., timing tier units—Goldsmith 1990; root nodes—Archangeli and Pulleyblank 1994). Groupings at both of these levels exert an influence on speech error distributions. Stemberger (1990, 2009) presents evidence from spontaneous speech errors in English suggesting that the repetition of entire segments (but not individual features or gestures) increases speech error rates. Additionally, articulatory imaging studies of speech sounds involving multiple gestures (e.g., labial closure and velum lowering for /m/) suggests coupling between sub-segmental representations. For these multi-gesture segments, the rate at which both gestures are misproduced exceeds the rate predicted by the rate at which errors target each gesture independently (Goldstein et al. 2007).

Many theories assume segment-sized units are grouped into syllables (Selkirk 1982) as well as constituents of intermediate size between segments and syllables (Vennemann

1988). Although spontaneous speech errors in English rarely involve the movement of entire syllables (Bock 1991) such errors are frequently observed in Mandarin (Chen 2000). These contrasting patterns have been argued to reflect the differing role of syllables in phonological processing in the two languages (O'Seaghdha, Chen and Chen 2010). Studies of spontaneous errors (English: Dell 1986; Shattuck-Hufnagel 1983, 1987; Stemberger 1983; German: Berg 1987; Japanese: Kubozono 1985) and short term memory errors (English: Treiman and Danis 1988; Treiman, Straub, and Lavery 1994; Korean: Lee and Goldrick 2008) have reported errors involving the movement of sub-syllabic constituents (e.g., "spill beer" → "spear bill;" Dell 1986; but see Berg and Abd-El-Jawad 1996 for null results in Arabic).

Syllabic and metrical structure constrains segmental errors. In spontaneous speech errors, interacting segments tend to occur in similar syllabic or prosodic positions (Dutch: Nooteboom 1969; English: Boomer & Laver 1968; Butterworth & Whittaker 1980; Fromkin 1971; Garrett, 1975; Laubstein 1987; MacKay 1969, 1970; Shattuck-Hufnagel 1979, 1983, 1987; Stemberger 1983; Vousden et al. 2000; Finnish: Hokkanen 2001; German: Berg 1991b, MacKay 1969, 1970; Spanish: Berg 1991b; Swedish: Söderpalm 1979). Similar effects have been reported in experimental paradigms (English: Shattuck-Hufnagel, 1987, 1992; Frisch, 2000; Wiltshire, 1998; Hindi, Japanese, Spanish, Turkish: Wells-Jensen 2007). Note that in Arabic, this effect appears to be limited to errors involving non-adjacent segments (Abd-El-Jawad and Abu-Salim 1987; Berg and Abd-El-Jawad 1996). Additionally, position within the word—which is highly confounded with syllabic and metrical position—exerts a strong, independent influence on errors (Shattuck-Hufnagel 1992; Wiltshire 1998).

Finally, speech errors are consistent with autosegmental theories that postulate a representational independence between various aspects of structure—e.g., tone and metrical prominence vs. segmental content (Goldsmith 1990). In most cases of exchanges involving a stressed and unstressed vowel, lexical stress does not shift with the vowel features (e.g., marsúpial → musárpial; Garrett 1980; Stemberger, 1983). In languages with lexical tones, the segmental content of two syllables can be exchanged without disrupting the tonal pattern (Mandarin: Chen 1999; Wan and Jaeger 1998; Thai: Gandour 1977).

3.2 PHONOLOGICAL RELATIONS

One of the primary goals of phonological theory is to characterize the systematic relationships that hold between linguistic forms (Anderson 1985). Speech errors are sensitive to these relationships; when segments shift in spontaneous speech errors, they tend to surface not as the variant appropriate to the intended environment but as the variant appropriate to the environment they are pronounced in (this is frequently referred to as 'accommodation'). This holds both for allophonic (e.g., terrifi[k] → [k^h]errifi[k]; Stemberger 1983) as well as allomorphic (e.g., run[z] out → run out[s]; Garrett 1980) variation in spontaneous speech errors (e.g., Arabic: Abd-El-Jawad & Abu-Salim 1987; English: Fromkin 1971; Garrett 1975, 1980; Stemberger 1983; Finnish: Niemi and Laine 1997; Welsh: Meara and Ellis 1982) as well as in experimental paradigms (Ewe: Stemberger and Lewis 1986; Hindi, Japanese, Spanish, Turkish: Wells-Jensen 2007). These effects include not just local assimilation but also vowel harmony (Niemi and Laine 1997;

Wells-Jensen 2007), reduplication (Stemberger and Lewis 1986) and consonant mutation (Meara and Ellis 1982).

