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phonology development in infancy and early childhood: implications for theories of language learning

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introduction

Jakobson (1941/1968) proposed that: (i) infants babble the sounds of all languages; (ii) there is discontinuity between babbling and first words; and (iii) phonemes are acquired in a universal order. Since then, all of these hypotheses have been rejected on empirical grounds and the importance of the prelinguistic foundations of phonology has been recognized. However, questions about the relationship between babble and words, the timing and extent of the impact of the ambient language on early speech perception and production, and individual differences in phonological development continue to energize research. General cognitive as well as purely linguistic foundations for phonological development, not directly addressed by Jakobson, have also been the source of fruitful recent investigations thanks to methodological advances in psycholinguistics and neurolinguistics. These issues have important implications for phonological theory, which must account for developmental as well as adult data. Claims about innate knowledge versus learning must refer to the processes by which the child develops and manifests a phonological system. Yet certain well-documented phenomena that are highly characteristic of child phonology remain to be integrated into theories of adult phonology. The goal of this chapter is to elucidate the state of the art with respect to issues and questions in child phonology, including recent findings, research methodologies and theoretical models.

In the first half of the chapter we review prelinguistic and early linguistic foundations for phonology, highlighting universal versus language-specific and child-specific aspects of phonological emergence. We then address aspects of child phonology that pose particular challenges for phonological theory. Next, neurocognitive theories are reviewed, with a focus on recent findings that shed important light on human language learning capacities. Finally, we provide brief overviews and critiques of key phonological theories. The chapter ends with a proposal for an integrated model of phonological development that embraces both neurocognitive capacities and the full range of universal, language-specific, and child-specific phenomena.

prelinguistic perceptual and vocal behaviors

Infants discriminate and produce sounds that are absent from the languages they are hearing. The non-native sounds they produce during the first six months are mainly traceable to physiological factors, such as incomplete consonantal closure and natural physiological linkages of tongue and jaw position; these effects have some impact in later stages as well (Davis and MacNeilage, 1995; Kent, 2000).[1] Physiology also has a profound effect on the sound systems that infants must learn. For example, the consonant-vowel (CV) co-occurrence patterns found in babbling have also been identified as statistical tendencies for consonant-vowel pairs in most of the world's languages (MacNeilage, Davis, Kinney, and Matyear, 2000). The most characteristic, or *unmarked*, features of phonological systems, such as labial stops [b, p], are not only more common in languages, but are also generally acquired earlier than marked ones such as interdental fricatives [θ, ð] (Locke, 1983). Unmarked features include common sound combinations (phonotactic or distributional patterns) as well as individual sounds and sound classes, such as:

- stops, nasals, glides
- coronals (dentals or alveolars)
- CV syllables
- two-syllable words

Universal markedness patterns are largely predictable based upon the principles of articulatory ease and perceptual discriminability (Liljencrants and Lindblom, 1972; Stevens, 1989). For example, voiced fricatives (e.g., [v,z]) are less common and later learned than voiceless fricatives (e.g., [f, s] because they are more difficult to produce for aerodynamic reasons

(Ohala, 1983). The interdental voiceless fricative [θ] may be rare because of its perceptual similarity to [f].

Despite similarities in their phonological systems, languages differ at the level of phonetic implementation. For example, different languages manifest different coarticulatory effects (Kingston and Diehl, 1994). Fortunately, human infants are well-equipped to learn the particulars of the language to which they are exposed. This has been established by experiments designed to elicit differential infant responses to familiarized versus novel auditory stimuli. Familiarization responses are measured either via habituation (e.g., the infant's rate of sucking a rubber nipple decreases when the same stimulus repeats) or arousal (e.g., the infant maintains a behavior, such as gazing fixedly at a visual display, upon learning that this will elicit a particular auditory stimulus). Once the infant shows familiarization, the auditory stimulus is changed (experimental condition) or not (control condition). A differential response (e.g., in sucking rate or eye gaze) to a changed stimulus indicates that the baby detected the change.

