Intervention for speech production in children and adolescents: Models of speech production and therapy approaches. Introduction to the issue.

Interventions en production de la parole chez les enfants et les adolescents : modèles de production de la parole et méthodes d'intervention. Une introduction.

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Abstract

Although phonological intervention can be effective in the short-term (Law, Garrett & Nye, 2009), long-term normalization has been reported for only 20-50% of children (e.g., Rvachew, Chang & Evans, 2007). Furthermore, even in the short-term, not all children progress as quickly as might be hoped. Thus, it is important to continue to develop alternative approaches to intervention. The current issue describes recent studies concerning speech habilitation in children and adolescents, including an adaptation of nonlinear phonological assessment to Mandarin (Bernhardt & Zhao) and intervention approaches focusing on perception (Shiller, Rvachew & Brosseau-Lapré), discourse (Baker & McCabe) and visual feedback of tongue movements with ultrasound (Bacsfalvi). The range of approaches reflects the complexity of the speech production system. This introductory article discusses models of speech production processing as a foundation for the approaches presented.

Abrégé

Les interventions phonologiques peuvent être efficaces à court terme (Law, Garrett & Nye, 2009), mais la normalisation à long terme ne se produit que chez 20 à 50 % des enfants, selon la recherche (p. ex., Rvachew, Chang & Evans, 2007). De plus, même à court terme, les enfants ne progressent pas tous aussi vite qu'on ne l'espèrerait. C'est pourquoi il est important de continuer à établir de nouvelles méthodes d'intervention. Le présent numéro compte des études récentes sur la thérapie de la parole auprès des enfants et des adolescents, y compris l'adaptation d'une évaluation phonologique non linéaire en mandarin (Bernhardt & Zhao) et des méthodes d'intervention axées sur la perception (Shiller, Rvachew & Brosseau-Lapré), le discours (Baker & McCabe) et la rétroaction visuelle des mouvements linguaux à l'aide d'ultrasons (Bacsfalvi). La diversité des axes d'intervention de ces méthodes reflète la complexité du système de production de la parole. Cet article d'introduction examine des modèles de traitement de la production de la parole en tant que fondements des méthodes présentées.

Key words: Models of speech production, interactive activation models, phonological intervention, articulation and phonology

Children with protracted phonological development (PPD, sometimes called speech sound disorders of unknown origin) comprise the largest group in paediatric caseloads (ASHA, 2003). Although phonological intervention can be relatively effective in the short-term (Almost & Rosenbaum, 1998; Law, Garrett & Nye, 2009), studies report long-term normalization for only 20-50% of children (Shriberg, Kwiatkowski & Gruber, 1994; Bernhardt & Major, 2005; Rvachew, Chang & Evans, 2007). Even in the short-term, not all children progress quickly, especially if there are associated factors such as hearing impairment, orofacial anomalies, language or other cognitive processing difficulties. Thus, it is important for clinicians and researchers to continue to develop and evaluate approaches to speech habilitation.

The current issue describes recent research concerning speech habilitation in children and adolescents. Methods address both assessment and intervention: nonlinear phonological assessment adapted for Mandarin (Bernhardt & Zhao, this volume) and intervention focusing on perception (Shiller, Rvachew & Brosseau-Lapré, this volume), discourse (Baker & McCabe, this volume) and visual feedback of tongue movements with ultrasound (Bacsfalvi, this volume).

The range of approaches described reflects the complexity of speech production, which minimally requires integration of information from (a) perception; (b) representation (semantic, morphosyntactic and phonological); (c) articulatory parameters including speech timing and aerodynamics; and (d) discourse parameters. In the last few decades, psychologists, speech scientists and linguists have proposed a variety of models of speech production processing (see e.g., the issue of *Language and Cognitive Processes*, 2009, 24(5)). Models are abstractions of a dynamic process and thus underdetermine what actually occurs. However, reflection on the various aspects of speech production processing has the potential to stimulate new approaches to intervention. This introductory article thus discusses models of speech production processing as a foundation for the approaches presented in the issue. (See also Baker, Croot, McLeod, & Paul, 2001, for an earlier, still useful tutorial on the use of psycholinguistic processing models in speech therapy.)

Models of Language Production

Language production is a process that recodes a meaningful message into an output form that can be decoded by others to recreate the original message. While the creation of this message (i.e., what the speaker decides to say) is important, models of language production focus on what happens after that. Figure 1 indicates the various components involved in language production. Within the circle are the main linguistic levels for the processing of words and their pronunciations (ordered from early in processing at the top to later in processing at the bottom). Syntax is in a box at the right, showing interactions with multiple levels; the network of elements within the circle will be discussed in more detail below. Outside the circle are other aspects of cognition that influence language as well as cognition more broadly.