3.3 PHONOLOGICAL WELL-FORMEDNESS

A third focus of generative phonological theory is characterizing the relative well-formedness of phonological structures (Prince and Smolensky 1993). Speech errors are sensitive to such distinctions. One basic well-formedness distinction is between phonological structures that are present vs. absent within a language (e.g., English contains words beginning with /h/ but none ending in /h/). Spontaneous speech errors are sensitive to these constraints; they tend to result in structures that are present in the language (e.g., in English, errors like /mæd/ → [hæd] are much more likely than errors like /dæm/ → [dæh]). This has been reported in many languages (Arabic: Abd-El-Jawad and Abu-Salim 1987; English: Boomer & Laver 1968; Fromkin 1971; Garrett 1975; MacKay 1972; Motley 1973; Stemberger 1983; Vousden et al. 2000; Wells 1951; Finnish: Hokkanen 2001; German: MacKay 1972; Mandarin: Wan and Jaeger 1998). Similar results have been reported in cases of acquired speech production impairments (Marshall 2006).

Note that this is not inviolable; spontaneous errors can result in the production of phonological/phonetic structures outside the language's inventory (Hockett 1967; Stemberger 1983). This has been noted in experimental transcription studies (Butterworth and Whittaker 1980) and more prominently in quantitative acoustic (Frisch and Wright 2002; Laver 1980) and articulatory studies (Boucher 1994; Mowrey and MacKay 1990; Goldstein et al. 2007; McMillan and Corley in press; McMillan, Corley and

Lickley 2009; Pouplier 2003, 2007, 2008; Pouplier and Goldstein 2010). Note that in certain error-induction contexts, quantitative acoustic (Goldrick and Blumstein 2006) and articulatory (Buchwald, Rapp and Stone 2007) analyses reveal that the phonetic properties of productions are well within the range of typical productions.

The distinction in well-formedness between presence vs. absence can also be induced experimentally. Dell, Reed, Adams and Meyer (2000) presented participants with tongue twisters where consonants were restricted to a subset of the environments they naturally occur in (e.g., for English speakers, /f/ was restricted to coda position). The vast majority of the participants' speech errors respected these experiment-specific phonotactic constraints. Learning in this experimental paradigm clearly reflects speakers' knowledge of linguistic structure. It is influenced by sub-segmental (featural/gestural) structure (Goldrick 2004), the structural complexity of the phonotactic being acquired (Warker and Dell, 2006) and is specific to the co-occurrence of phonological elements (but insensitive to non-structural properties such as speech rate; Warker, Dell, Whalen and Gereg, 2008).

Beyond simple presence vs. absence in a language, speakers are also sensitive to a variety of other well-formedness distinctions. A long-standing concern of phonological theory is characterizing well-formedness patterns that hold across languages, where *marked* structures are relatively ill-formed and *unmarked* structures relatively well-formed (e.g., Prince and Smolensky 1993). Speech errors are sensitive to these distinctions; they are more likely to target marked structures and result in the production of unmarked structures. For example, in absolute initial and final position voiceless /s/ is unmarked relative to voiced /z/; such studies report that /z/ has a higher error rate than /s/, and /z/

→ /s/ errors are more likely than the reverse. Patterns such as this have been reported in studies of experimentally-induced errors (Goldrick 2002; Kupin 1982). Various dimensions of cross-linguistic markedness have been shown to influence the errors of individuals with acquired neurological impairments. These include segmental or featural markedness (English: Blumstein 1973; Goldrick & Rapp 2007; Hatfield & Walton 1975; French: Béland & Favreau 1991; Nespoulous, Joanette, Béland, Caplan, & Lecours 1984; Nespoulous, Jeanette, Ska, Caplan, & Lecours, 1987); as well as markedness of syllable structure (Dutch: den Ouden 2002; English: Blumstein, 1973: Buchwald 2005, 2009; Buchwald et al. 2007; Goldrick and Rapp, 2007; French: Béland 1990; Favreau, Nespolous and Lecours 1990; Nespoulous and Moreau 1997, 1998; Béland and Paradis, 1997; Béland, Paradis and Bois 1993), including a number of studies with a more specific emphasis on sonority-based markedness and syllable structure (Dutch: Bastiaanse, Gilbers and van der Linde 1994; Stenneken, Bastiaanse, Huber and Jacobs 2005; English: Buckingham 1990; Christman 1992 a,b, 1994; Code and Ball 1994; Kohn, Melvold and Shipper 1998; Italian: Romani and Calabrese 1998; Romani and Galluzzi 2005; Romani, Olson, Semenza and Grana 2002).