The mammalian auditory system makes it possible to discriminate many aspects of speech. Human newborns already discriminate word-like stimuli based on number of syllables. Newborns can also discriminate between languages with different rhythms, even when phonetic and intonation information is filtered out, leaving only rhythmic cues (Ramus, 2002). Newborns also discriminate between lists of grammatical (*function*) words (e.g., prepositions and articles) versus lexical (*content*) words, presumably based upon prosodic and segmental cues, such as shorter vowel durations, weaker amplitudes, and simplified syllable structures in function words (Shi, Werker, and Morgan, 1999). These capacities extend to discrimination of segmental differences. Human neonates already respond differentially to different vowels. Very young babies (1–2 months) can also discriminate many consonantal contrasts, including voicing (e.g., [d] versus [t]), place of articulation (e.g., [p] versus [t] versus [k]), and manner of articulation e.g., [m] versus [b]).

Although some discriminatory abilities are present at birth, other speech discrimination abilities may require learning. This learning occurs very early: within days of birth infants attend more to their own mother's voice, to the prosody of infant-directed speech (IDS, or "baby talk"), based on its exaggerated rhythm and pitch contours, and to the prosody of the ambient language in conversational speech. By 2 months infants respond to changes in both pitch and duration and discriminate syllables in three-syllable patterns as long as IDS prosody is used. By 4 months, infants attend more to their own name than to others (Mandel, Jusczyk, and Pisoni, 1995) and listen longer to running speech presented in IDS prosody with clauses that are phonologically coherent (not interrupted). By 6 months, infants already attend longer to word lists in their own language than in a prosodically contrasting language. In addition, 6-month-olds are able to categorize maternal utterances of different types (comforting versus approving), based upon the prosodic characteristics of each type (Moore and Spence, 1996).

In the second half of the first year of life, infants are increasingly able to recognize significant information in the language around them. Ten-month-old infants display preferences for stress patterns (Jusczyk, Cutler, and Redanz, 1993) and for consonants and sequences of consonants and vowels from their own language (Gerken and Zamuner, 2004). They also respond more to disyllabic sequences as if they were single words if the disyllables include medial consonant sequences that are common in their language – e.g., [ŋk], as in *mo<u>nk</u>ey*, for English-learners – than if they include less common medial consonant sequences – e.g., [pt], as in *re<u>pt</u>ile* – (Morgan, 1996), indicating that the babies are associating segmental phonological cues with the prosodic cues that mark word boundaries. At this age infants also prefer uninterrupted phrases and words that follow the common phonotactic patterns of the ambient language. At 11 months, babies attend longer to lists of untrained familiar over unfamiliar words (Vihman, Nakai, DePaolis, and Hallé, 2004), indicating that word learning has begun.

Prelinguistic children can segment the speech stream into word-level units despite the lack of pauses between units and the masking effects of coarticulation. Jusczyk and colleagues have used tasks in which the infant is familiarized with a word – e.g., *cup cup cup cup* – and then presented with a passage in which that word occurs repeatedly – e.g., *The cup was bright and shiny. A clown drank from the red cup.* (Jusczyk and Aslin, 1995). By 7.5 months of age English-learning babies show by their attentional responses to passages containing the trained words that they can identify the words in running speech (although neither Dutch nor French infants show the effect so early: Nazzi, Iakimova, Biertoncini, Fredonie and Alcantara, 2006). Disyllables with a trochaic (stressed-unstressed) rhythmic pattern, predominant in English, can also be picked out by infants at 7.5 months, but disyllables with the less common iambic (unstressed-stressed) rhythmic pattern are not segmented until 9 months of age (Mattys, Jusczyk, Luce, and Morgan, 1999). English infants are able to segment only in their own language or rhythmically similar languages, e.g., Dutch (Houston, Jusczyk, Kuijpers, Coolen, and Cutler, 2000) but not Chinese (Jusczyk, 1998).