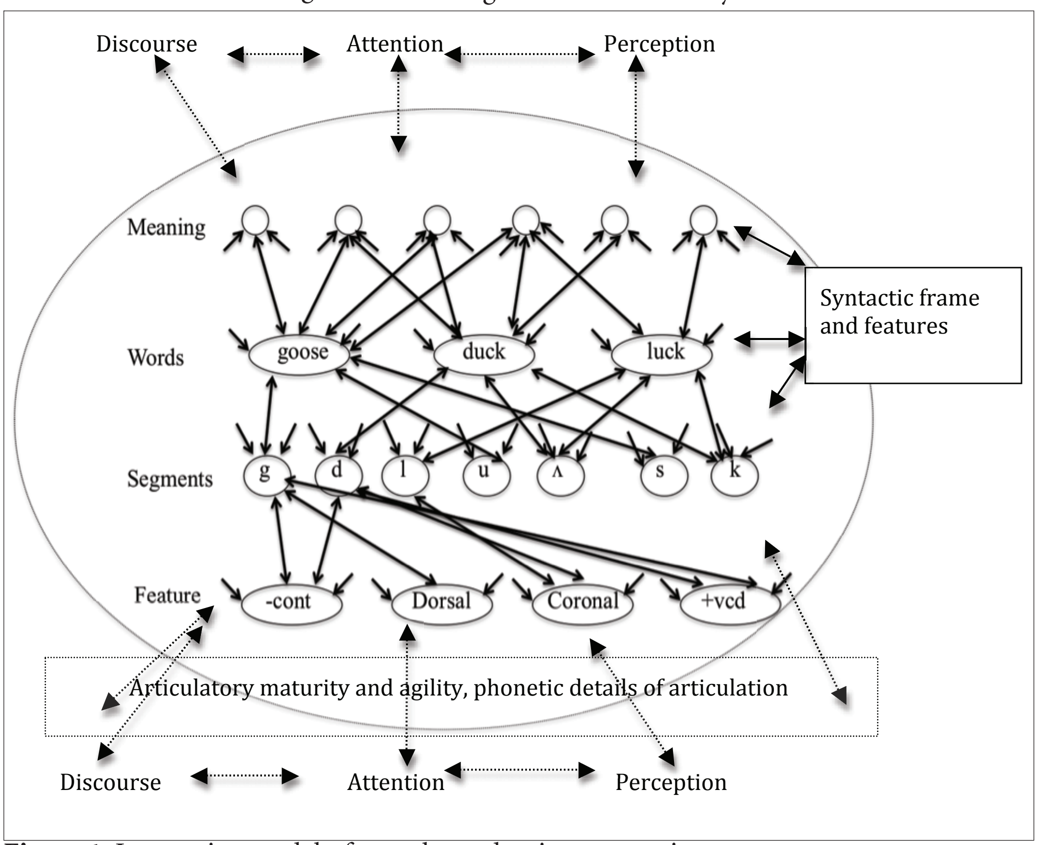

Figure 1: Interactive model of speech production processing.

Attention, perception, discourse constraints and pragmatics play a large role in message construction, but also play a role at other levels in language production. The message itself is meaning-based, and is generally viewed as involving the simultaneous representation of all parts of a proposition; i.e., in a sentence like *the red ball is rolling*, the ball, its color and its activity are represented simultaneously in the brain. The spoken output form, in contrast, is necessarily linear: a sequence of words and sounds. Part of the recoding process converts nonlinear meaning-based representations into linear sequences at several levels (words/morphemes, phonology/phonetics). Models may be similar in their positing of multiple levels of units between meaning and phonetics (i.e., words, syllables, phonemes/segments, features) and in inclusion of mechanisms for ensuring proper sequencing (syntax, syllable structure), but they differ in details and perspective. The following overview contrasts symbolic and interactive (connectionist) models, suggesting clinical implications where relevant. The discussion focuses first and foremost on the phonological domain, the core domain for speech production processing. The ensuing discussion outlines potential interactions of phonology with other domains or factors, i.e., the lexicon, morphosyntax, discourse, perception and attention.

Phonology

Language production involves a mapping from meaning (semantics and pragmatics) to output form (ultimately, articulation). Models differ in their description of how this mapping is achieved, i.e., (a) on whether the mapping is direct (in one step) or via a series of levels, which can be organized serially or interactively; (b) on whether output forms are permanently stored and accessed directly or constructed each time used; (c) on how developmental errors (or mismatches with the adult language targets) occur; and (d) on the mechanism for generalization (and overgeneralization) across elements in output forms. These dimensions are discussed in subsequent sections in terms of the various models.

We note here that the ultimate mapping in speech production is onto acoustics, and consequently some have questioned whether speech sounds are coded in terms of acoustic targets, with realization in articulatory/motor form aimed solely at reaching those acoustic targets (e.g., Callan, Kent, Guenther, & Vorperian, 2000; Guenther & Perkell, 2004; Perkell, Matthies, Svirsky & Jordan, 1995). Others (e.g., Browman & Goldstein, 1992; Fowler, 1993) argue that targets may be articulatory and reflect (invariant) constraints on articulator movement. Bernhardt and Stemberger (1998) argue that the majority of systematic errors in child phonology appear to be based on articulatory similarity rather than acoustic similarity. For example, the nasals [m, n] generally pattern with oral stops (as expected on the basis of articulation), and not with fricatives or glides (as might be expected on the basis of acoustic similarity, i.e., continuous acoustic energy or formant structure). They also note, however, that there are specific minority patterns which suggest an acoustics-based explanation. Both articulation and acoustics clearly play a role in production (for children and adults), and the decision here to view the articulatory encoding as the target must be viewed as controversial or at least oversimplified.