Phonological theories have also aimed to capture language-specific degrees of well-formedness that distinguish among the various structures that are possible within a language (Hume 2003). Rose and King (2007) demonstrate that experimentally-induced errors in two Semitic languages are sensitive to language-specific consonantal co-occurrence restrictions. Transcription-based studies of experimentally induced speech errors (Kupin 1982; Levitt and Healy 1985; Motley and Baars,1975) and individuals with neurological impairments (Blumstein 1973; Laganaro and Zimmermann 2009) suggest that errors are more likely to occur on low-frequency target sounds (and result in the production of a high-frequency segment as an error outcome). For example, /s/ is more frequent than /z/ in English; such studies report that /z/ has a higher error rate than /s/, and /z/ → /s/ errors are more likely than the reverse. Goldrick and Larson (2008) found a similar pattern utilizing the implicit learning paradigm of Dell et al. (2000).

As suggested by the examples above, language-specific frequencies are highly correlated with cross-linguistic markedness (e.g., /s/ is both more frequent and less marked than /z/; Berg 1998; Frisch 2000; Greenberg 1966; Zipf 1935). Given that well-formedness distinctions specific to particular languages (Rose and King 2007) and experimental contexts (Goldrick and Larson 2008) influence speech errors, it is unclear if appeals to cross-linguistic markedness are in fact required. Some results from transcription-based studies of aphasia suggest that markedness provides a superior account of error patterns than within-language frequency (Goldrick and Rapp 2007; Romani et al. 2002). Other transcription-based experimental studies have reached the opposite conclusion (Motley and Baars 1975). Finally, some studies suggest that both frequency and markedness contribute to error patterns (Buchwald 2005; Goldrick and Larson 2010; Kupin 1982).

The studies above report a tendency for errors to *improve* well-formedness (e.g., replacing less frequent/marked phonological structures with more frequent/unmarked structures). Some studies of experimentally induced (Stemberger 1991a,b; 2004; Stemberger and Treiman 1986) and aphasic errors (Béland and Favreau 1991; Kohn, Melvold and Smith 1995) have found the complementary pattern; errors are more likely to occur on highly frequent forms (and result in the substitution of a lower frequency form).

For example, Stemberger (1991a, 1991b, 2004) reports that high frequency /s/ tends to be misproduced as lower frequency /ʃ/ more often than the reverse. This 'anti-frequency' effect has been attributed to the 'default' status of high frequency forms (e.g., Stemberger 1991a, b; Stemberger 2004).

More recent work challenges these reported anti-frequency effects, as well as well-formedness effects more generally. Articulatory imaging of experimentally-induced speech errors fails to reveal the reported asymmetries in error probabilities (Goldstein et al. 2007). However, listeners are biased to perceive these articulatory errors as corresponding to lower frequency structures (Marin, Pouplier and Harrington 2010; Pouplier and Goldstein 2005)—suggesting that some of the results above reflect perceptual, not production-based, processes. Although these findings certainly suggest caution is warranted in interpreting transcription-based work, it is unlikely that *all* reported well-formedness effects can be reduced to transcriber biases. The strongest evidence against such an account comes from the influence of experiment-specific phonotactic constraints. For example, in Dell et al.'s (2000) implicit learning paradigm, /f/ was restricted to coda in one condition but unrestricted in another. Since the same transcribers examined data in both conditions, it is unlikely that a listener bias accounts for the observed differences in error distributions. Furthermore, because the intrinsic articulatory properties of forms are held constant across these conditions, the asymmetries in error distributions in these experiments specifically reflect differences in participants' experience with these forms (Goldrick and Larson 2008). This suggests that under certain processing conditions, well-formedness exerts an influence on speech errors arising in the production system. Clearly, additional empirical and theoretical work is required to clarify the relationship between these results and the articulatory studies reviewed above.

