Phonological Knowledge in Typical and Atypical Speech and Language Development: Nature, Assessment, and Treatment

Benjamin Munson

Department of Speech-Language-Hearing Sciences

University of Minnesota, Minneapolis

Jan Edwards

Department of Speech and Hearing Sciences

Mary E. Beckman

Department of Linguistics

Ohio State University, Columbus

Address Correspondence to:

Benjamin Munson
Department of Speech-Language-Hearing Sciences
University of Minnesota
115 Shevlin Hall
164 Pillsbury Drive, SE
Minneapolis, MN 55455
(612) 624-0304
Fax: (612) 624-7586
Munso005@umn.edu

Abstract

This article discusses four types of phonological knowledge: knowledge the acoustic and perceptual characteristics of speech sounds (*perceptual knowledge*), knowledge of the articulatory characteristics of speech sounds (*articulatory knowledge*), higher-level knowledge of the ways that words can be divided into sounds, and sounds can be combined into meaningful sequences in words (*higher-level phonological knowledge*), and knowledge of the ways that variation in pronunciation can be used to convey social identity (*social-indexical knowledge*). The first section of the article discusses the nature of these types of knowledge in adults. The second describes how they develop in children with typical language development. The third section outlines how different types of knowledge may be compromised in children with functional language impairments and phonological impairments. The fourth section discusses ways to assess each type of phonological knowledge. The fifth section discusses different ways to facilitate growth in these different types of phonological knowledge. Together, these five sections serve as a review for practicing clinicians of the types of phonological knowledge that underlie accurate and fluent speech production, with suggestions for how to use existing assessment and treatment protocols to measure and facilitate them.

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Introduction

A child's first words do not sound like those spoken by adults. Children's earliest words are coarse approximation of the target forms. They are characterized by systematic sound substitutions, deletions, additions, and distortions relative to the forms produced by adults. In children acquiring phonology typically, these mismatches with the adult forms gradually attenuate throughout development. In children with atypical phonological development, such as children with phonological impairments (henceforth *PI*), the rate of this attenuation is considerably more protracted. Children with atypical phonological development may require speech and language intervention to achieve intelligible speech.

A full understanding of typical and atypical phonological development must begin with an understanding of the different types of knowledge that people have of the sound structure of language. This knowledge is highly multidimensional. To illustrate the many different types of knowledge of sounds, consider what people know about a single sound, /s/. First—and perhaps foremost—people know the acoustic and perceptual characteristics of /s/. Though people may not have the metalinguistic knowledge to be able to characterize /s/ as a sound with a relatively long duration; a period of aperiodic noise with a high frequency peak and a negatively skewed spectrum, they are able to successfully identify sounds with those characteristics as tokens of /s/ and as not other closely related sounds, like /f/, /**θ**/, or /**ʃ**/. Second, people know the articulatory characteristics of /s/. Again, this knowledge is likely quite tacit: people are not likely to be able to tell you that /s/ is produced with either a movement of the tongue tip to the alveolar ridge or of the tongue lamina to the upper incisors; nonetheless, people's successful production of words with /s/ suggests that they know that these are the movements needed to produce or reproduce the acoustic characteristics of /s/ that they have heard. Third, people know the function of /s/ within our phonological system. That is, people know that changing the word-initial /s/ in *sack* to an /**ʃ**/ will change the word's meaning from 'a brown paper bag used to carry groceries' to 'a small, ramshackle house'; they know that /s/ cannot appear in a word-initial cluster following a /p/ (i.e., that there is a *phonotactic constraint* against initial /ps/ clusters), and, consequently, that the sequence /**psɑri**/ is not a possible word of English. Finally, people know that the acoustic characteristics of /s/ vary systematically, and that some of this variation is exploited by talkers to code social-group membership, referred to as *social-indexical variation*. For example, people know that some male talkers exploit allowable variability in the spectral skewness of /s/ to express their sexual orientation (Munson, McDonald, DeBoe, & White, 2005).

This description of the complexities associated with phonological knowledge runs sharply contrary to people's overt knowledge of the sound structure of language. Ask a person what they know about the word *sack* or the sound /s/ and he or she is likely to describe the meaning of the word *sack* or the fact that the sound /s/ is spelled with the letter *s*. The likelihood that a person can tell you about the articulatory or acoustic characteristics of the sound /s/ in isolation or in a word like *sack* is exceedingly low, as is the likelihood that a person would show overt knowledge of phonotactic constraints or social-indexical variation. One salient illustration of the tacit nature of knowledge of the sound structure of language is illustrated by the protracted nature of university-level instruction in this area. Most university undergraduate curricula in speech-language-hearing sciences and disorders include at least one course in phonetics. One of the primary goals of a phonetics course is to teach students to associate a simple alphabetic system of phonetic symbols to the speech sounds that they hear and produce every day. The fact that such courses typically include approximately 45 hours of classroom instruction, and that many people fail to learn this system to a level of proficiency needed for practical application of this skill (e.g., Munson & Brinkman, 2004) is testament not only to the extremely tacit nature of knowledge of the sound structure of language, but to how ingrained that tacit knowledge is. The description in the above paragraph demonstrates that our knowledge of the sound structure of language is not only highly tacit, it is also dauntingly complex. Given this complexity, it is not surprising that one of the most common functional communication disorders in children is a failure to learn the sound system of the ambient language in the absence of impairments in other areas.

This article consists of five sections. First, we review the different types of phonological knowledge that adults have. In the second section, we discuss the development of each of these types of knowledge. In that section, we present a model that proposes a structured relationship among the different types of phonological knowledge. Third, we discuss impairments in different types of phonological knowledge in children with speech and language disorders. Fourth, we discuss the implications that our model has for the assessment of speech-sound disorders in children. Finally, we discuss the implications that this model has for the treatment of speech-sound disorders in children.

The goal of this article is twofold. The first is to inform practicing clinicians of recent advances in our scientific understanding of knowledge of the sound structure of language by adults, typically developing children, and children with functional disorders of speech or language. Discussions of knowledge of the sound structure of language presented in the clinical literature by necessity often simplify their description. For example, most introductory textbook discussions of individuals' knowledge of sounds categorizes this knowledge into abstract categorical 'phonological' knowledge and articulatory and acoustic 'phonetic' knowledge (e.g., Peña-Brooks & Hegde, 2000). Recent investigations have called into question this sharp dichotomy (e.g., Beckman, Munson, & Edwards, in press). Consequently, we use the term 'phonological knowledge' broadly in this article, to refer to all aspects of knowledge of the sound structure of language. This encompasses both more abstract knowledge of sounds, as well as knowledge of the physical instantiation of sounds in articulatory and acoustic signals. Traditional descriptions of knowledge of the sound structure of language also typically rely on error patterns in spontaneous to make inferences about phonological knowledge. More recent investigations have used experimental techniques to gauge individuals' knowledge of sounds. This paper serves as a review of those theoretical and experimental advances for clinicians who work with children with deficits in phonological knowledge. Readers interested in a more-theoretically oriented approach to this topic are referred to Pierrehumbert (2002, 2003) and Beckman, Munson, and Edwards (2005). The second purpose of this article is to review how well-established assessment protocols and treatment techniques can be used to measure and build these different types of phonological knowledge.

Phonological Knowledge

Types of Phonological Knowledge in Adults

Perceptual Knowledge

It is axiomatic that the acoustic characteristics of the speech signal vary tremendously. This observation is not new. Indeed, the earliest spectrographic studies of the acoustic characteristics of speech (e.g., Peterson & Barney, 1952) noted great within- and between-speaker variability in the acoustic characteristics of speech. As an illustration, consider the sound /s/, the voiceless alveolar fricative. This category differs from other similar categories (such as the other voiceless fricatives /ʃ/, /f/, and /θ/) along a number of different phonetic dimensions, such as peak frequency, spectral skewness, intensity, duration, and patterns of formant transitions on adjacent vowels (e.g., Jongman, Wayland, & Wong, 2000). However, both within and across speakers, there is considerable variability in these same parameters in different productions of /s/. The spectral characteristics of the sound /s/ vary considerably within talkers as a function of phonetic context (Munson, 2004), and between talkers as a function of sex and sexual orientation (Munson, McDonald, DeBoe, & White, 2005).

How much knowledge do adults have of this variability? An answer to this question can be found in studies of speech perception. Consider /s/ again. Despite the variability in its acoustic characteristics, normal-hearing listeners appear to be able to perceive /s/ without much difficulty. This is illustrated by classic categorical perception experiments, in which listeners perceive a continuously variable acoustic signal to be members of discrete categories. For example, listeners perceive fricative stimuli that vary continuously in peak frequency as either /s/ or /ʃ/, and not as members of an intermediate category (Munson, Jefferson, & McDonald, 2005). Put differently, the kind of variability in /s/ acoustics noted by Munson (2004) and Munson, McDonald, DeBoe, and White (2005) is not necessarily related to a similar level of variability in perception: people perceive categories like /s/ or /ʃ/, rather than continuous phonetic variation.

Early research on speech perception accounted for the discrepancy between acoustic variability and invariance in perception by hypothesizing that the process of perception was one in which people 'threw out' seemingly irrelevant acoustic information and attended to only the crucial acoustic cues that differentiated among different phonemes (e.g., Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967). This view of speech perception has been challenged by recent studies in which it has been suggested that people are much more sensitive to fine-grained acoustic detail in perception than performance on categorical perception experiments would lead us to believe. One illustration of this type of knowledge of speech is given by Goldinger and Azuma (2004) and Shockley, Sabadini, and Fowler (2004). Both of these investigations found that listeners remembered fine acoustic details of words that they had heard in an experiment, and even modified their own productions of the same words so that they sounded like the words that they heard, without being instructed explicitly to do so.

Given the findings presented thus far in this section, we can characterize individuals' perceptual knowledge as involving two distinct types of knowledge. Acoustic-perceptual knowledge must include information about the fine-grained acoustic/perceptual characteristics of words that they have heard, to account for findings such as those presented by Goldinger and Azuma (2004). However, this acoustic-perceptual knowledge must also include information about the categorical structure of sounds, to account for the 'blindness' to within-category variability that is illustrated by categorical perception experiments like those presented in Munson et al. (2005).