Meaning-to-form mapping: Simultaneous, sequential or both?

Models differ in the assumed depth of processing and time needed for mapping between meaning and form. More traditional *linear* models (e.g., Garrett, 1975; Levelt, Roelofs, & Meyer, 1999; Shattuck-Hufnagel & Klatt, 1979) posit a distinct set of levels between meaning and form; information flow is considered sequential and unidirectional (from one level to the next later down, never with feedback to an earlier level). For example, Garrett (1975) presupposes that meaning is first mapped onto lexical items, which then give access to syntactic and phonological form. Levelt et al. (1999) splits lexical processing into two levels (access of meaning-based lemmas, then form-based lexemes). Shattuck-Hufnagel and Klatt (1979) presuppose that phonological form, after being fully accessed, is inserted into sentence structure. Other models assume at least some simultaneous processing. For example, *Parallel Distributed Processing models* (PDP, or distributed connectionist models) map from an input to an output, with the two levels being meaning and form (e.g., Dell, Juliano, & Govindjee, 1993; McClelland & Patterson, 2002). *Usage-based models* (e.g., Tomasello, 2003; Bybee, 2006) and *exemplar-based models* (e.g. Pierrehumbert, 2001) are explicit that meaning-to-form is the level of mapping. In principle, all output units that one would want to consider "simultaneous" are accessed at the same time, and can be influenced directly by any aspect of meaning. Interactive activation models (local connectionist, e.g., Dell, 1986; Stemberger, 1985, 1992), assume more temporal gradience, such that words first access fairly coarse information (phonemes and syllable frames), then finer information (phonological features), and eventually very fine information (phonetic details of articulation). In interactive models, information flow is always bidirectional, such that information activated on later levels affects the activation of information at earlier levels. This bidirectional flow of activation is illustrated in Figure 1 with bidirectional arrows between units of meaning with word units, between word units and segment (phoneme) units, and between segment units and feature units. Activation of the meaning units for {duck} leads to strong activation of the word unit *duck* (but also intermediate activation of the word unit *goose*). Activation of the word unit *duck* leads to activation of the phonemes /d/, /ʌ/, and /k/, from which activation flows back to semantically unrelated word units (such as *luck*). Activation flows from /d/ and /k/ to feature units such as [Dorsal] and [+voiced], from which activation spreads back to nontarget segments such as /g/ (which may be erroneously output, as in [gʌk]). Interactionist approaches to intervention assume that targeting one aspect of the linguistic system can have ripple effects throughout the system in any direction. In terms of clinical implications, this suggests that intervention could start from a number of access points, from discourse to phonetics (as is presented in this volume). More symbolic linear models suggest that intervention needs to address the earliest level of breakdown in the language production process and build to the other later levels from that level; if work is done at the level of phonetic implementation (articulation), this in principle should have minimal or no impact on larger more abstract units of the system (syllable structure, word structure, sentence structure).

Output forms: Off-line storage or on-line access?

Models also differ in assumptions about whether output forms are permanently (and stably) stored and then accessed during language production, or whether they must be constructed each time, leading to a system where instability is predicted. Most symbolic models (e.g., Garrett, Levelt, usage-based models, exemplar models) suggest that output form is stored in lexical entries. A stored word is placed in a discrete chunk of neural material that is dedicated to that word only and not used to store any other word (parallel to the storage of words on the page in a physical dictionary). Generalization across stored words is only possible if there are mechanisms external to the stored items designed for that purpose. All connectionist models take the opposite view, that output form is *constructed* each time on the basis of activation passing through connections from higher levels. It is often said that all words are "stored" in the same set of units, so that their representations overlap. It is impossible to discretely access one word without (positive or negative) interference from other words (an automatic form of overgeneralization). Because construction-based systems emphasize competition between outputs, accurate output is predicted to be impossible (or nearly so) in early stages of learning (and after brain damage); stable outputs are only possible after learning.

Clinically, all approaches to speech intervention are concerned with learning over a set of trials (whether perceptual or articulatory). Errors are expected in early phases of learning, and stability after sufficient practice. Thus, speech intervention appears to operate with at least some connectionist assumptions. Approaches that draw attention to perception (e.g., Shiller et al., this volume) may also assume that intervention enhances the representation of (stored) lexical entries.