Finally, it is important to note that many transcription studies have found neither within-language frequency nor cross-linguistic markedness effects. This has been reported in studies of spontaneous errors (Arabic: Abd-El-Jawad and Abu Salim 1987; English: Frisch 1997; Shattuck-Hufnagel and Klatt 1979, 1980; Swedish: Söderpalm 1979) experimentally-induced errors (Wiltshire 1999) and in cases of aphasia (Favreau, Nespolous and Lecours 1990 report mixed results; Niemi, Koivuselkä-Sallinen, and Hänninen 1985). (See §4.3 below for further discussion.)

4. Bridging speech error data and generative phonological theory

The substantial body of work reviewed in §3 suggests that the broad principles of linguistic theory provide insights into the nature of speech errors. Formal phonological theory may therefore provide a means to make these connections detailed and explicit. The sections below focus on possible ways to develop such connections in the context of Optimality Theory (OT; Prince and Smolensky 1993) and the related frameworks of Harmonic Grammar (HG; Legendre, Miyata and Smolensky 1990; Smolensky and Legendre 2006; see Legendre, Sorace and Smolensky 2006 for discussion) and Maximum Entropy grammars (MaxEnt; Hayes and Wilson 2008).

In these formalisms, the mapping between underlying and surface forms is specified by a set of ranked well-formedness constraints. For example, in 'classic' OT, well-formedness is determined by the relative ranking of MARKEDNESS constraints (specifying the well-formedness of surface forms) and FAITHFULNESS constraints (specifying the well-formedness of the relationship between the underlying and surface forms). Each underlying form is mapped to the surface form that best satisfies these ranked constraints. Since speech errors are a quintessential case of variation (the same intended form can be produced both correctly and as an error), utilizing constraint-based grammars to model speech error data requires a stochastic mapping between underlying and surface forms. The sections below review how two distinct approaches to producing stochastic patterns could be used to model speech errors. The final section turns to critical challenges facing such models.

4.1 MODELING SPEECH ERRORS USING GRAMMATICAL APPROACHES TO VARIATION

Constraint-based grammars have utilized a variety of formal mechanisms to model grammatical and sociolinguistic variation (Coetzee and Pater in press). In OT, the most common type of formal mechanism defines a function that assigns a probability to different rank orderings of the constraint set (Jarosz 2006, 2009; for specific mechanisms for assigning probability, see Antilla 1997; Boersma 1997; Boersma and Hayes 2001; Reynolds 1994).

The restrictive nature of OT grammars makes these variationist mechanisms inappropriate for modeling speech error distributions (Goldrick and Daland 2009). As noted above, speech errors *tend* to respect well-formedness. A number of studies suggest that although errors are more likely to target less frequent/more marked structures, they also occur on more frequent/less marked structures. This latter type of mapping—where a well-formed correct form is mapped onto a less well-formed error form—cannot be specified by an OT grammar that relies on a full ordering of the constraint set to determine the underlying-surface mapping (Moreton 2004; Prince 2007). Consider the grammar fragment shown in (1). There is no ranking of the constraints MAX ("Do not delete underlying segments") and ONSET ("Syllables must have onsets") such that candidate (b) is more well-formed than candidate (a). This grammar fragment would therefore never allow the well-formed target "bat" to be replaced by the less well-formed error "at." This is too restrictive to account for the full range of speech error distributions; although speech errors favor the production of more well-formed forms, they can also result in the production of less well-formed structures.

(1)

/bæt/	MAX	ONSET
a. [bæt]		
b. [æt]	*	*

Other variationist mechanisms in OT, HG and MaxEnt grammars are less restrictive and are thus plausible candidates for modeling speech error distributions. One type of mechanism assumes that the probability of an underlying-surface form mapping is a function of its relative well-formedness. Such a mechanism can assign non-zero (but smaller) probability to mappings where the intended correct form is more well-formed than the error. For example, in tableau (1) above, candidate (b) would merely be assigned a *lower* (but non-zero) probability. Within OT, Coetzee (2006) proposes that the rank order in well-formedness of underlying-surface mappings determines their probability. In MaxEnt grammars (Hayes and Wilson 2008), the probability of underlying-surface form mappings is directly specified by a non-linear function of their relative well-formedness.