How might this dual-level perceptual knowledge arise? One likely scenario is that people learn phonological categories (of the type invoked in categorical perception experiments) as a consequent of learning variation in different acoustic-perceptual dimensions. Consider, for example, a child's learning of the sound /s/. During a child's ongoing perception of language, he or she would accrue knowledge of the likelihood of occurrence of different phonetic parameters associated with /s/, such as formant frequencies, duration, and spectral characteristics. These distributions might look like those illustrated in Figure 1. We refer to these distributions as *density distributions*.

Insert Figures 1 about here

Figure 1 shows hypothetical density distributions of variants along a hypothetical phonetic parameter, such as peak frequency of a fricative. The top of Figure 1 shows a distribution that clearly has one mode, which is highlighted with a box. An individual learning this distribution might infer that it reflects a single underlying phonological category, which the learner would then ascribe a label to, such as the label 'Category C' in this Figure. Contrast this with the bottom of Figure 1, which shows a bimodal distribution. An individual encountering that distribution might infer that it reflects an underlying two-category structure, reflected by the peaks that are labeled 'Category A' and 'Category B'. For example, if this distribution were to reflect peak frequency, then this would be a plausible reflection of the distribution that a learner would encounter when learning the sounds /s/ and /ʃ/, which differ primarily in peak frequency. However, these examples are simplifications. Real phonetic categories involve systematic variation along multiple phonetic parameters. Recall the example of /s/, which differs from the other voiceless fricatives of English in a variety of parameters, including peak frequency, spectral skewness, intensity, and duration, among other parameters. Individuals would be able to infer the existence of the /s/ category from distributions of multiple phonetic parameters, as well as from correlations among these parameters.

Indeed, there is evidence that real-world speech-sound learning proceeds in this manner. Maye, Werker, and Gerken (2002) and Maye and Weiss (2003) show that infants use distributional information of the type illustrated in Figure 1 to learn phonetic categories. Maye's findings suggest that coarse-grained perceptual knowledge of sound structure arises as individuals acquiring speech encode and make generalizations over the phonetic parameters. The encodings allow them to remember and incorporate fine phonetic detail in their production, while the generalizations allow them to infer the category structure of the language.

Articulatory Knowledge

In addition to knowing the perceptual characteristics of sounds, fluent speech production relies on knowledge of the articulatory characteristics of sounds. Articulatory characteristics of sounds vary systematically due to a variety of factors, including phonetic and prosodic context (e.g., Beckman & Edwards, 1990), word-specific factors such as frequency of usage (Munson & Solomon, 2004), and task demands, such as the ease with which an item was accessed from memory (Bell et al, 2003; Munson, in press). To produce a sound accurately, individuals must possess motor plans for sounds that are sufficiently flexible to allow accurate production in a variety of contexts and with a variety of task demands. Hence, the second type of phonological knowledge is knowledge of the articulatory characteristics of sounds.

In contrast to acoustic-perceptual knowledge, there is considerably less consensus on the degree of specificity in articulatory representations of sounds. One popular class of models of articulation, Articulatory Phonology (Browman & Goldstein, 1989) specifies articulatory movements as rather abstract task oriented movement plans, which are flexibly coordinated with one another as a function of task demands. For example, /k/ would be specified as two goals, one to raise the tongue dorsum, and one to abduct the vocal folds. These two movements would be coordinated differently as a function of a variety of factors, including rate of speech and the prosodic structure in which the sound was embedded. An alternative perspective on the specificity of articulatory movements is presented in a recent study by Trembley, Schiller, and Ostry (2003). They suggested that individuals' knowledge of articulatory movements is highly specific, analogous to the level of specificity seen in perception tasks like that presented by Goldinger and Azuma (2004).

One aspect of articulatory knowledge that is key to accurate and fluent speech production is knowledge of the correspondences between articulation and acoustics. That is, individuals must know the articulatory movements required to affect a given acoustic output. Consider again Goldinger and Azuma's (2004) finding. In order for individuals to successfully imitate the words that they hear, they must not only encode their acoustic characteristics, but also reconfigure their articulatory movements to mimic those acoustic characteristics. This relationship is highly dimensional: multiple articulatory configurations can result in the same acoustic output. This is illustrated by Savariaux, Perrier, and Orliaguet's (1995) study of people's ability to produce the vowel /u/ when a biomechanical perturbation prevents lip-rounding. Some individuals are able to compensate for this ability by producing articulatory movements other than lip rounding to produce a natural-sounding /u/. Consequently, one key component of articulatory knowledge is knowledge of articulatory-acoustic relationships. Individuals must know the many different articulatory configurations that may be used to produce a sound, so that they can do so accurately when task demands change.

Knowledge of Higher-Level Phonological Categories

The two types of phonological knowledge described thus far, articulatory and perceptual knowledge, can be though of as lower-level knowledge of how sounds are instantiated and perceived in the physical world. The next type of phonological knowledge is knowledge of how sound categories are used to code meaning in the language. That is, this section discusses individuals' knowledge of the ways in which they can be combined with other sounds to form words. Consider again the sound /s/. English speakers' knowledge of /s/ includes the knowledge that it cannot occur word-initially following stop consonants, before /r/ (except in some exceptional foreign place names, like *Sri Lanka*), or before an aspirated voiceless stop; that it cannot occur word-finally after a voiced stop consonant, etc. We can think of this as *higher-level* phonological knowledge because it is considerably more abstract than acoustic and perceptual knowledge. For example, listeners will judge an /sr/ sequence as an unacceptable sequence of sounds in English regardless of the specific articulatory or acoustic characteristics of /s/. Higher-level knowledge is language-specific. For example, the word-initial sequence /ps/ does not occur in real English word; consequently, sequences like [**psɑri**] are judged to be unacceptable English word-forms. However, this same sequence is frequently attested in Greek, in which the sequence [**psɑri**] (the Greek word for *fish*) is judged to be well-formed.

There is ample evidence that people's higher-level phonological knowledge affects their performance on a variety of experimental measures of phonological processing. For example, when considering whether a nonword (a sequence of phonemes that does not correspond to an actual word of the language) could be possible word of English, listeners appear to refer to their knowledge of likely combinations of phonemes in words in the lexicon. Nonwords that contain sequences of sounds occurring in many real words are typically rated as 'better' additions to the English lexicon than those containing sequences of sounds occurring in few real words (Frisch, 2001; Frisch, Large, & Pisoni, 2000, Munson, 2001; *inter alia*). This knowledge is likely to be gradient, rather than absolute. That is, listeners are likely to know that a word-initial /st/ cluster is a very likely sequence of phonemes, given that it is attested in many words, while /sf/ is a relatively unlikely sequence, occurring in only a few low-frequency words like *sphinx* and *sphere*. Consequently, nonwords that contain /st/ are rated as 'better' than ones containing /sf/, which are rated as 'better' than those containing completely unattested sequences, like /ps/.

Social-Indexical Knowledge

The last component of phonological knowledge that is relevant to this discussion is social-indexical knowledge. Social-indexical knowledge refers to knowledge of how linguistic variation is used to convey and perceive membership in different social groups. Social-indexical knowledge encompasses a variety of different factors, including social class, race, gender, and regional dialect. Social-indexical variation can relate to any aspect of linguistic structure, including syntax, morphology, and the lexicon, among others. This discussion in this paper is limited to social-indexical variation in the production and perception of speech sounds.

One illustration of social-indexical knowledge is given in Munson, McDonald, DeBoe, and White (2005), who examined the relationship between acoustic characteristics of speech and perceived sexual orientation in 44 women and men. These individuals varied in their self-identified sexual orientation: one half were self-identified as heterosexual, and the other half were self-identified as gay, lesbian, or bisexual (GLB). Munson et al. found that both men and women marked their sexual orientation through distinctive production of certain phonemes, including /**s**/, /**æ**/, and /**ɛ**/, though there was considerable overlap between the groups. Subsequent research (Munson, Jefferson, & McDonald, 2005) showed that listeners were sensitive to these differences in a variety of perception tasks. In one task, self-identified GLB people were rated as more-GLB sounding than self-identified heterosexual people. In another task, listeners participated in an experiment in which they heard stimuli created by pairing a synthetic nine-step /s/-to-/**ʃ**/ continuum with natural tokens of /**æk**/ from the 44 talkers. In this experiment, more *sack* than *shack* percepts were elicited from women whose voices were reliably rated to sound lesbian/bisexual than women whose voices were not, paralleling earlier findings on the influence of talker sex on fricative categorization (Strand, 1999). Together, these results illustrate that knowledge of sounds includes knowledge of the ways in which variation in acoustic characteristics relates to social identity and social-group membership.

Phonological Knowledge in Typical Phonological Development

The previous section outlined four types of phonological knowledge: perceptual knowledge, articulatory knowledge, higher-level phonological knowledge, and social-indexical knowledge. This section considers how each of these types of knowledge develops in children acquiring language typically.

Perceptual Knowledge

The development of perceptual knowledge can be seen in studies of children's speech perception. Speech perception studies have shown that children's development of adult-like perceptual knowledge is extremely protracted. One way to examine this is to use categorical perception experiments. Nittrouer (1992) conducted a categorical perception experiment showing that preschool and early elementary school-aged children do not show adult-like pattern of attention to acoustic cues when categorizing fricative-vowel syllables as /**ʃa**/, /sa/, /**ʃu**/, or /su/. Hazan and Barret (2000) showed that children as old as 10 years of age continue to show patterns of phoneme identification that are identifiably different from those of adults. Another way to study children's perceptual knowledge is to examine their ability to identify words that have been acoustically modified or degraded. Using the gating paradigm (in which people identify words from which acoustic information has been removed), it has been shown that children require more acoustic information than adults to accurately recognize words (Walley, 1988). Results from both categorical perception tasks and word-recognition experiments suggest that children as old as 10 years of age continue to show immaturities in perceptual knowledge

The other type of perceptual knowledge discussed earlier is knowledge of acoustic detail about individual instances of words that listeners have encountered during language use. There is evidence that children do not have adult-like knowledge of this. Ryalls and Pisoni (1997) examined preschool children's ability to recognize words presented in single- and multiple-talker lists. Preschool children were shown to have a larger decrement than adults in word-recognition accuracy on multiple-talker lists when compared to single talker lists. Accurate recognition of words in multiple talker lists requires people to have encoded enough fine phonetic detail to learn about the systematic sources of variation in pronunciation among talkers. Ryalls and Pisoni's finding suggests that children's fine-grained perceptual representations of words do not include enough variation to support adult-like recognition of multiple talkers.