Sources of speech production errors (mismatches) during development

Models differ in how they view the systematic errors (mismatches between target and child pronunciations) that arise during development. Most symbolic models (e.g., Garrett, Levelt, usage-based models, exemplar models) are based on adult language and thus do not attempt to account for development. Usage-based and exemplar-based models address learning as generalizations across stored forms, but do not provide explanations of early phonological phenomena. Sosa and Bybee (2008), for example, discuss the implications of usage-based phonology relative to frequency and neighbourhood effects, but do not mention the mechanisms responsible for phonological patterns such as reduplication or the realization of fricatives as stops. Bybee (2006: 15) refers to "articulatory routines that are already mastered," which possibly implies that child phonological phenomena arise in the mapping from adult-like phonological representations (which the theory addresses in detail) to pre-packaged articulatory routines as described in Levelt et al. (1999), but which are not addressed in the Bybee paper. Presumably, the phenomena that arise during this mapping are unrelated to the basic generalization process of the usage-based approach. Generalization and accuracy in processing in such models favour high-frequency information, but high-frequency elements, e.g., [l] (one of the five most frequent consonants in English) and codas (found in about three-quarters of English monosyllables) are in fact often missing from child pronunciations. If the statistically constructed stored items are not the source of all errors that occur in development, then the source of at least some errors must be in a separate component, e.g., during phonetic implementation (articulation). Bernhardt and Stemberger (1998) agree that some aspects of mismatch pronunciations are articulatory-phonetic in origin, and that every model must have some way to account for that. They argue, however, that articulatory-phonetic effects reflect interactions between phonological and phonetic levels. Phonetic output states that are difficult to achieve make it more difficult for the phonological system to settle into the output state that would lead to that articulation (see below). The paper by Bacsfalvi (this volume) addresses the interaction of phonetic and phonological development, by its focus on the details of phonetic implementation (with a combination of visual and auditory feedback) while working to establish the cognitive basis for development of phonemes. (See also Bernhardt, Stemberger, & Bacsfalvi, 2010.)

Stemberger (1992) argues that connectionist models automatically produce the sort of systematic mismatches that we observe in child phonology, including variability across children, but notes that there are no computer simulations proving such claims. Such processing models assume that mapping from words to segments to features to phonetics must be learned, and so initially there are many aspects of the mapping that are inaccurate. Before any words are produced, the system (which began with partially random settings, such that different children have settings preadapted to accurate production of different sounds) learns some mappings during babbling. Sounds that are frequent during babbling thus tend to appear in the pronunciations of early words. When the child attempts to produce a sound that is impossible in his/her output (e.g., [l]), there will be accurate activation of some features, which then via feedback activate competing phonemes that share some features. Resonance between secondarily-activated segments and features ultimately leads to the access of a non-target segment that shares features with the /l/, such as [d] or [w]. Competition between the different segments leads to one segment being accessed, and which wins is different for different children and across time for a given child. One factor that affects the output is the weight settings of connections between segments and features. For example, do these settings favour the output of a coronal ([d]) or a sonorant ([w]), both of which share different features with the target /l/? While the details of what is output depend on the details of the system, the fact that there are changes from the target is derived automatically. Any construction-based processing model will account for the fact that children produce mismatches.

The individual nature of phonological development supports an individualized approach to assessment and intervention. While standardized articulation tests can give some idea of the developmental level of a child, norms are just statistical predictions about what phonemes may appear when and what types of deletions and substitutions are 'typical' or less typical. Each child has his or her own developmental path, and a comprehensive assessment and treatment plan (as in Bernhardt & Zhao, this volume) can help accelerate change along that path. Symbolic models may not preclude individualized treatment, but there is often a stronger universalist assumption about order of development in such accounts (from Jakobson, 1968/1941).

Further to accuracy of production, there are several important effects that models must account for, deriving from type and token frequencies of various types, including:

1. Lexical frequency: High-frequency lexical items may have more accurate phonology than low-frequency lexical items (for adults, e.g. Stemberger & MacWhinney, 1986; for children, e.g., Tyler & Edwards, 1993).

2. Phonological frequency: High-frequency phonemes and features are generally processed more accurately than low-frequency items (for adults, e.g. Stemberger, 1991; for children, e.g., Pye, Ingram, & List, 1987). Stemberger (e.g., 1991) notes, however, that there are (arguably predictable) exceptions in which the highest-frequency competitor is at a processing disadvantage and shows higher error rates than lower-frequency competitors.

3. Resemblance to other lexical items: Words that share elements of phonological form interact, such that aspects of the output that are shared with many words are more accurate than aspects that are shared with few words (for adults, e.g. Stemberger, 2004; for children, e.g., Zamuner, Gerken, & Hammond, 2004). This is type frequency. Words from high-density neighbourhoods are phonetically different from words from low-density neighbourhoods (see Baese-Berk & Goldrick, 2009, for recent discussion).

Further to neighborhood effects, words which are very similar to each other (differing by a single phoneme) tend to have the greatest amount of influence on each other. Symbolic models (most explicitly usage-based and exemplar-based models) draw a categorical distinction between words being in the neighbourhood or not. They have a direct effect on the size of the neighbourhood and no structure within the neighbourhood. However, Stemberger (1985, 1992) notes that, from a connectionist perspective, neighbourhoods comprise only the words that are most similar to the target word, and we also expect lesser effects from words that are similar to lesser degrees. Vitevitch (2002) and Dell and Gordon (2003) argue that large neighbourhoods lead to more accurate phonological processing in language production (at least for normal adults and adults with neurogenic disorders). However, Stemberger (2004) argues that the size of neighbourhoods *per se* has no effect, but rather subsets of words within the neighborhood. Words in the neighbourhood that have a particular characteristic in common with the target word (e.g., word-initial /s/) are "friends" that reinforce that characteristic in the output; the more friends, the greater the reinforcement of that output. Words in the neighbourhood that do not have that characteristic are "enemies" and reinforce something else. However, if each word reinforces something different (e.g., word-initial /f/ vs. /p/ vs. /k/, etc.), then the enemies form a diffuse group that has little overall impact on processing. Only when enemies share a common characteristic (e.g., beginning with a single consonant and not with a cluster, or ending with past-tense -ed) do they form a 'gang', and there is then a detectable impact on the accuracy of processing. None of the articles in this volume directly address the implications of neighborhood effects for intervention, but the models do suggest that word selection for treatment activities may affect rate of change (see, e.g., Morrissette & Gierut, 2002).