Another type of variationist mechanism that could be used to model speech error distributions is one that leads to reversals of typical distinctions in well-formedness. In HG, the contribution of each constraint to well-formedness is determined by a real-valued weight. Boersma and Pater (2008) and Pater (2009) propose to account for variation by subjecting these weights to randomly varying noise. By altering the relative strength of constraints, this noise can alter the relative well-formedness of different underlying-surface form mappings—producing variation between surface forms. This can result in errors that map correct forms to relatively ill-formed errors by changing the sign of constraint weights. A change of sign would invert a constraint's well-formedness preferences, causing it to prefer structures that are typically ill-formed. For example, if the sign of the weight on the constraint ONSET in tableau (1) was reversed, this constraint would now prefer syllables *without* onsets. This mechanism could therefore give rise to errors that map (typically) well-formed correct targets to (typically) ill-formed errors.

4.2 SPEECH ERRORS AND MECHANISMS UNDERLYING GRAMMATICAL COMPUTATIONS

An alternative type of approach to speech errors assumes that the stochastic mapping between underlying and surface forms reflects disruptions to the algorithm that computes this mapping. One approach is to limit the resources available for computation. For example, constraint satisfaction problems (e.g., finding the underlying-surface form mapping that best satisfies a set of well-formedness constraints) are frequently solved by algorithms that stochastically search through solutions (Aarts and Korst 1989; see Biró 2005a,b, 2006, for applications to OT; for applications to HG, see Soderstrom, Mathis and Smolensky 2006; Smolensky, Goldrick and Mathis 2010). If given sufficient time, this search will terminate on the optimal underlying-surface form mapping. If placed under time pressure, the search may fail to find the optimal form; the probability of a given error outcome is a function of its well-formedness (Biró 2005a,b, 2006; Smolensky et al. 2010). This could give rise to error distributions that probabilistically respect well-formedness.

Instead of disrupting the mechanisms that search for a well-formed underlying-surface mapping, an alternative approach is to stochastically disrupt the mechanisms that compute well-formedness itself. Goldrick and Daland (2009) outline such a proposal in the context of HG grammars implemented within connectionist networks. In such networks, HG constraints and their relative weightings are encoded by weights or connections that link representational units (Smolensky and Legendre 2006; see also Legendre, Sorace and Smolensky 2006; Smolensky et al. 2010; Soderstrom at al. 2006). Goldrick and Daland modeled speech errors as resulting from stochastic noise that disrupts these weights. This noise allows the relative strength of constraints to vary; this results in variation much as in other HG approaches reviewed above (Pater 2009). Additionally, because the *content* of HG constraints are realized by these weights, this noise can produce variation by altering the constraints themselves. For example, Goldrick and Daland discuss a case where noise causes a constraint which normally refers to both voiced and voiceless stops to split into two constraints specific to each voicing category. They show that although these disruptions produce a wide variety of error types, they provably result in error distributions that probabilistically respect well-formedness distinctions.

4.3 CHALLENGES IN LINKING GENERATIVE PHONOLOGICAL THEORY AND SPEECH ERRORS

Few studies have actually utilized the broad approaches outlined above to quantitatively model empirically observed speech error distributions. Goldrick and Daland (2009) is the sole study to quantitatively model experimentally induced speech errors. Two other sets of studies present quantitative models of mis-productions in other domains. Biró (2005a, 2006) treats variation and reduction in fast speech as resulting from processing errors. Finally, Davidson, Smolensky and Jusczyk (2004) and Davidson (2006) model mis-productions of non-native clusters. Thus, although speech error data are clearly influenced by grammatical principles, they present a mostly unexplored empirical domain for testing the predictions of grammatical theories.