In sum, children show a protracted development of perceptual knowledge, both of the categorical structure of sounds (as evidenced by their non-adult like performance on categorical perception tasks and gated-word recognition tasks), and of fine-grained auditory-perceptual knowledge (as shown by their performance on word recognition experiments manipulating the number of talkers).

Articulatory Knowledge

In development, children must establish detailed articulatory representations, so that they can produce sounds accurately in all of the different segmental and prosodic contexts in which they might need to produce them. There is evidence that these detailed articulatory representations are subject to a somewhat protracted period of development. It is well known that typically-developing children, as well as children with phonological disorders, produce systematic error patterns during the process of acquiring adult-like articulatory representations. These include such familiar errors as [w] for /r/ and [**θ**] for /s/, as well as other idiosyncratic errors that children might produce While these errors are commonly considered to be simple substitutions of one sound for another, there is acoustic and articulatory evidence that at least some of these so-called "substitutions" might be better described as "covert contrasts." Covert contrast is a statistically significant acoustic or articulatory difference between two phoneme categories that is perceived reliably by the transcriber, usually because the two pronunciation variants fall within a single adult perceptual category. The classic example of covert contrast comes from an investigation of the acquisition of the voicing contrast for stop consonants by Macken and Barton (1980). They found that some children produced a statistically significant contrast in voice onset time between voiced and voiceless stop consonants, but that all of the voice onset times fell within the adults' voiced category. Consequently, all of the productions were perceived as voiced. Since then, covert contrast has been observed for both typically-developing children and children with atypical speech and language development for a variety of contrasts, including the voicing contrast for stop consonants, the contrast between velar and alveolar place of articulation for stops, /θ/ for /s/ substitutions, /ʃ/ for /s/ substitutions, and the omission of /s/ in initial /s/-clusters (e.g., Maxwell & Weismer, 1982; Gierut & Dinnsen, 1986; Forrest & Rockman, 1988; Forrest, Weismer, Hodge, Dinnsen, & Elbert, 1990; Baum & McNutt, 1990; Gibbon, 1999; Scobbie, Gibbon, Hardcastle, & Fletcher, 2000; Tsurutani, 2002; White, 2001).

It has also documented that even "correct" productions by children differ systematically from those of adults. Children produce longer speech sounds and words than adults. These are produced with greater trial-to-trial variability in temporal and spectral characteristics. A number of researchers have shown that both segment duration and temporal and spectral variability decrease as age increases (e.g., Eguchi & Hirsh, 1969; Kent & Forner, 1980; Lee, Potamianos, &

Narayanan, 1999; Munson, 2004; Smith, 1978, 1992; Smith, Sugarman, & Long, 1983). These age-related differences are largest for young children (4- and 5-year-olds), but exist for some measures even for adolescent and teen-aged children as compared to adults (Lee et al., 1999; Kent & Forner, 1980; Smith et al., 1983).

Together, these findings show that children's acquisition of mature articulatory knowledge is protracted. Children produce more frank speech-production errors than adults. Moreover, children's early production of sounds shows less differentiation among different sounds than adults, as illustrated by studies of covert contrast. It also shows less precision than adults, illustrated by studies of the variability of children's speech production.

Knowledge of Higher-Level Phonological Categories

Children's knowledge of higher-level phonological categories is also subject to development. The tasks that have been used to assess this knowledge in children are considerably different those that have been used in adults. One aspect of higher-level categorical knowledge is knowledge of the segmental structure of words. That is, to be able to make generalizations like "/ps/ is not a possible word-initial cluster in English", people must have the knowledge that /p/ and /s/ are sounds that exist outside of the words in which they occur. That is, they must know that words like *pig* and *fast* can be decomposed into strings of phonemes like /p/, /ɪ/, /g/, and /f/, /æ/, /s/, /t/; and that the sounds /p/ and /s/ can be combined in different orders with the vowel /æ/ to form the words *asp*, *sap*, and *pass*. There is evidence that children's knowledge that words are comprised of strings of phonemes is subject to development. This can be seen in psycholinguistic tasks that measure children's knowledge of similarity in words' segmental structure. For example, Storkel (2002) showed that children's judgment of words' dissimilarity was based on less-mature segmental representations than those that are purported to exist for adults. Munson, Swenson, and Manthei (2005) showed that the influence of the similarity of real words to other words in the lexicon (sometimes termed *phonological neighborhood density*) on response times in repetition tasks increased during development. Munson and Babel (2005) found that children were less able than adults to suppress lexical items and utilize recently activated phoneme-level motor plans in a reiterant speech task. Together, these studies support the claim that segmental knowledge is subject to a protracted developmental time-course.

Recently, Munson (2001) and Edwards, Beckman, and Munson (2004) examined developmental changes in higher-level phonological knowledge using a nonword repetition task. These investigators asked children to repeat pairs of nonwords, one of which contained a sequence of phonemes that occurs in many real words of English (e.g., /sk/, which occurs in words like *ask*, *sky*, *escape*, and *rescue*) and one that contains a sequence that occurs in few or no real words of English (e.g., /ʃk/, which only occurs in the extremely low-frequency word *Ashkenazi*). To repeat a high-frequency sequence accurately, individuals may resort to knowledge already in their lexicons. That is, a person repeating a nonword-embedded /sk/ sequence may utilize stored knowledge of the articulatory movements for this sequence from words like *escape* or *rescue*. In contrast, repetition of a low-frequency sequence cannot be accomplished unless the individual has representations of phonemes separate from the words in which they occur—i.e., their phonological knowledge has grown to include knowledge of phonemes. Both Munson (2001) and Edwards et al. (2004) found that the influence of phoneme-sequence frequency (which they termed the *frequency effect*) decreased throughout development. That is, performance on the nonword repetition task showed evidence of increasingly rich higher-level phonological knowledge. Edwards et al. (2004) used multiple regression to study predictors of nonword repetition performance. They showed that raw measures of vocabulary size best predicted the developmental decrease in the frequency effect. Children with larger vocabularies showed evidence of more mature higher-level phonological knowledge.

How does higher-level phonological knowledge develop? One hypothesis is that it emerges as a consequence of early word learning. It could be that, as the child acquires more and more words containing the same consonants and vowels in different novel combinations, higher-level knowledge of consonant and vowel phonemes emerges. We can think of this knowledge as a 'layer' of knowledge that relates acoustic and articulatory knowledge to each other, and to representations of words. This is shown in Figure 2. This higher-level knowledge would serve a number of different functions. First, it would supplement the child's knowledge of the correspondences between articulation and acoustics (Bailly, Laboissiere, & Schwartz, 1991; Jordan, 1990). This would help the language learner to make a fast and relatively automatic association between the sounds that they hear and the articulatory movements required to reproduce them. It would also allow a child to recognize a newly-encountered word as being a string of known categories rather than an unanalyzable whole—i.e., the nonword /**voʊp**/ can be analyzed as a string of the known categories /v/, /**oʊ**/, and /p/. We can describe this as a 'fast mapping' of a word's phonological structure, comparable to the fast mapping of its meaning and morphosyntactic characteristics that has been studied previously (Carey, 1978). In these ways, this higher-level phonological knowledge would facilitate ongoing word learning. It would make it easier to 'parse' an unfamiliar nonword as a string of known phonological representations, and it would facilitate the association between perception and production required to reproduce a novel sequence. This model is presented in Figure 2. The model in

Figure 2 has been implemented in computational simulations of phonological development (Plaut & Kello, 1999).

Insert Figure 2 about here

In essence, this model claims that there is a lexical basis to the development of higher-level phonological knowledge. Higher-level phonological knowledge emerges as a consequence of word learning, and serves to facilitate future word learning. The notion that early phonological knowledge is lexically based is not new. It goes back at least to Ferguson and Farwell (1975) who proposed that "a phonic core of remembered lexical items and the articulations that produced them is the foundation of an individual's phonology" (p. 36). More recently, Werker and Curtin (2005) have proposed a model of infants' and toddlers' speech perception and word learning (PRIMIR) in which early lexical development and phonological development are highly inter-related. Werker and Curtin suggest that there are three multidimensional planes that underlie speech perception and word learning: a general perceptual plan, a word form plan, and a phoneme plane. Information on the phoneme plan develops gradually, based on regularities that emerge from the multi-dimensional clusters on the word form plane. This model predicts an interaction between word learning and phonological acquisition.

Evidence for the PRIMIR model comes from Werker, Fennell, Corcoran, and Stager (2002). They found that most 14-month-old infants were unable to distinguish between minimal pairs such as /bɪ/ and /dɪ/ in a word-learning task, although they were able to do so in a simpler speech perception task. In contrast, many 17-month-old and most 20-month-old infants could do so. Werker et al. found that an estimate vocabulary size predicted the 14-month-old infants' performance in the word learning task. More generally, they found that infants with a productive vocabulary of at least 25 words or a receptive vocabulary of at least 200 words were successful on this task. Werker and Curtin (2005) interpreted the results of Werker et al. (2002) in terms of representations on the phoneme plane. As predicted by the PRIMIR model, children who knew more words have a more highly developed phoneme plane and children with a more highly developed phoneme plane were better word learners.