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How do infants segment connected speech? Both prosodic and distributional cues are likely sources of information. English-learning 9- but not 6-month-olds perceive unfamiliar pairs of syllables as belonging to a single unit only if they are trochaic (Morgan, 1996). Given that newborns are already sensitive to rhythmic differences, this role of prosody is not surprising. Distributional cues include such factors as transitional probabilities, i.e., that certain units are likely to follow one another. High transitional probabilities are exemplified in formulaic expressions: the word *pancake* has a high probability of occurrence following *flat as a*... Transitional probabilities for within-word phoneme or syllable sequences are necessarily higher than for sequences across word boundaries. Thus, recurrent pairs of sounds or syllables are likely to form part of the same word. Adults can learn the transitional probabilities and therefore segment out the "words" of a nonsense language presented aurally with no prosodic information. Their performance improves with the addition of one prosodic cue, final syllable lengthening (Saffran, Newport, and Aslin, 1996).

In real life, both prosodic and distributional information is available to the infant. Morgan and Saffran (1995) assessed babies' use of the two types of information by comparing their performance on perceptual tasks with (i) distributional information: syllables that were consistently adjacent (e.g., [ɡakoti], [degako]) or not ([ɡakoti], [ɡadeko]) versus (ii) prosodic information: syllables that were consistently presented within trochaic units ([GAko] [KOɡa]) or not ([ɡaKO], [KOɡa]). Six-month-olds treated the syllable pairs as units whenever either distributional or prosodic cues were consistent with this conclusion. Nine-month-olds treated syllable pairs as units only when both rhythmic and distributional patterns were consistent. The older infants appear to be better at integrating the two types of cues.

These examples of infant capabilities amply demonstrate a pattern of cumulative learning based on the linguistic patterns that they have experienced. Some of the effects of the input language on the infant's developing linguistic system involve narrowing or loss of capacities that the infant had at an earlier stage. By 10–12 months infants are less able than at earlier ages to discriminate segmental contrasts not found in their own language. For example, at that age English-learning babies no longer respond differentially to velar versus uvular ejectives, two consonant types that do not occur in English. However, their differential sensitivity to familiar versus unfamiliar phonemic contrasts is neither sudden nor absolute. Infants maintain their ability to discriminate nonnative contrasts at places of articulation that are less frequently used in their language longer than contrasts at more common places of articulation (Anderson, Morgan, and White, 2003). Anderson et al. argue that infants develop knowledge of the more frequently encountered contrasts earlier, leading them to disregard nonnative contrasts along that dimension earlier. This implies that not only the (categorical) presence or absence of a contrasting sound or feature but also the (gradient) frequency of occurrence in the ambient language can affect children's perceptual processing. The more a child is exposed to a class of sounds, the more the child's perception becomes biased towards those sounds.

The statistical distribution of contrastive segments in input speech also has an effect on infant perception. A focus on points of maximal difference in a continuum of nonnative speech sounds facilitates 8-month-old infants' learning of contrasts (Maye and Weiss, 2003). Infants whose attention is focused on the area of acoustic overlap between two speech sounds lose the ability to discriminate between them (Maye, Werker, and Gerken, 2002). Infants likely benefit from the fact that speakers' pronunciations of difficult contrasts (e.g., /f/ versus /θ/ in English) are usually distinct rather than overlapping.

Well before producing their first words children begin to tailor their vocal production to input speech patterns. From 6–12 months infants' vocalizations come to reflect ambient language prosodic patterns, vowels, and consonants. For example, as expected based upon the prosody of the ambient languages, a falling pitch contour predominates in English babies' vocalizations while falling and rising contours are equally distributed in French children's vocalizations. The vowels of 10-month-olds differ in ways that match frequencies of occurrence in their languages. Prelinguistic consonants also differ by ambient language; labials, which are more frequent in French and English than in Swedish and Japanese, are also more frequent in the vocalizations of 9–10-month-olds learning French and English. Thus, the view that babbling is a purely motoric behavior unaffected by exposure to a language (cf., e.g., Lenneberg, 1967; Locke, 1983; Petitto, 1991) cannot be accepted. Rather, children's prelinguistic vocalizations as well as their speech perception show the effects of the input language.[2]

early linguistic perception and production

Like babble, early words are largely but not exclusively characterized by unmarked elements and structures: stops, nasals, and glides; simple vowels; and simple CV syllables within two-syllable words. However, ambient language influences on production increase rapidly as the child acquires a productive vocabulary of 50–100 words. The babbling and early words of French and English-learning children show significant differences in accentual patterns (Vihman, DePaolis, and Davis, 1998), as do the vocal productions of children learning French, English, and Swedish with respect to length in syllables and frequency of use of final consonants (codas). English-learning children use shorter words and more codas, as English does. Spanish-learners produce more weak initial syllables and fewer codas than English-learners (Roark & Demuth, 2000). French, English, Swedish, and Japanese learners also display significantly different patterns of consonant use as regards both place and manner of articulation.