There are numerous ways that the positive or negative effects of other items in the lexicon could arise. In interactive activation models, activation is seen as spreading from one activated element to all elements to which it is connected, whether those elements are "later" in processing (closer to phonetic implementation) or "earlier" (closer to meaning) than the activated element (see Figure 1). As noted earlier, language production begins with the activation of meaning elements (semantic and pragmatic) that express some message that the speaker wants to share with an interlocutor. The activated elements activate lexical items, which sum activation and attain an activation level that depends on how many meaning units activate it. Thus, the meaning {duck} will activate the word *duck* most strongly, but will also activate related words such as *goose*; Stemberger (1985, 1992) assumes that target words inhibit competitors, such that only a single item is accessed at high levels, and that all others are reduced to low levels of activation. Inhibited competitors are still at non-zero activation levels (especially early in processing) and can influence elements later in processing, but at a low level that constitutes noise; only if large numbers of inhibited competitors share some phonological characteristic (e.g., word-final /k/) would phonological processing be affected to any great degree. The target word (here *duck*) spreads activation to its component phonemes (/d/,/ʌ/,/k/), which in turn activate their features. But the phoneme /k/ also spreads activation back to the word *luck* and to all other words that end with /k/. Each word of this gang is kept at a low activation level by the target word *duck*, but because they are a coherent gang in which all members reinforce the final /k/, they are friends that improve the processing of the final /k/. The phoneme /k/ also spreads activation forward to its features [Dorsal], [-voiced], etc., which are also accessed by other phonemes. To the extent that these are activated by other phonemes, their processing is improved, which in turn improves the processing of the /k/ (and of the word *duck*). Token frequency is encoded via resting activation level: higher-frequency words, phonemes, and features have higher resting activation levels and need less additional activation to be accessed. Resonance with competing lexical items and phonemes leads to type frequency effects (weighted by the resting activation level of the competing elements). Token-frequency effects thus arise early in processing (inherent in the access of a unit), while type-frequency arises later (via resonance with other units). Elements which are not represented as a single unit (e.g., the consonant cluster /bl/, which is represented as the two phonemes /b/ and /l/) are predicted not to have direct token-frequency effects, but only type-frequency effects (weighted for the lexical frequency of each word that contains /bl/, leading to some indirect token-frequency effects). The complex interaction of elements within words further reinforces the perspective that word selection is important during treatment. For a speaker who produces velars as coronals, words with two velars may be more accurately produced than words with one velar and one coronal in early phases of intervention.

Resonance in the system has two further consequences. First, resonance between phonological output elements and articulatory states either reinforces the activation of the phonological units, and hence facilitates access, or does not because a target articulation is either impossible or marginal. This leads to impaired processing of the phonological units, and the increased possibility of error/mismatch. In practice, if an articulatory state is impossible or marginal, the system will settle into some other phonological output pattern. Which phonological output state it settles into is related to similarity, in terms of shared phonological elements such as features, and resonance with the lexicon. Because the lexicon is constantly growing during development, the likely alternative output state can change over time due to changes in the lexicon. Secondly, resonance causes generalization and overgeneralization between different words and phonemes, another issue on which models disagree.

Generalization and over-generalization

In an interactive activation model, if access of /k/ is impossible or marginal, a related phoneme (e.g., [t]) that shares many features will tend to be accessed instead. This is because /t/ is activated by feedback from the features of [k], is reinforced by many lexical items containing /t/, and (unlike [k]) is already a possible output. As noted above, usage-based and exemplar-based models do not account well for the difficulties shown in phonological development, relegating such effects to a separate performance component. Insofar as predictions are made by such models, however, high-frequency patterns will be overgeneralized to replace low-frequency patterns, whether high-frequency in general or in a very specific environment. For example, if [k] is not possible in the output, the high type and token frequency of anterior coronals may lead to the overgeneralization of [Coronal, +anterior], for the output [t], in which the tongue is flat ([-grooved]). If a cluster such as /kl/ coalesces to a coronal fricative, however, the fact that /s/ is of far higher frequency than /θ/ in English may lead to the output [s] (e.g. *climb* /klaɪm/ [saɪm]), even though neither target is [+grooved]. Predictions from usage-based and exemplar-based accounts differ from connectionist predictions in two ways, both stemming from the fact that usage-based and exemplar-based models are locked into statistical generalization across stored forms: (1) connectionist models additionally allow for a random component in the initial weights in the system, before any learning takes place (see above), and tuning of the system to non-lexical phenomena such as babbling; and (2) weights in a connectionist model can be changed without any change in the make-up of the lexicon (see below).