Evidence for a relationship between word learning and phonological development can also be found in studies of the relationship between the development of the lexicon and the development of phonological knowledge. Vihman, Macken, Simmons, Miller, and Simmons (1985) showed a relationship between the phonological characteristics of prelinguistic babbling and the phonological forms of early words, suggesting that children's acquisition of lexical items was related to the earlier phonological knowledge that was accrued during infancy. Schwartz and Leonard (1982) showed that children at the onset of word learning were more likely to learn novel words that contained sounds that they produced frequently than ones that contained infrequent sounds, and this was unrelated to children's comprehension. Storkel (2001) found that children were more likely to learn novel words containing sequences of sounds that occur frequently in the ambient language. Stoel-Gammon (1998) examined the phonological characteristics of children's early-word productions, as assessed through normative data on a parent report measure of early communication, the *MacArthur Communicative Development Inventory*. Data from this instrument suggest that words that are generally acquired earlier (at approximately 19 months) contain a more restricted set of consonants than those acquired later (between 20 and 30 months). Moreover, the words that are acquired late are more likely to contain sounds that are generally found to be later acquired in large-scale normative studies of consonant acquisition, such as Templin's (1957) study. Together, these findings suggest a relationship between lexical acquisition and phonological acquisition.

Social-Indexical Variation

The final type of phonological knowledge is knowledge of social-indexical variation in speech. There is evidence that this type of knowledge is subject to development. One aspect of social-indexical variation is socially conditioned variation in production. The question of whether or not children show evidence of adult-like variation in pronunciation similar to that of adults has received relatively little attention. Roberts (1997) showed that Philadelphia-area children's deletion of final /t/ and /d/ showed patterns of variable production similar to that of adults, in which deletion is conditioned by a variety of lexical and grammatical factors. Chambers (1992) found that children moving from one dialect to another are able to learn lexical and phonological forms characteristic of the new dialect to which they were exposed. Perry, Ohde, and Ashmead (2001) showed that boys and girls produced sex-specific pronunciation patterns in advance of the anatomical differences that would necessitate such differences. All of these studies show that social-indexical variation in present in the speech of even very young children.

There is also evidence that children's perception is sensitive to social-indexical factors. Nathan, Wells, and Donlan (1998) examined 4- and 7-year-old children's ability to comprehend and repeat words spoken in their native dialect (the variety of English spoken in London) and a phonologically distinct dialect (the variety spoken in Glasgow) to which they had relatively little exposure. Nathan et al. showed that children's ability to process words in an unfamiliar dialect was subject to development. Children's comprehension was significantly reduced when presented with words in an unfamiliar dialect. In the repetition task, younger children's repetitions of the unfamiliar-dialect words showed greater reliance on the phonetic composition of the stimuli than that of the older children. That is, the younger children showed a reduced ability to map systematic differences between the two dialects.

Phonological Knowledge in Children with Atypical Speech and Language Development

The previous section demonstrated that each of the types of phonological knowledge discussed in this article is subject to development. This section reviews the results of studies examining different types of phonological knowledge in children with functional speech and language impairments. The emphasis in this section is on functional impairments—that is, impairments in which there is no obvious etiology that would compromise the development of speech or oral language, such as cleft palate, cerebral palsy, or hearing loss. In each section, we discuss how the different components of phonological knowledge are impaired in the populations, as well as how the different types of phonological knowledge relate to one another.

Children with Language Impairments

Children with functional language impairments (LI) of an unknown origin demonstrate a broad range of communication difficulties. In research studies, these children are typically referred to as having Specific Language Impairment (SLI), under the assumption that these children have sustained an impairment that is specific to language. More-recent investigations have used the term Primary Language Impairment, in recognition of the mounting evidence that children with so-called 'specific' language impairments are not truly specifically impaired in language, but also show subtle deficits in cognitive-linguistic and perceptual-motor processing across different domains and different tasks (Kohnert & Windsor, 2004; Windsor & Kohnert, 2004).

In the preschool and early elementary-school years these children, the deficits of children with LI are demonstrated as a late emergence of speech; a protracted development of grammatical morphology, particularly as it relates to tense-marking of verbs, small-sized vocabularies, and less-complex syntactic structures, among others (see Leonard, 1998, for a review). Importantly for this discussion, children with LI very often have smaller-sized vocabularies than their peers, and show difficulty in learning new words in both explicit and implicit learning tasks (e.g., Dollaghan, 1987; Oetting, Rice, & Swank, 1995). Individual children's language profiles may be highly variable and specific to the ambient language to which the child is exposed. Though the aspects of communication that are typically assessed and treated in these children fall under the label of 'language' (semantics, syntax, morphology, etc.) a number of investigations have demonstrated that these children may have subtle deficits in phonological knowledge. That is, although there is a relatively low comorbidity rate between language impairments and PI (Shriberg, Tomblin, & McSweeny, 1999), there is some evidence that children with language impairments show subtle phonological knowledge deficits. This section reviews those deficits.

There is evidence that children with language impairments show subtle deficits in perceptual knowledge. For example, Sussman (1993) showed that children with language impairments perform differently from their typically developing peers on categorical perception tasks. Dollaghan (1998) showed that children with language impairments have deficits in spoken-word recognition: children with language impairments required more acoustic information than adults to words and nonwords from which acoustic information had been removed. Moreover, children with language impairments show subtle deficits articulatory knowledge. Goffman (1999, 2004) showed that children with language impairments showed greater kinematic variability in lip movement than typically developing age-matched children when producing nonsense sequences. This suggests that they have less-precise articulatory representations than their typically developing peers.

The deficits in perceptual and articulatory knowledge are rather subtle when compared to the possible deficit in higher-level phonological knowledge that children with LI appear to demonstrate. Children with LI typically have smaller-sized vocabularies than their peers with typical language. The model presented in Figure 2 makes clear predictions regarding the development of higher-level phonological knowledge in children who have atypically small-sized vocabularies. If the emergence of higher-level knowledge of consonants and vowels is related to the size of the lexicon, then children with language impairments should show decreased higher-level phonological knowledge, given that they very often know fewer words than their same-age peers. In a nonword repetition task of the type used by Munson (2001) and Edwards et al. (2004), this should be reflected by a larger-sized frequency effect than peers with larger, age-appropriate vocabularies.

This hypothesis was tested by Munson, Kurtz, and Windsor (in press). Munson et al. (in press) examined nonword repetition in three groups of children. The primary group of interest was a group of 16 8- to 13-year-old children with language impairments of an unknown origin. These children were compared to two groups of children who were acquiring language typically. The first of these were 16 8- to 13-year-old children matched to the children with LI on chronological age (the *CA* children). The second was a group of 16 6- to 10-year-old children matched to the children with LI on an estimate of expressive vocabulary size (the *VS* children). Munson et al. utilized three- and four-syllable nonwords from a previous study (Frisch et al., 2000) that contained either all high-frequency or all low-frequency two-phoneme sequences.

These data were analyzed similarly to that in Edwards et al. (2004), described above. Average nonword repetition accuracy was calculated separately for high- and low-frequency nonwords. Analyses of variance showed that all three groups of participants repeated the high-frequency nonwords more accurately than the low-frequency ones. The frequency effect was for the children with LI and for the younger VS children than for the CA matched children. Regression analyses showed that estimates of vocabulary size predicted the a significant proportion of variance in the frequency effect, although a second measure, standard scores on the *Clinical Evaluation of Language Fundamentals-3* (Semel, Wiig, & Secord, 1995), accounted for nearly as much variance as the vocabulary-size measures.

Thus, Munson et al. (in press) found evidence that children with language impairments have less-robust higher-level phonological knowledge than their peers with typical development. These deficits appear to be due entirely to the smaller size of their vocabularies, as shown by the fact that the size of their frequency effect did not differ from that of their VS matches. Munson et al. (in press) conjectured that the larger phonotactic-probability effect seen in children with language impairments is related to their word-learning difficulties: children with LI may experience more difficulty than their age peers in learning higher-level phonological knowledge from lexical items. Consequently, the robust 'scaffold' that phonological representations serve in word-learning is not available to them, and their subsequent word-learning suffers.

In sum, children with language impairments show a variety of deficits in phonological knowledge. Some of these, such as the deficits that they display in articulatory and perceptual knowledge, are quite subtle. Other deficits, such as the deficit in higher-level phonological knowledge that is revealed in repetition tasks, is more pronounced, and may partially explain at least some of their language deficits.

Children with Phonological Impairment

Children with articulation or phonological impairments (*PI*) of an unknown origin produce a variety of speech-sound errors. These are more numerous, and persist longer, than those in typically developing (TD) children. The errors made by children with PI occur in the absence of a clear etiology, such as hearing impairment, neuromotor dysfunction, or a broad cognitive impairment. Children with PI may require intervention to achieve intelligible speech. Indeed, these children have typically comprised a large percentage of the caseloads of school speech-language pathologists (Whitmire, Karr, & Mullen, 2000). This section considers different types of phonological knowledge that may be impaired in children with PI.

There is strong evidence that children with PI show decreased perceptual knowledge relative to their TD peers. This is illustrated by studies that have examined the ability of children with speech-sound impairments to identify and discriminate sounds that they produce in error. For examine, Rvachew and Jamieson (1989) found that a subgroup of children with PI could not discriminate between word-initial /s/ and /ʃ/. Moreover, the two groups differed substantially in performance on a categorical perception experiment with these same phonemes. Furthermore, Rvachew and Jamieson found that speech perception training improved production of /ʃ/ in children with discrimination problems, but had no effect in children without discrimination problems. Similarly, Ohde and Sharf (1988) found that children who misarticulated /r/ had difficulty discriminating between synthetic /r/ and /w/. These perceptual difficulties can also be seen in word-recognition experiments. Edwards, Fox, & Rogers (2002) also found differences between children with PI and their typically developing age peers in an auditory word recognition task with gated and ungated stimuli. Children with PI performed less well than their age controls, even in the ungated condition in which the entire word was presented.