In some cases, what is acquired early is *not* what is more common in adult languages (i.e., unmarked). This provides an interesting type of test case, in which physiological (motor and perceptual) effects on early learning can be separated from the formal effects of markedness based on adult linguistic universals. These two factors (physiology and markedness) interact with each other and with the effects of different language environments in different ways at different points in time.

For example, "marked" long (geminate) consonants are typical of early word production regardless of the input language (Vihman and Velleman, 2000). By the time children have a 50-word vocabulary, the long consonants have disappeared in English and French due to lack of an adult model but have begun to be deployed appropriately in relation to accent in Welsh, in which consonant lengthening is part of the stress pattern (Vihman, Nakai, and DePaolis, 2006) and to be overused in Finnish and Japanese (Kunnari, Nakai, and Vihman, 2001; Vihman and Kunnari, in press). Universal ease of production factors favoring long consonants (for infants, with their slow articulation: Smith, 1978) have now yielded to ambient language patterns. In Russian, similarly, (marked) palatalized consonants are produced more successfully than their (unmarked) plain counterparts (Zharkova, 2005), arguably due to the motoric effect of the large tongue contacting the palate in the production of lingual consonants. The CV syllable is the least marked (most widely distributed) syllable type in adult languages, perhaps for physiological reasons (MacNeilage et al., 2000), yet in many languages, including Estonian, Finnish, French, Hindi, and Welsh, children have been found to omit even such early-learned initial consonants as stops in their first words (Vihman and Croft, in press). The cause may be perceptual: initial consonant omission is generally seen when, in the ambient language: (i) an unaccented initial syllable is followed by an accented final syllable (e.g., French 'baNANE') or (ii) a medial geminate consonant in the target word (e.g, Finnish /pallo/ 'ball') pulls the child's attention away from the onset consonant. In these cases, where physiological availability or perceptual salience converge with ambient language patterns but conflict with markedness as determined by adult languages generally, physiology and perceptual salience take precedence over markedness.

The picture is even more complex than this, however. Contrary to Jakobson's "discontinuity" proposal regarding the lack of connection between babbling and first words, early word productions parallel babbling in many ways. Infants do not always employ the physiologically easiest or most frequently occurring sounds and word structures. Individual children's "favorite babbles" or prelinguistic *vocal motor schemes* (McCune and Vihman, 2001) shape their early words as well as their late-stage babbles. For example, one English-speaking child, Emma, demonstrated a labial-alveolar pattern in her babble (e.g., [wedawidamenaminʎmunimi nimini]) and also in her early words: [wedi] 'raisin', [budi] 'berry, bird, booster' (Studdert-Kennedy and Goodell, 1995). Atte, a Finnish child, babbled many VCV[3] forms, and 61% of his early word forms were of the shape VCV (e.g., [ɪcʼi] *isi* 'daddy'). Similarly, by age 10 months a French baby, Laurent, was already producing variants of the consonant [l] (Vihman, 1993), which is uncommon in infant productions. This consonant persisted into his word attempts and formed the basis of one of his regular word production patterns, or *templates*. The children appear to be selecting words for production based upon a match to their own prelinguistic production experience. Both physiology and the ambient language have influenced this experience, but the children's responses are individual.