Some researchers have claimed that standard terminology (substitution, deletion) implies that the output must be (a) phonetically identical to a similar sequence that correctly matches the adult target, and (b) can have no trace of the target elements. There is much research that shows that these putative implications are false, for at least some errors by some children (e.g., Gibbon, 1990) and by normal adults and adults with neurogenic disorders (e.g., Pouplier & Hardcastle, 2005). These subthreshold differences are referred to as “incomplete neutralization” or “covert contrasts.” However, Bernhardt and Stemberger (1998) and Stemberger (2007) note that these implications do not hold for connectionist models. Given variability of processing, and the complex interaction of elements at all levels, (a) no two tokens of the same word are identical in terms of timing of processing or final output strength of elements at any level, and (b) there is a large amount of subthreshold activation that constitutes “noise” and may occasionally have observable articulatory effects that are imperceptible to the listener. Bernhardt and Stemberger suggest that e.g. [t] as an error for /k/ has a strength distribution with a lower mean activation level than for target /t/ which, among other possibilities, is less effective at inhibiting the feature [Dorsal] and may be associated with subthreshold velar movement. Blumstein and Goldrick (2006) have recently shown for (tongue-twister) errors by normal adults that these small subthreshold differences are observable when the errors create nonwords but not when they create words. This is because resonance with the real word in the lexicon reinforces the strength of the output of the error segment. Developmentally, subthreshold differences are expected to arise especially just prior to changes in outputs; just before [k] becomes a possible output (meaning that it achieves higher activation levels than [t]), there may be a period at which the final activation level of target [k] is still low, but is high enough to decrease the activation level of error [t], leading to phonetic traces of the /k/. Any implication that errors and targets should be phonetically identical is restricted to other types of processing models, if any.

No matter what the intervention approach, treatment strategies are designed with a goal of efficiency, i.e., with hope of systemic generalization rather than element-by-element, item-by-item learning. Over-generalization may be seen as an impediment to efficiency. The usage- or exemplar-based and interactionist models both suggest that generalization will occur, but the greater variability across children predicted by the connectionist models suggests that this may not always occur easily for all children. Furthermore, both types of models imply that over-generalization is a possibility.

Further to this topic, interactive activation models operate with a perspective of 'error-driven learning', which is also seen to influence the nature of errors and generalization/over-generalization effects. The learner's system, after producing a mismatch with the language adult target, alters the weights on the connections between units on different levels, such that a mismatch will be (slightly) less likely on the next token of this particular target. Thus, if /l/ is pronounced as [d], the strength of the connection between the phoneme element /l/ and the features [+lateral] and [+continuant] will be increased, leading to greater activation of these features. But if target /l/ is still inaccessible, these error-driven changes in the weights make [+continuant] consonants better competitors than before, and so the mismatch for target /l/ may change from [d] to [z] or [j]. Over time, a child's pronunciation is expected to improve gradually, even if no new words are learned during this period, so that there are no changes in phonological type frequencies. In addition, as weights are increased or decreased to prevent mismatches, the balance of activation may shift so that one feature improves, but another gets less accurate, resulting in a (usually temporary) instance of U-shaped learning, often termed a *regression* in the phonological-development literature. Regressions can occur during intervention (all coronals becoming velars for a time after velars enter the system, with or without therapy); this is a possible and natural occurrence during error-driven learning and generally resolves itself as the system reorganizes itself.

Previously in this section, the relevance of word selection in treatment was indicated (neighborhood effects, type or token frequency). The concept of error-driven learning entails that, in clinical practice, it should be effective to work with known words, and that improvements can be made to the child's system without learning new words (to alter the statistical properties of the lexicon). Insofar as usage-based and exemplar-based models are compatible with such an expectation, the locus of the effect must belong to performance (about which the models provide little information and hence no guidance for clinical practice). New words, including nonsense words, are not precluded in treatment and may have the added advantage of increased attention (see the discussion below concerning interactions between phonology and other factors). But once lexicalized, nonwords are real words, and thus the system will react to them in a way that is similar to that of other words already in the lexicon.

Summary

The above discussion gave a brief overview of models of language production, showing some contrasts in perspectives and possible implications for phonological development and intervention. Models always underdetermine data and it is only through systematic exploration that creation, refinement or discarding of models can occur. The discussion suggests that an interactive activation model may be more congruent with an intervention process. Strength of activation of target units is enhanced through therapy input, and learning is promoted throughout the system by intervention starting at one or more points in the system. It is unknown whether there are stored, and possibly statistically defined, representations that also change as a result of intervention. Many alternative models (e.g., usage-based, exemplar-based, Levelt et al., 1999) do not always have clear clinical implications for protracted phonological development because they have not been sufficiently elaborated to account for phonological development. However, they have been profitably employed for, e.g. acquired neurogenic impairments in adults, where the adult system was achieved before the onset of the insult. For example, Laganaro (2008) applies the Levelt et al. (1999) model to the processing of syllables in aphasia. Maassen, Nijland & Van der Moelen (2001) did investigate syllable processing in children, based on the Levelt model. When testing children with and without a diagnosis of developmental apraxia of speech, they observed that children with the diagnosis of developmental apraxia showed less refined syllable boundaries, suggesting a breakdown in processing at the syllable level.

Phonology is not the only component of speech production as we observed at the outset of this section. The next section outlines potential interactions of phonology with other domains.