There is some evidence that children with PI show a deficit in encoding perceptual detail about individual tokens of words. Forrest, Chin, Pisoni, and Barlow (1995) examined the ability of children with PI and typically developing children to perceive speech in single- and multiple-talker lists. As described above, children have a larger decrement in performance than adults on multiple-talker lists as compared to single-talker lists (Ryalls & Pisoni, 1997). Forrest et al. (1995) found an even larger decrement of performance for children with phonological disorders, as compared to typically developing children, although this difference was not statistically significant because of the small sample size.

There is also evidence that children with PI show deficits in articulatory knowledge. The hallmark of PI is significantly below age-level production of consonants, based on transcription of a standardized test that elicits each consonant in English in all possible word positions. However, deficits in articulatory knowledge also can be seen in kinematic and acoustic studies. Electropalatographic studies, which measure patterns of tongue-palate contact during speech production, have shown that children with PI have deficits in articulatory knowledge. Gibbon (1999) found that 12 children with PI produced what she called "undifferentiated lingual gestures" for the stop consonants /t/ and /k/. That is, the productions did not clearly distinguish between alveolar and velar constrictions for stop closure – instead, there was broad tongue-palate contact at both places of articulation during the constriction. White (2001) presented acoustic evidence that also suggests that some children with PI produce undifferentiated lingual gestures for target /t/ and /k/.

Another example of deficits in articulatory knowledge is given by Edwards (1992). Edwards examined whether children with PI were less able than their typically developing peers at compensating for the presence of an articulatory perturbation during speech production. It is widely observed that adults are able to compensate for the presence of an articulatory perturbation—such as the restricted jaw movement that occurs when individuals must hold a bite-block between their molars—and produce speech that is acoustically and perceptually indistinguishable from speech produced without a perturbation (Gay, Lindblom, & Lubker, 1982). It is presumed that this ability reflects individuals' tactic knowledge of the multiplicity of mappings between the articulatory characteristics of speech and their acoustic consequences. Edwards (1992) found that children with PI were less able than their same-age peers to compensate for the presence of a bite block during speech production, suggesting that they have a decreased knowledge of the articulatory characteristics of sounds.

The textbook use of the term *phonological* impairment (rather than articulatory impairment or speech-motor impairment) to describe children with severe speech-sound errors (e.g., Peña- Brooks & Hegde, 2000) implies strongly that a deficit in higher-level phonological knowledge underlies this disorder. Indeed, is a standard assumption in most introductory textbooks on speech-sound disorders that the systematic nature of sound errors by children with PI implies a higher-level basis to this disorder: a deficit in higher-level knowledge is presumed to underlie error patterns that don't have a clear articulatory or perceptual. However, despite the extremely common practice of calling severe speech-sound disorders *phonological impairments*, there is a relative paucity of research examining whether children with PI differ from their typically developing peers on experimental measures of higher-level phonological knowledge.

The question of whether children with PI show deficits in higher-level phonological knowledge was examined experimentally by Munson, Edwards, and Beckman (2005). Munson et al. (2005) examined the higher-level phonological knowledge of children with PI using the same nonword-repetition task as Edwards, Beckman, and Munson (2004) used. Munson et al.

found that children with PI repeated nonsense words less accurately than children with TD, as would be expected from their overall less-accurate speech production. Both groups of children repeated high-frequency sequences of phonemes more accurately than they repeated low-frequency ones. However, the magnitude of the difference in high- and low-frequency sequence repetition was quite similar for the two groups. That is, the children with PI did not appear to have a specific deficit in higher-level phonological knowledge. If that had been true, we would have expected them to have an overall greater influence of sequence frequency than children with TD.

Munson, Edwards, and Beckman (2005) also examined these different types of phonological knowledge relate to one another. In addition to examining the accuracy children's productions of high- and low-frequency diphone sequences in nonwords, Munson et al. also measured vocabulary size, perceptual knowledge, and articulatory knowledge. Vocabulary size was estimated by using the natural logs of raw scores on two standardized tests of articulation, the *Peabody Picture Vocabulary Test-III* (PPVT-III, Dunn & Dunn, 1997) and the *Expressive Vocabulary Test* (EVT, Williams, 1997). Perceptual knowledge was estimated by using an measure of perceptual sensitivity in an auditory word recognition task (Edwards et al., 2002), while articulatory knowledge was estimated by using raw scores from a standardized test of articulation (*Goldman-Fristoe Test of Articulation*, GFTA, Goldman & Fristoe, 1986). As in Edwards et al. (2004), Munson et al. found that the influence of phoneme-sequence frequency on accuracy was mediated by vocabulary size – the larger the vocabulary, the smaller the effect of frequency. The most interesting finding of the Munson et al. study was the lack of an association between the frequency effect and measures of perceptual and articulatory knowledge. Not surprisingly, both measures were correlated with overall accuracy. However, there was no interaction between these measures and the effect of sequence frequency on repetition. If we are to interpret these results relative to Figure 2, these results suggest that many children with phonological disorders have deficits in articulatory and perceptual knowledge, but do not have deficits in the higher-level phonological knowledge, as it is measured on the nonword repetition task.

Finally, at least one study provides evidence that children with PI have deficits in social-indexical knowledge. Nathan and Wells (2001) examined the ability of children with phonological disorders to process words spoken in their native accent (London English) and an unfamiliar accent (Glasgow English). They found that children with PD showed a greater influence of accent on lexical decision accuracy than age-matched typically developing children. This suggests that children with PD know less than their typically developing peers about systematic correspondences among different social-indexical phonological variants.

In sum, children with PI show a variety of deficits in phonological knowledge. It appears that their deficits that they display in articulatory and perceptual knowledge are quite substantial. Other deficits, such as the deficit in higher-level phonological that is revealed in repetition tasks, are considerably less pronounced. Munson et al. (2005), that compared multiple types of knowledge concurrently, found evidence that the deficits in articulatory and perceptual knowledge were more strongly associated with PI than were deficits in higher-level phonological knowledge.

Implications for Assessment

Given the model reviewed above, what are the implications for the way that we assess and treat phonological knowledge in children who demonstrate functional delays in speech and language? This section will present ways that practicing clinicians can assess the four types of phonological knowledge—articulatory knowledge, perceptual knowledge, higher-level phonological knowledge, and social-indexical knowledge—using established protocols and procedures. As in the previous section, the focus in this section is on functional disorders of speech and language; this section will not consider the implications that this model has for organic speech and language disorders.

Many of the measures discussed in this section are not standardized or norm-referenced. Clinicians should think of these as parts of a dynamic assessment of children's abilities. Dynamic Assessment (Peña, 1996) is a class of nonstandard assessment tools designed to measure, among other things, the basic-level cognitive, linguistic, perceptual, and motor skills that underlie a language behavior. The assessments in this section would be appropriate to incorporate in a comprehensive dynamic assessment of the skills that underlie fluent, accurate speech production.

Assessing Vocabulary Size and Vocabulary Knowledge

The first implication of the model reviewed above is that phonological knowledge should never be assessed separate from lexical knowledge. Edwards et al. (2004) and Munson et al. (2005) both found a strong relationship between vocabulary size and higher-level phonological knowledge: children with smaller-sized vocabularies had less-robust higher-level phonological knowledge. One simple measure of lexical knowledge is a measure of the size of the vocabulary itself. Most children with language impairments have smaller vocabularies relative to age peers. In fact, many of these children first come to the speech-language pathologist's attention because of their small expressive vocabularies relative to their age peers. Furthermore, it is well documented that children with language impairment have difficulties on novel word-learning tasks relative to age controls (e.g., Dollaghan, 1987; Oetting et al., 1995). While most children with PI do not have smaller vocabularies relative to age peers, Munson et al. (2005) found that a small number of children (approximately 10%) had significantly smaller vocabularies than their typically developing controls. It is relatively easy for speech-language pathologists to include standardized measures of receptive and expressive vocabulary in a phonological evaluation. This can be assessed using a variety of standardized tests and parent-report measures, including the *Peabody Picture Vocabulary Test-III* (PPVT-III, Dunn & Dunn, 1997), the *Expressive Vocabulary Test* (EVT, Williams, 1997), and the *Macarthur Communicative Development Inventory* (MCDI, Fenson et al., 1993), among others. Children whose vocabularies are atypically small should be considered at risk for having deficits in higher-level phonological knowledge.

Assessing Perceptual Knowledge

Another implication of the model above is that we should assess the robustness of children's perceptual representations for sounds. Recall from the earlier discussion that this perceptual knowledge really encompasses two types of knowledge. One type of perceptual knowledge is knowledge of the range of variation in the acoustic speech signal, sensitivity to which is illustrated in studies on people's ability to remember episodic detail in speech perception. The other type of perceptual knowledge is knowledge of the categorical structure of sounds, which is measured through tests of speech-sound identification and discrimination.

Currently, there are few clinical tools to assess children's perceptual knowledge. However, given that some children with PI have a deficit in this type of knowledge, it is important to assess it using the available tools. In particular, clinicians should strive to assess whether children can discriminate between the errors that they produce, and the target sounds. One clinically feasible speech-perception assessment procedure is outlined by Locke (1980a, 1980b). Locke's procedure requires the clinician to use live voice. In Locke's procedure, clinicians test children's ability to identify pictures representing words with three sounds: the target sound they produce in error, the substituted sound, and a control sound. For example, a child who produces an [f] for target /**θ**/ might be presented with a picture of a thumb and asked *Is it a [**θ**]umb? Is it a [f]um? Is it a [s]um?* Children would be presumed to have a problem perceiving the difference between target sounds and their errors if they answer "yes" to the first two responses but not the third. Children who answer "yes" to all three questions would be presumed to have a perception problem that extends beyond the target sound and its error. This procedure introduces two potential confounds. One is that the clinician may not reproduce a child's error accurately. As reviewed earlier, children with 'covert contrasts' may appear to produce a sound neutralization error but nonetheless produce subtle, reliable, but nonetheless imperceptible acoustic differences between sounds in their production. Consider a child who appears to produce a pattern in which [**θ**] and [f] both sound like [f] but whose productions show acoustic differences between target [**θ**] and target [f]. A clinician using live-voice assessments of perception may find this child is able to perceive the difference between [**θ**] and [f] in the clinician's speech; however, the same child may not be able to perceive the difference between [f] and the sound that they produce for target [**θ**]. This information could never be obtained in a live-voice assessment, unless the clinician was exceptionally skilled at perceiving and reproducing covert contrasts. A second confound is that the use of live-voice presentation may lead the clinician to hyperarticulate the target sounds. The result of a perception test using hyperarticulated stimuli may not predict children's ability to discriminate among sounds that are produced more naturally.