Examples such as these, combined with the findings about the prelinguistic influence of the native language on perception and production reviewed above, force a rejection of the assumption frequently made in the current Optimality Theory literature (see below) that the early word production period can be equated with the *initial state* of the child's phonology (Dinnsen, McGarrity, O'Connor, and Swanson, 1999/2000; Gnanadesikan, 2004). Rather, at the onset of word production the child's phonological development is already affected by three factors: (i) human physiological and cognitive capacities; (ii) ambient language patterns; and (iii) the child's individual response to perceptual and vocal experience (DePaolis and Vihman, 2006).

The influence of frequencies of occurrence in the ambient language on production continues throughout childhood. On a nonsense word repetition task 2-year-olds produce coda consonants more accurately if the preceding syllabic context (i.e., the CV preceding the coda) is more frequent in their language (Gerken and Zamuner, 2004; Zamuner, 2003). This influence grows with the child's linguistic system; 3-year-olds with larger vocabularies show a stronger effect of phonotactic frequency on their production than do those with smaller vocabularies (Storkel, 2001; Beckman, Munson, and Edwards, 2004).

challenges for phonological theories

Certain aspects of early phonology, such as consonant harmony and metathesis, are inconsistent with patterns seen in the world's languages. For example, consonant assimilation, in which a feature of one consonant (e.g., labialization) spreads to an adjacent consonant (as in 'in' + 'possible' = 'impossible'), is common in adult phonologies. Consonant harmony, in which such spreading occurs "across" an intervening vowel (e.g., [s] becomes [ʃ] in Chumash to agree with another [ʃ] in the word: [saxtun] 'I pay' versus [ʃaxtunitʃ] 'to be paid'; Poser, 1982), is rare and limited to certain classes of consonant sounds (Shaw, 1991; Vihman, 1978). Vowel harmony is much more common in adult phonology (e.g. in Turkish the past tense suffix is pronounced [dum] in [durdum], 'I stood', but [dim] in [ɡeldim], 'I came').

In sharp contrast, in child phonology consonant harmony is almost universal (Smith, 1973). Children's consonant harmony occurs across vowels with all types of consonants and affects manner as well as place features (McDonough & Myers, 1991). For example, Daniel used initial and final velars in 13 of his first 50 words (e.g., [ɡɑk] for *clock, sock, rock, quack*: Stoel-Gammon and Cooper, 1984). "P" harmonized all consonants in a word with a nasal in any position, palatalized all of the resulting nasals (perhaps due to the "large tongue, small oral cavity" effect hypothesized above for the early emergence of Russian palatalized consonants), and also tended to harmonize vowels, resulting in forms like [njenje, njinji] for *finger (*Waterson, 1971). Jacob produced words with consonant place harmony and also vowel harmony, e.g. [ɡɛɡo] and [dɛdo] for 'thank you', [bibi] and [bɑbɑ] for 'baby' (Menn, 1976). Overall, harmony is much more prevalent in children than in adults and can affect up to 32% of any one child's lexicon (Vihman, 1978).

Metathesis, in which two elements are reordered, also occurs relatively rarely in adult phonology, primarily as a trading of adjacent elements (e.g., *desk* as [dɛks]). Most cases involve resonants, especially liquids and vowels (Hume, 2004). In contrast, metathesis is common in children's speech. Instances of metathesis yield regular output patterns in a child's phonology (Velleman, 1996). Alice, for example, produces consonants in a front to back order in terms of articulatory place (e.g., labial before palatal or velar), regardless of their order of occurrence in the target word (Jaeger, 1997). Thus, *sheep* becomes [piç] ([ç] is a voiceless palatal fricative), *kite* [tɑʲk], and *T.V.* [piti] ([p] substitutes for /v/). Similarly, Spanish-speaking Si produces /sopa/ 'soup' as [pwᵘta] and /libro/ 'book' as [pɪtdʎ] (Macken, 1979). These apparent production constraints (or output constraints) may result from the influence of patterns familiar from prior perception and production experience, which the child overgeneralizes (Vihman and Kunnari, in press). Other child patterns involve *consonant migration* (i.e., the child changes the position of a particular consonant). For instance, a child studied by Leonard and McGregor (1991), "W", moved initial fricatives to final position ([af] 'fall', [neks] 'snake'). The frequency as well as the nature of these child patterns constitutes a significant challenge for phonological theories.