Phonology and Other Linguistic Domains: Semantics and Morphosyntax

In the mapping from meaning to output, a simultaneous, non-linear semantic representation for all parts of a proposition is converted into a linear sequence of words and sounds. Speakers must coordinate phonological processing with other levels of language processing, including selecting words whose semantic content matches the intended message, and building sentence structure. Production models remind us that phonological access may interact with or be influenced by these activities in different ways. In interactive activation models, modular feed-forward models and usage-based/exemplar-based storage models, phonological access depends at least in part on activation input from "higher level" representations of the word's meaning and grammatical category (Levelt et al., 1999; Stemberger, 1992). Interactive activation models are characterized by simultaneous processing for the access of a word and its sounds (via feedback). Most models do not require that all processing on a given level must go to completion before any processing may begin on the next level. Production can be *incremental*; e.g., when lexical access of a particular word in the sentence goes to completion, the speaker can begin processing that word phonologically, even though lexical access is still ongoing for other words in the sentence. As such, phonological processing for a given word can be completed concurrently with work completed at other levels for other parts of the sentence (e.g., Bock & Levelt, 1994; Dell, 1986; Ferreira & Slevc, 2007). Researchers are currently investigating how large a chunk of phonological content for a syntactic unit will receive activation at once. Proposals range from the phonological word (e.g., Levelt et al., 1999) to larger, phrase-sized units (e.g., Damian & Dumay, 2007; Jescheniak, Schriefers, & Hantsch, 2003). Most models additionally assume that the building of syntactic structures occurs at the same time as, and interactively with, lexical access (e.g., Bock & Levelt, 1994).

How might interactions arise between semantic and syntactic levels and phonological processing? The notion of *accessibility* is particularly useful for thinking about how these effects could occur. The accessibility of a phonological form – and thus the likelihood of error – is affected by the amount of activation it receives from connections to lexical-semantic levels. The accessibility of a phonological form may also be affected by the current activation level of other units. Simultaneous activation of more than one word – as might occur in syntactic phrase planning – increases the opportunity for either interference or support (Stemberger, 1992).

Finally, much of the child-focused research on interactions between semantics, syntax, and phonology has been guided by a *limited capacity* perspective, to which the notion of accessibility can also be usefully applied. According to this perspective, cognitive activity is made possible by a finite amount of processing resources that allow us to activate, manipulate and store or maintain information (Kail & Bisanz, 1982). Most discussions of processing resource and capacity include the notion of working memory, which refers to the system(s) responsible for computation and maintenance of information (Baddeley, 2002; Just & Carpenter, 1992; Miyake & Shah, 1999). However, models of working memory vary considerably (Miyake & Shah, 1999), as does the extent to which the terms "processing capacity" and "working memory" seem to be used interchangeably. Moreover, researchers describe the nature of processing resources and the limits on capacity in different ways, sometimes referring to the amount of mental fuel or energy that is available for a task, the size or amount of cognitive workspace that is available, or how quickly or efficiently a person can use available resources (Kail & Salthouse, 1994). Central to all of these descriptions, however, is the idea that the availability of processing resources imposes limits on the amount or complexity of cognitive work that an individual can complete at any given time (Kail & Bisanz, 1982). When a task demands more resources than are available, performance may suffer.

Language researchers have proposed that capacity limitations can lead to performance *trade-offs* between language domains due to processing resource allocation at the time of speaking: When work that is completed in one domain of language demands too much resource, decrements in performance in other domains might be observed (see Charest & Johnston, 2009; Crystal, 1987, for further discussion). For the purposes of this discussion, commitment of mental resources to complex or effortful work elsewhere in the production process may affect the accessibility of a phonological form because fewer resources are available to commit to the work of producing that form.

A small body of research has explored the effects of lexical semantics and syntax on children's phonological output. In the lexical realm, phonological success seems to vary with word class (Camarata & Schwartz, 1985; Weston & Shriberg, 1992). Camarata and Schwartz demonstrated that very young children with typical and impaired language development produced similar phonological mismatch patterns in action and object words, but had more mismatches overall in action words. The authors speculated that semantic processing is more challenging for verbs than objects, leading to decrements in phonological processing.

In the syntactic realm, some children appear to produce more phonological mismatches in multi-word than in single-word contexts. This has been observed in the transition from single-word to multi-word speech (Donahue, 1986; Scollon, 1976), and in comparisons of preschool-aged children's single-word productions to their productions of the same words in sentences (Andrews & Fey, 1986). In keeping with frequency effects as discussed above for models, Morrison and Shriberg (1992) reported that mismatch increases from single-word to sentence contexts were limited to those sounds that the children produced with generally high (i.e., > 50%) mismatch rates in single words. That is, forms with marginal accessibility were more vulnerable to interference from interactions of linguistic levels during production. Some studies have also reported that children with and without phonological and other language impairments show more phonological mismatches in long, complex sentences than in short sentences (Crystal, 1987; Masterson & Kamhi, 1992; Panagos, Quine, & Klich, 1979; Weston & Shriberg, 1992).