Some standardized tools are available to measure perceptual knowledge. For example, the *Goldman-Fristoe-Woodcock Test of Auditory Discrimination* (GFWTD, Goldman, Fristoe, & Woodcock, 1970) and the *Word Intelligibility by Picture Identification* test (WIPI, Ross & Lerman, 1979) use a picture-naming paradigm to measure children's ability to discriminate among sounds. The GFTWD has a tape-recorded stimulus tape and provides standard scores. Another more sophisticated tool used to assess perceptual knowledge is the computer-based *Speech Assessment and Interactive Learning System* (SAILS, Avaaz Innovations, 1995). SAILS allows clinicians to assess children's discrimination and identification of correct and incorrectly produced sounds using digitized speech tokens produced by a number of talkers. Both SAILS and the GFTWD, have an advantage over live-voice tests, in that they use pre-recorded tokens.

There are currently no clinically feasible tools to assess children's sensitivity to variation in the speech signal, as it is measured through perception of words in single- and multiple-talker lists. SAILS uses multiple talkers, but it does not systematically compare perception of words in single- and multiple-talker presentation conditions. Forrest et al. (1995) used a version of the WIPI to measure this knowledge. The first author has also developed a computer-implemented version of the WIPI with single and multiple talkers, modeled on the description given in Forrest et al.; however, this tool is not currently available for clinical dissemination. Clinicians wishing to assess this type of knowledge would need to modify existing perceptual tests to include single and multiple talkers.

Assessing Articulatory Knowledge

The next implication of our model for assessment is that we should measure the robustness of children's articulatory representations. This knowledge is measured somewhat indirectly in the tests of articulation that are standard components of assessment batteries, such as the *Goldman-Fristoe Test of Articulation*. However, performance on those tests does not give a fine-grained assessment of children's articulatory knowledge of the type shown in Gibbon (1999), Goffman (1999, 2004) and White (2001), among others. Here again, there is a relatively large gap between the tools available in research studies and those that are feasible for use in clinical assessments. For example, the system used by Goffman (1999, 2004) to measure articulation in children with language impairments is designed (and priced) for use in research settings, rather than for use in clinical settings. A more clinically promising piece of technology is the electropalatography (EPG) system described by Gibbon (1999). EPG systems allow for the measurement of tongue-palate contact patterns, and, for some error types, can show whether children who apparently produce sound substitutions actually maintain a distinction between the target sound and its substitution. The acoustic analysis techniques like those presented in White (2001) also hold promise as potential clinical assessment tools.

A less direct measure of the robustness of articulatory knowledge can be provided from transcription of lists of probe words containing multiple instances of sounds in multiple phonetic contexts. For example, the phonetic inventory described by Munson, Edwards, and Beckman (2005) elicits English vowels in multiple words, and consonants in multiple words and in multiple word positions, for a total of three repetitions of each vowel, and nine repetitions of most consonants. Accuracy measures from lists like this give a much clearer picture of the strength of children's articulatory knowledge than standardized tests. For example, a child whose accuracy of /**θ**/ production in initial, medial, and final position is 100% on a standardized measure like the *Goldman-Fristoe Test of Articulation,* but whose performance on the phonetic inventory presented by Munson et al. (2005) is only 33% (one correct production of three in each word position) could be presumed to have substantially poorer articulatory knowledge than a child with 100% accuracy on both measures. Moreover, lists that systematically varied other factors known to influence production, such as phonetic context, word length, and prosodic structure, could be used to examine whether a child's articulatory knowledge of a particular sound was limited to a specific context or structure.

Assessing Higher-Level Phonological Knowledge

Finally, how could we assess children's higher-level phonological knowledge? Recall that previous research on adults and typically developing children has used a variety of measures to examine this type of knowledge, including nonword repetition (e.g., Edwards et al., 2004; Munson et al., 2005), judgments of perceptual similarity (Storkel, 2002), and novel-word learning tasks (e.g., Storkel, 2001), among others. All of these measures are easy to make in clinical settings, and could be used as part of a dynamic assessment of phonology. For example, the nonword repetition task described by Edwards et al. (2004) and Munson et al. (2005) could be administered to examine a child's higher-level phonological knowledge. Storkel's novel-word learning tasks could be used to measure children's ability to use phonological knowledge to support new-word learning.

There is a class of standardized norm-referenced assessment instruments that assess one aspect of higher-level phonological knowledge. These are tests of children's metalinguistic knowledge of phonology, sometimes termed *phonological awareness*. Phonological awareness tasks measure child's ability to make overt judgments about the sound structure of words and nonwords. Phonological awareness tasks require children to have robust higher-level phonological knowledge. For example, in one common phonological awareness task, children are asked to pronounce a word with one or more phonemes removed (i.e., a child might be required to pronounce the word *sick* in response to the prompt *say* stick *without the* t *sound*).

Success in this task requires children to have robust knowledge of the sound structure of words, and the ways in which phonemes can be combined to form both known and novel sequences. Measures of phonological awareness are more complicated and more difficult than other experimental measures of higher-level phonological knowledge in that they require children not only to possess the knowledge, but to express their knowledge overtly. Consequently, a child might be able to demonstrate robust higher-level phonological knowledge in an experimental task but not in a measure of phonological awareness. One standardized, norm-referenced test of phonological awareness is the *Comprehensive Test of Phonological Processing* (CTOPP, Wagner, Torgeson, & Rashotte, 1999). The CTOPP includes measures of phonological awareness, as well as a measure of nonword repetition. Performance on the CTOPP can be considered a rough estimate of a child's higher-level phonological knowledge, with the caution that the difficulty of this test relative means that it might not be as appropriate to use with younger children as the experimental measures described earlier.

Assessing Social-Indexical Knowledge

Perhaps the least-frequently addressed area of assessment relates to children's knowledge of systematic uses of speech-sound variation to convey social identity. Currently, there are no tools—either formal or informal—to assess this knowledge. However, clinicians can make rough estimates of the robustness of knowledge by observing children's speech production behavior in a variety of social settings. Research reviewed earlier suggests that even young children use variation in production in adult-like ways. If a clinician were to observe that a child were not demonstrating systematic differences in sound production in different conditions in which you might expect it (i.e., speaking casually with a peer versus speaking formally), then that child might be considered to have a deficit in social-indexical knowledge.

Implications for Treatment

This section considers the implications that the model presented in Figure 2 has for the treatment of children with deficits in phonological knowledge. The primary focus in this section will be on children with PI, although these techniques are broadly applicable to any population of children who demonstrate deficits in phonological knowledge, including the subtle phonological-knowledge deficits displayed by children with language impairments.

Building Perceptual Knowledge

The first type of phonological knowledge that we consider is perceptual knowledge. As discussed earlier, perceptual knowledge includes two types of knowledge: knowledge of the category structure of sounds, as revealed through speech identification and discrimination experiments, and knowledge of variation in speech signals. We discuss each of these separately.

Speech Discrimination and Identification

Speech identification and discrimination may be trained in children by simply training sounds with minimal pairs of words. Minimal-pair treatment includes a focus on children's development of between-category discrimination (between the target and its minimal pair in words) and within-category identification (among words which contain the same target sound) (e.g., Gierut, 1989). The child is usually presented with the target sound in different vowel contexts in a single word position in stressed syllables (or monosyllabic words). As noted above, given the model of phonological knowledge presented in Figure 2, eventually the child should be presented with discrimination and identification tasks that require the child to discriminate and identify target sounds and contrasts across different word positions, different stress patterns, and different speakers.

Computer-based tools to facilitate speech discrimination and identification are becoming increasingly more-widely available. One such tool is the SAILS. In addition to the assessment components of SAILS (described above), SAILS has components that focus on teaching children to identify a variety of speech sounds. There is evidence SAILS has been shown to facilitate children's identification and discrimination of speech sounds as well as to generalize to their production accuracy (Rvachew, 1994). This learning occurs irrespective of the type of articulation therapy being given (Rvachew, Novak, & Cloutier, 2004).

Diverse Perceptual Representations

Therapy programs can also focus on building diversity in children's perceptual representations. A basic tenet of one widely used therapy program, the Cycles Approach, is that “auditory bombardment” of the target sound is an important component of each therapy session (Hodson & Paden, 1983). In this portion of treatment, for a short period during each treatment session, the child listens to words which contain the target sound. Often the sound is presented only in a single word position (Hodson & Paden, 1983, p. 50). However, given the multi-dimensional nature of perceptual representations, it is probably important, at least at some point in therapy for children to be exposed to the target sound in different vowel contexts, in different word positions, in different prosodic positions (in both stressed and unstressed syllables), and produced in different speech styles (i.e., hyperarticulated 'clear' speech styles, as well as more natural speech styles). Auditory bombardment with these different types of words would expose the child to a broader range of variation in perceptual characteristics of words. These diverse perceptual representations may facilitate later phonological-category learning. Maye's research (Maye, Werker, & Gerken, 2002; Maye & Weiss, 2003) suggests that children learn phonetic categories by through encoding phonetic distributions, such as those shown in Figure 1.

Providing a child with a natural phonetic distribution potentially would allow the child to learn phonetic categories in a manner similar to that of typically developing children.

Given the model of phonological knowledge presented above, a child with a PI cannot simply learn between-category discrimination and within-category identification of target sounds in a single word position. Rather, at least at some point in therapy, the child will need to be presented with target sounds and contrasts across different vowel contexts, different word positions, different stress and accent patterns, and spoken by different speakers.