The variability of children's word forms also poses a problem for many models based upon adult phonology, in particular because of infants' *whole word processing*. Many young children appear to produce word forms holistically, maintaining the features or segments of a target word but not in the expected order (Waterson, 1971). Furthermore, multiple productions of the same word share certain characteristics but differ in detail. Some have proposed that this variability simply reflects poor "performance" or immature motor control (e.g., Hale and Reiss, 1997). We argue below that variability can only be explained on the basis of a deeper or more abstract level.

A challenge for a performance-based account of early child errors and variability is that children's lexical forms may be quite accurate initially (Ferguson and Farwell, 1975), especially the first 10–20 expressive words. Regression is then observed as the child systematizes the phonology. In many children, this systematization (phonological reorganization) takes the form of routinized patterns or production templates such as those described above for Atte, Alice, and Si. The child seemingly "selects" words for production that match the patterns that have already been mastered in babble or previously learned words (e.g., CVCV[4] forms). Generalizations of the production pattern into a more broadly applied template may initially serve to solve particular phonetic problems. As the template takes hold, however, it may be overgeneralized to include word forms unrelated to the original problem. For instance, Molly's pattern of adding a vowel to facilitate word-final consonant production (e.g., [dɑnʌʎ] 'down') was overgeneralized to words without final nasals or even final consonants, e.g., [ɪnːi] for 'Nicky' (Vihman and Velleman, 1989). Children's phonological experimentation and nonlinear progression make it evident that early phonological development is neither an automatic "unfolding" of an innate articulatory program nor a gradual increase in phonetic skill. Something has changed: Abstract patterns have begun to be induced. Such a developmental pattern cannot be accounted for within a simple performance model (Smolensky, 1996).

Because children produce highly variable and inaccurate word forms it is difficult to determine exactly how much they "know" about the words they attempt. For example, does a child who consistently uses consonant harmony nevertheless have the correct underlying representation of the word, with two distinct consonants? Word recognition studies suggest that children become increasingly focused on phonetic detail as their experience of the language increases. Seventeen-month-olds can discriminate minimal pair differences in an artificial word-learning task but 14-month-olds succeed only when word meanings are not needed. Those with larger vocabularies are better at the task (Stager and Werker, 1997; Werker, Fennell, Corcoran, and Stager, 2002). Nineteen-month-olds are worse at recognizing words with segmental substitutions – e.g., [g] for [d], as in [gɔg] for 'dog' – than words that are pronounced correctly (Swingley, 2003). Thus, at least at this age, children are listening to more than holistic word shape; they are aware of some phonetic detail.

neurocognitive theories

One of the most highly debated issues in child phonology, as in child language generally, is what knowledge the infant has about language to begin with. *Nativists* such as Chomsky (1975) and Pinker (1994) have argued that *positive evidence* alone, based on the limited and "degenerate" quality of speech input, could never suffice as a basis for learning a linguistic system. Instead, according to this view, infants are born with knowledge of universal linguistic structure, so that only details about the individual language need be learned. Acquisition is then merely a process of selecting from the linguistic options prewired into the human brain. In the *principles and parameters* version of this theory (e.g., Chomsky, 1981), certain pieces of information about the language are said to "trigger" expectations about other structures, which therefore need not be observed in order to be acquired. For example, Ramus (2002) has proposed that rhythmic cues will indicate the basic rhythm type of the ambient language (e.g., *stress-timed*, in the case of English). Each rhythm type is associated with other properties, such as syllable structure variety and complexity, and the occurrence or non-occurrence of vowel reduction

(Ramus, Nespor, and Mehler, 1999). In this view the child need not directly experience the other properties.

The "positive evidence" argument is that children are not typically corrected when they speak unless what they say is untrue. Without correction (or "negative evidence"), the argument runs, children – who clearly do produce utterances they have never heard – could be expected to produce a wide variety of universally unacceptable linguistic forms. Yet only limited types of errors actually occur. Since experimental psycholinguistic and neurolinguistic research could not explain this surprising fact 30 years ago, Chomsky concluded that universal linguistic constraints must be innate. However, as Bates, Thal, Aram, Nass, and Trauner (1997) remark, "our belief that a structure [or a process] is inexplicable may be nothing more than a comment on our ignorance" (p. 6). The remedy for ignorance is research, and the results of neurobiological research conducted since the 1970s "underscore the extraordinarily plastic and activity-dependent nature of cortical specialization, and buttress the case for an emergentist approach to the development of higher cognitive functions" (ibid., p. 3).