One critical area for developing such links will be bridging generative grammars and gradient phonetic data. As discussed above, much of the evidence in speech error research comes from transcription studies. As emphasized above, this does not invalidate the entirety of speech error research. For example, it is unlikely that experiment-specific well-formedness effects on speech errors merely reflect transcriber biases (Dell et al. 2000). However, it is likely that transcription-based analyses provide an incomplete picture of the empirical patterns. In particular, acoustic transcription is ill-suited for the observation and analysis of sub-phonemic or even sub-featural variation (Munson, Edwards, Schellinger, Beckman and Meyer 2010; Pouplier and Goldstein 2005). Experimental studies have documented such effects using quantitative acoustic analysis (Frisch and Wright 2002; Goldrick and Blumstein 2006; Laver 1980) and articulatory imaging (Boucher 1994; Mowrey and MacKay 1990; Goldstein et al. 2007; McMillan and Corley in press; McMillan et al. 2009; Pouplier 2003, 2007, 2008; Pouplier and Goldstein 2010). Importantly, these gradient effects are not simply 'motoric distortions.' They are modulated by more abstract, lexical properties; for example, whether the error outcome forms a word or nonword (Frisch and Wright 2002; Goldrick and Blumstein 2006; McMillan et al. 2009).

Theories of speech errors must therefore address not just the distribution of speech sound categories but also the gradient variation within these categories. Similar arguments have been made with respect to other phenomena in phonology and phonetics, in the specific context of Articulatory Phonology (Browman and Goldstein 1989; see Goldstein and Fowler 2003 for a recent overview), as well as more generally in the context of laboratory phonology (Pierrehumbert, Beckman and Ladd 2000) and dynamical systems approaches to cognition (Gafos and Benus 2006). These approaches offer a radically different perspective on phonological cognition than the constraint-based generative theories reviewed above. To capitalize on work conducted in generative frameworks, it may be productive to consider approaches that integrate these perspectives (see, e.g., Davidson 2006 for a recent review of work integrating Articulatory Phonology and OT).

Smolensky et al. (2010) propose an alternative approach based around generative grammars that aims to integrate gradient variation with categorical, combinatorial structure. In their Gradient Symbol Processing framework, linguistic representations are realized as continuous numerical pattern of activity. During language processing, an optimization process favoring representations that satisfy well-formedness constraints (specified by an HG) operates in parallel with a process favoring discrete symbolic structures. As noted above, when this optimization process operates under time pressure, speech errors result (with error probability reflecting well-formedness). Time pressure also interferes with the process that favors discrete symbolic structures—allowing for gradient effects in speech errors (see Smolensky et al. 2010 for simulation results and discussion).

Another challenge to work aiming to link generative grammars and speech errors is situating grammars within the cognitive system. As noted by Chomsky (1980: 188) "the system of language is only one of a number of cognitive systems that interact in the most intimate way in the actual use of language." Attributing any particular behavioral effect to some specific component(s) of the cognitive system requires one to parcel out these interactions (Goldrick in press).

Some of the seemingly inconsistent empirical results in the literature are likely to result from failing to address this issue. As noted above, some studies of both spontaneous errors and errors in aphasia have failed to document an influence of well-formedness on error probability. The contrast between these and other errors may reflect different functional loci of disruption to the speech production system. For example, Goldrick and Rapp (2007) present evidence that phonological errors arising during access to the lexicon are insensitive to phonological well-formedness. This factor only influences errors arising during subsequent post-lexical processes.

Results such as these suggest that grammatical knowledge is not uniformly distributed throughout the cognitive system. Connecting behavioral data such as speech errors to grammatical knowledge requires more than simply observing the distribution of phonological structures produced by speakers. Because not all speech error distributions are relevant for grammatical theory, one must consider how grammatical knowledge is instantiated within the interacting set of cognitive processes underlying speech production. Articulating how errors arise within these processes will allow a more principled link to be made between behavioral data and grammatical knowledge.

5. CONCLUSION

A wealth of empirical evidence suggests there are deep connections between speech errors and the principles of linguistic theory. Errors reflect the structure of linguistic representations throughout the prosodic hierarchy. They are sensitive to the productivity of phonological alternations and the distinction between phonological structures that are possible vs. impossible within a language. Although the evidence is somewhat mixed, cross-linguistic and within-language well-formedness distinctions also appear to influence speech error distributions.

Despite these deep connections, very little work has explored connections between generative phonological theories and speech errors. Errors could be modeled through formal mechanisms used to account for sociolinguistic and grammatical variation or through disruptions to algorithms that compute the function specified by the grammar. Future work developing such connections will have to confront two general issues in the modeling of data from speech production: capturing phonetic gradience as well as phonological structure; and articulating how the grammar interfaces with the other cognitive processes underlying speech production.

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