Not all children show greater phonological difficulty as their language complexity increases, however (Panagos et al., 1979; Kamhi, Catts & Davis, 1984; Masterson & Kamhi, 1992), and some mismatches in sentences may be due not to resource limitations but to other difficulties that can arise in the sentential context, such as difficulties with sequences of consonants arising at word boundaries (e.g., the /km/ sequence in the phrase *pick me up*). Whether or not phonology is affected might depend on several factors, including the child's overall speech, language and cognitive skills (and attention to such skills), whether or not the child (in spontaneous productions) attempts sufficiently challenging language forms, and individual differences in whether or not the child tolerates variability in their phonological output (Kamhi et al., 1984).

The above research suggests that, in some cases, children's phonological success will be affected – for better or worse – by lexical and syntactic processing. Given that it is not uncommon for phonological impairments to co-occur with challenges in other aspects of the language system (e.g., Paul & Shriberg, 1982), a perspective that includes consideration of lexical and syntactic influences can contribute helpful information about the strength of a child's access to a targeted speech form, factors influencing variable success rates, and strategies for improvement. The paper by Bernhardt and Zhao (this volume), based on Bernhardt and Stemberger (2000) draws attention to the interactions of phonology with other domains in the last phases of the phonological intervention planning process.

Phonology and Other Factors in Language Processing: Discourse, Attention and Perception

Interactions between distant parts of the system (e.g., discourse units and phonology) are not equally possible in all models of speech production. In modular feed-forward systems such as Levelt or Garrett, we expect no direct effects of pragmatics/discourse on phonological features, though a possible mechanism is there (if we allow the forwarding of pragmatic/discourse representations to lower levels). Interactive activation models are functionally modular between distant levels, because the amount of activation is attenuated by each level that it passes through. Phonological elements and discourse considerations should thus have little effect on each other. Distributed connectionist models and usage-based/exemplar-based models, in contrast, could in principle posit strong interactions due to their one-step processing from meaning to form. Pragmatics and discourse may have their greatest effects concerning phonological output via the control of different levels of formality (register) or dialects related to social factors. The "right" way to implement this is unclear. One possible way would be to implement it in a way similar to attention, with certain elements selected out and their activation thus increased. The paper by Baker and McCabe (this volume) provides data for further development of models in relation to discourse and speech production processing.

Attention has additional influences on acquisition and processing that may also allow strong interactions within interactive and modular feed-forward models, although such models have not yet addressed the issue of attention. Bernhardt and Stemberger (1998) note that children can and do pay greater attention to processing sometimes, and that their accuracy may improve because of that attention. The mechanism, however, is unclear. Norman and Shallice (1986) suggested that attention selects out particular elements and increases their activation levels, thereby improving processing. Attention may play a role in other phenomena that have been observed in the clinic. Morrisette and Gierut (2002) suggest that nonsense words can be more effective during treatment than known words. It has been suggested that the child's phonological mismatches on known words may be stored, and that greater accuracy can thus be obtained with nonwords (because they have no stored mismatches). Attention may also play a role. Known words can be produced automatically (e.g., in a picture naming task), The clinician wants the child to pay close attention to the sounds and to try to eliminate mismatches, but the child can produce the words without such attention. Nonwords by their very nature require attention in order to be produced, and thus may more effectively focus the child's attention on the task of eliminating mismatches with the target pronunciation.

Finally, although our focus in this issue is on the production of speech and language, perception of course cannot be ignored. Accurate production presupposes perception that is accurate (at least under optimal circumstances). If, for example, the interdental fricatives /θ, ð/ are misperceived as /f, d/, and true /f, d/ are never produced as interdental fricatives (in words such as *fish*, *door*), then we do not expect the interdentals to ever be produced accurately. However, the reverse is not true: even when perception is accurate, production may be inaccurate. It is our position (as in Bernhardt & Stemberger, 1998) that children with typical hearing have fairly accurate perception in general, especially for very salient acoustic differences (e.g., /s/ vs. /t/). Production difficulties arise in the process of accessing phonological output forms, on the basis of reasonably adult-like perceived forms. It does not follow, however, that training a child in perception will have no effect on production. Training perceptual contrasts can be effective if it successfully draws the child's attention to the fact that two categories (e.g., /s/ and /t/) are different categories and should be *produced* differently. If the child has heretofore not perceived that there is a contrast, perceptual contrast training can lead to the establishment of more accurate lexical representations, which (after a lag) can lead to more accurate production. However, perceptual contrast training also focuses the child's attention on the contrast *even when* they can already perceive the contrast accurately. This focus of attention can lead the child to also focus attention in production, which can lead to improved processing and the establishment and/or more frequent use of more accurate output pronunciations. Any technique that successfully leads to that focus of attention should lead to improvements in the child's pronunciations. Perception-based training is one possible technique for doing this. The paper by Shiller et al. (this volume) provides further elaboration of this topic for both English- and French-learning children.

The approaches in this issue are a small indication of what could be applied based on models of speech production. As Figure 1 reminds us, the production of an utterance, however short, is a complex process that occurs in a discourse context, has meaning and many types of form. It is surprising that the system is as robust as it is, considering the possibilities for error within and between domains. The interactive activation model assumption taken in this issue is that intervention can be initiated at different points in the process, and have effects both within and across domains. Only time will tell if the various approaches meet the rigours of randomized control trials in intervention outcomes. We thank the contributors to this volume for their time, research and thoughts, and encourage the readers to foray into new territory of their own through consideration of the various approaches and models of language processing.

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