Building Articulatory Knowledge

Another component of phonological knowledge is knowledge of the articulatory characteristics of sounds and words. One of the oldest techniques in articulation therapy is phonetic placement (Secord, 1989). This approach to therapy emphasize, particularly in its early stages of therapy, that speech-elicitation activities contain strong sensory feedback. Presumably, this sensory feedback would increase the child's awareness and learning of the articulatory characteristics of sounds. It is easier today to implement than it has ever been, given the "candy" powders and sprays on the market that can be used to provide proprioceptive feedback for correct place of articulation for sounds such as /s/ and /r/.

Another technique to facilitate robustness of articulatory representations is to train sounds in multiple phonetic contexts. This notion is consistent with the sensory-motor approach first presented by McDonald (1964). Frequently, speech-language pathologists begin by teaching a sound in isolation, then in syllable-initial and syllable-final position, then in words, then in sentences, and finally in connected speech. It may also be important that clinicians make sure that children practice target sounds in both stressed and unstressed syllables and in different positions within a sentence. That is, the child is taught to produce the target sound in a gradually more demanding environment, from the point of view of motor control and linguistic demands. An emphasis is placed on reaching automaticity at each level of demand, before continuing onto the next level.

The procedures outlined in the previous two paragraphs are consistent with the model of phonological knowledge that we've presented in Figure 2 and throughout this paper. One component of phonological knowledge is a set of well-practiced articulatory-motor representations. Although it has not been emphasized in traditional approaches, like those of McDonald (1964) and Secord (1989), another equally important aspect of articulatory knowledge that falls out of our model is the opportunity to learn the correspondence between articulatory knowledge and perceptual knowledge. Accurate speech production requires children to know what articulatory movements must be made for a target acoustic output to occur. This knowledge has been characterized as 'many to one', because more than one articulatory movement may result in the same perceptual output. It is important for children undergoing speech therapy to learn this 'many to one' concept. Consider the articulatory movements that adults may use to produce the sound /r/. Two distinct movements—a retroflex movement of the anterior portion of the tongue, or a bunching movement of the tongue root—can be used to produce the sound /r/. Children who are taught a single way to produce a sound in therapy (such as a retroflex articulation for /r/) would have decreased knowledge of these correspondences, relative to a child who had been taught multiple ways to produce this sound. To develop knowledge of the systematic correspondences between articulation and acoustics, clinicians must be willing to train multiple ways to produce sounds.

It is important to emphasize that building knowledge of the articulatory characteristics of sounds is considerably different from the types of 'oral-motor' therapies that are sometimes used with children with PI. These therapy regimens focus on facilitating basic-level strength, flexibility, stability, and range of motion through nonspeech exercises like sucking and blowing. The efficacy of these regimens is reviewed by Lof (2003). Lof presents comprehensive evidence arguing that these treatment protocols do not have sufficient empirical evidence to support their use.

Facilitating Higher-Level Phonological Knowledge

The next type of phonological knowledge we consider is higher-level phonological knowledge. Recall that this type of phonological knowledge encompasses children's knowledge of the segmental structure of words (i.e., their knowledge that a word like *pig* is comprised of the sounds /p/, /ɪ/, /g/) as well as their knowledge of the ways that sounds can be combined into sequences in words (i.e., knowledge that a sequence like /fk/ is not likely to occur in words, while /ft/ is).

Just as we cannot assess higher-level phonological knowledge without considering vocabulary knowledge, we cannot treat these two areas separately. Children who have been identified as having a deficit in higher-level phonological knowledge engage in activities to facilitate their word learning. Children who know more words will have more opportunities to develop higher-level phonological knowledge. Indeed, there is evidence that therapy focused on building the lexicon influences children's phonological knowledge (Girolametto, Pearce, & Weitzman, 1997).

One way to facilitate higher-level phonological knowledge is to work directly on children's metalinguistic knowledge of the sound structure of language, i.e., to facilitate their phonological awareness. However, children's higher-level phonological knowledge is also reflected in their generalization learning of sounds during speech therapy. When a child learns what is taught in therapy and generalizes this knowledge to untrained items, then we can presume that the child's generalization learning occurred because the child developed an aspect of higher-level phonological knowledge beyond what was taught in the therapy session. For example, a child who generalizes correct production of /ɡ/ to words not taught in therapy is presumed to have learned something about how /ɡ/ is used to change word meanings; a child who is taught the sound /ʃ/ and then spontaneously learns other sounds like /s/ and /f/ has demonstrated higher-level phonological knowledge about how an entire class of sounds, voiceless fricatives, codes meaning in the language. This section will consider techniques to facilitate higher-level phonological knowledge by reviewing techniques that foster this type of generalization learning.

A focus of work by Gierut and colleagues (e.g., list references) has been on how choice of target contrasts and target words can facilitate phonological generalizations. Children with severe speech-sound impairments often have multiple sounds that are missing from the productive phonetic repertoires. How can we design therapy to result in maximum generalization learning of untreated sounds? Gierut and colleagues have found that there are two factors which tend to maximize generalization to untreated sounds. The first is the choice of target contrasts. Gierut, Elbert, and Dinnsen (1987) found that the most generalization occurs when the clinician chooses a maximal contrast rather than a minimal contrast. That is, rather than choosing a contrast such as /k/ versus /ɡ/, which differ only along the single dimension of voicing, they recommend choosing a contrast such as /r/ versus /s/, which contrast in place, manner, and voicing. Furthermore, Gierut et al. (1987) found that maximal generalization resulted when both target sounds in the contrast were sounds that the child was not stimulable for, were late-developing, and that the child did not produce at all. This approach runs counter to traditional wisdom that target sounds and contrasts should be early-developing, produced inconsistently, and sounds that the child is stimulable for.

Another way to facilitate higher-level phonological knowledge is through careful selection of therapy targets. Gierut, Morrisette, and Champion (1999) and Morrisette and Gierut (2002) demonstrated that children's phonological learning during therapy was influenced by the frequency of occurrence of words used to teach sounds, as well as the similarity of those words to other real words that the child might know. When sounds were trained in words with a high frequency of occurrence that were similar to relatively few other real words, the child was more likely to generalize correct sound production to untrained words than when sounds were trained in words with the opposite characteristics.

Facilitating Social-Indexical Knowledge

The last component of phonological knowledge that has been emphasized in this paper is the use of phonetic variation to code social-group membership. As emphasized earlier, this topic has not received much attention in research on atypical phonological development. However, we believe that it is of great relevance to practicing clinicians. Therapy regimens typically involve clinicians producing hyperarticulated sounds to children. The assumption behind this is that these hyperarticulated models will be easier for children to perceive and, perhaps, to imitate. The unintended consequence of this is that children in therapy may learn phonological categories that do not encompass the natural range of variation in those of children who are exposed to a more-natural distribution of sounds. It is possible, then, that children who are exposed to this limited distribution will not develop phonological categories that contain the variability needed to use phonological variation to convey social identity. This jibes with many people's clinical impressions that many children who have completed therapy may speak rigidly when compared to their peers whose phonological development occurred naturally. That is, children may successfully complete therapy, as gauged by their performance on measures like single-word naming tests and tests of connected speech, but still be unable to switch flexibly among different variants of sounds needed to convey social identity. Consider again the results of Munson, McDonald, DeBoe, and White (2005), who examined adults' use of distinctive pronunciation to convey sexual orientation. A person whose therapy regiment had only including the teaching of a single mode of pronouncing a sound would not necessarily possess the flexibility in production needed to use pronunciation to convey their social identity.

One possible solution to this problem is for therapy, particularly in the later stages, to include multiple models for pronunciation. Children who are exposed to a variety of different social-indexical variants of the sounds that they are taught in therapy will have more opportunities to be exposed to the full range of variation in pronunciation. They will also have more opportunities to implicitly learn the association between different pronunciation variants and different social-indexical categories. The paucity of research on this topic has already been emphasized earlier in this article. We believe that this topic will provide a fruitful topic for future research, both in typical phonological development and in speech and language disorders. Ultimately, it may be revealed that children's knowledge and expression of social-indexical variation relates strongly to more impressionistic measures of their communicative effectiveness upon completing therapy.

Summary and Future Research

This article reviewed different types of phonological knowledge. Throughout this paper, we have emphasized the importance of understanding, measuring, and treating four types of knowledge: perceptual knowledge, articulatory knowledge, higher-level phonological knowledge, and knowledge of social-indexical variation in sounds. It is our hope that practicing clinicians who have read this article have gained an appreciation for the importance of measuring and facilitating these different types of knowledge. We began this paper with a discussion of the different types of knowledge that adults have of /s/. If a child who fails to learn /s/ normally undergoes therapy and learns only one of these types of knowledge—for example, only the articulatory knowledge that would be facilitated in a traditional sensory-motor approach to therapy—then the resulting knowledge that the child has will be incomplete. A comprehensive therapy regimen would consider all four types of phonological knowledge.

The model of phonological knowledge presented in Figure 2 is supported by a wealth of experimental and observational data. However, there is much need for future research. One highly salient area of future research concerns social-indexical knowledge. Sociolinguistic investigations have made it clear that adults' knowledge of sounds includes a great deal of knowledge of socially motivated variation in pronunciation (Munson, Jefferson, & McDonald, 2005; Munson, McDonald, DeBoe, & White, 2005; Strand, 1999). Models of the acquisition of knowledge of sounds can no longer ignore the role of social factors and social knowledge in development. The next generation of models of development must make explicit the role of this knowledge in typical phonological development. Similarly, the next generation of models of disorders must make equally explicit statements about the extent to which this knowledge may be impaired in children with functional impairments of speech and language, and the importance (or potentially, lack thereof) of measuring and treating deficits in this type of knowledge. Preliminary studies on this topic are in progress (e.g., Docherty, Foulkes, Tillotson, & Watt, in press), and many others are needed.

Another particularly pressing area for future research is to examine the relative dependence and independence of different types of phonological knowledge. Our own research has examined this in typical development (Edwards, Munson, & Beckman, 2004) and in children with PI (Munson, Edwards, & Beckman, 2005); however, this research topic is still in its infancy. Recent research (Munson, DeMarco, Yim, & Babel, 2004; Simmons, 2004) has further examined these topics using a set of on-line processing measures and measures of children's ability to form new articulatory and acoustic representations for sounds. The preliminary results of these studies provide evidence that converges with the earlier studies by Edwards et al. and Munson et al. Specifically, we have found that children's ability to learn new phonological representations in implicit phonological learning tasks (Fischer, Hunt, Chambers, & Church, 2001) is related to their phonological accuracy in spontaneous speech. Children with more accurate speech production are more skilled at learning new phonological representations in implicit learning tasks than children with less accurate speech production (Simmons, 2004). This is true even when other measures like age, nonverbal IQ, and experimental measures of higher-level phonological knowledge were controlled statistically (Munson et al., 2004). If replicated, these findings provide a powerful suggestion that children's phonological accuracy may be more strongly related to their lower-level articulatory and perceptual knowledge than to their higher-level phonological knowledge, a finding consistent with Munson et al. (2005). We hope that our and others' future research on this topic are able to clarify more precisely the types of phonological knowledge that are most crucial to children's mature, accurate, and fluent speech production, so that we may make the strongest, most evidence-based recommendations for the types of phonological knowledge that speech-language pathologists should work on facilitating.

Acknowledgements

The preparation of this manuscript was supported by NIH grant R03 DC005702 to Benjamin Munson. The research described in this manuscript was supported by NIH grants R01 DC02932 to Jan Edwards and R03 DC005702 to Benjamin Munson. We also thank the people with whom we collaborated on the research described in this article: Molly Babel, Kenda Blasing, Adriane DeMarco, Marios Fourakis, Robert Fox, Miriam Krause, Beth Kurtz, Shayla Manthei, Catherine Rogers, Dawn Simmons, Cyndie Swenson, Jennifer Windsor, and Dong-Sun Yim.

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Figure Captions

Figure 1. Hypothetical distribution along a phonetic parameter reflecting one underlying category (top) and two underlying categories (bottom).

Figure 2. Relationships among three types of phonological representation that are posited to be associated with words in the lexicon.

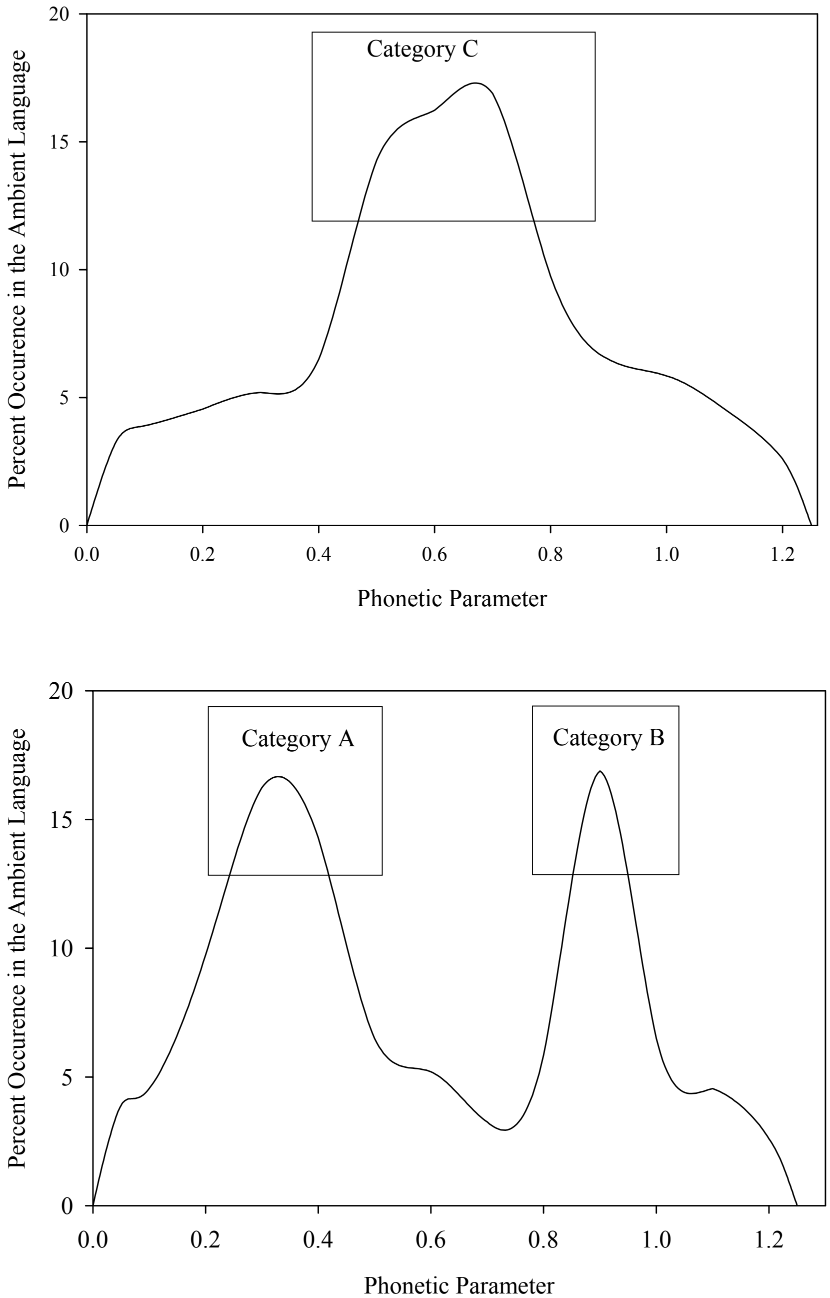
Category C
Percent Occurence in the Ambient Language
Phonetic Parameter
20
15
10
5
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Category A
Category B
Percent Occurence in the Ambient Language
Phonetic Parameter
20
15
10
5
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2

Figure 1.

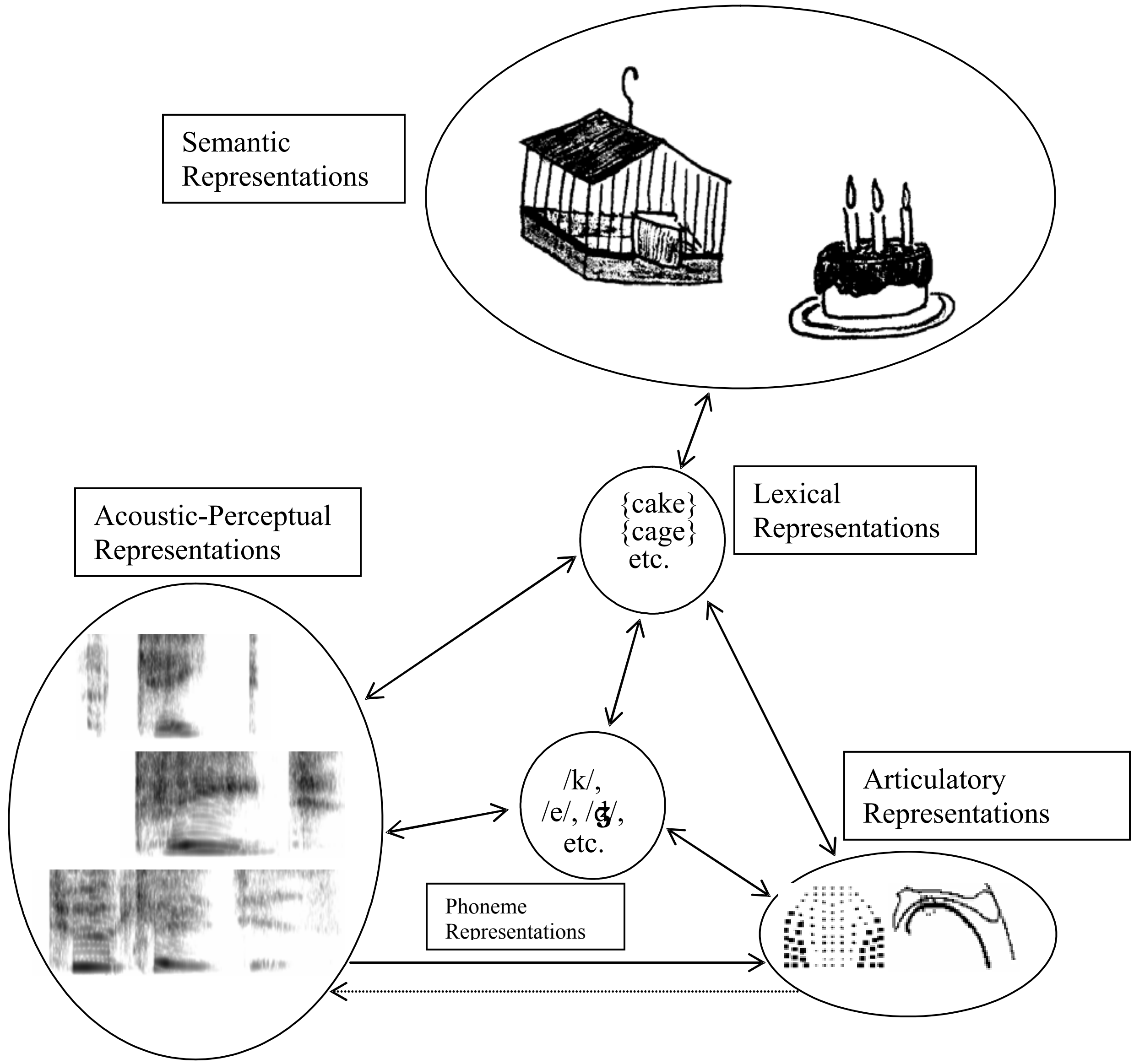
Semantic
Representations
Lexical
Representations
{cake}
{cage}
etc.
Acoustic-Perceptual
Representations
/k/,
/e/, /ʤ/,
etc.
Articulatory
Representations
Phoneme
Representations

Figure 2.