New findings from experimental psychology, especially regarding implicit statistical learning and infant responses to speech in the first year of life, shed important new light on language learning mechanisms and processes and must be reflected in new theoretical models. For example, another nativist assumption was that it would be impossible for listeners to store the many details about linguistic elements and structures to which they are exposed. However, recent psycholinguistic research has provided answers to both the "no negative evidence" and the storage problems. It has been found that very specific auditory traces, not only of phonetic detail but also of sociophonetic aspects such as voice quality, are retained in memory and even impact speakers' productions (Pierrehumbert, 2001, 2003); the brain does have room for these details.

At the same time, the probabilities of occurrence of various elements and structures are tallied on an ongoing basis and this statistical information has detectable impacts upon subsequent language behavior. Even when instructed to focus on concurrent nonlinguistic events, both children and adults incidentally pick up the statistical regularities of artificial speech played in the background and – to their own surprise – are able to respond accurately to questions about whether new elements and structures are consistent with the unattended speech (Saffran, Newport, Aslin, Tunick, and Barrueco, 1997). Infants as well as adults and older children make generalizations based upon very short periods of exposure to artificial languages – as little as 2 minutes for infants, 20 minutes for adults and children (Saffran, Aslin, and Newport, 1996; Johnson and Jusczyk, 2001). Thus, “statistical underrepresentation must do the job of negative evidence” (Pierrehumbert, 2002, p. 13). That is, what is not heard is taken to be impermissible in the language.

The existence of this type of *implicit learning* can help to explain the findings described above: over the first year, infants develop familiarity with the commonly occurring prosody, consonants, vowels and consonant-vowel sequences of the ambient language. Macken (1995) argues against probabilistic (stochastic) learning of phonology because “Stochastic learning is cumulative and where paths differ, outcomes differ” (p. 695). However, differences in learning outcomes are a desired result of a learning model based on induction of patterns from statistical regularities. Outcomes do differ depending upon linguistic experience: Each adult’s phonological system is subtly different from that of any other. Humans are skilled at adapting their output to the sociolinguistic situation to minimize communication failures and to mark their group identity (Labov, 1966, 2001).

Further evidence against innate linguistic knowledge is provided by the recent finding that infants can implicitly learn phonologically unnatural as well as natural distributional patterns (Seidl and Buckley, 2004). Infants aged 8–9 months heard distributional patterns that either occur in some languages but not in English (i.e., intervocalic fricatives and affricates but not stops; labial consonants followed by rounded vowels only; coronals followed only by front vowels) or are unattested in any language (e.g., word-initial fricatives and affricates but not stops; labial consonants followed by high vowels only; coronals followed only by mid vowels). Subsequently, the infant participants heard novel words that did or did not follow the familiarized patterns. They learned both the natural and the unnatural patterns based upon distributional patterns. Thus, statistical learning is not limited to patterns that occur naturally. Nor is it limited to language or even to the auditory modality: infants learn visual patterns implicitly as well (Kirkham, Slemmer, and Johnson, 2002).

How does the human brain manage statistical accounting on such a grand scale? Recent research has demonstrated that neocortical (especially frontal) and basal ganglia structures are specialized for just such learning:

> This system underlies the learning of new, and the computation of already-learned, rule-based procedures that govern the regularities of language – particularly those procedures related to combining

items into complex structures that have precedence (sequential) and hierarchical relations. (Ullman, 2004, p. 245)

This is termed *procedural learning*. It involves the gradual induction of patterns from multiple instances of related stimuli, ranging from concrete sensorimotor procedures such as riding a bicycle to higher-level cognitive procedures such as the comprehension and production of grammar. Procedural learning is slow and implicit; the learner is typically unable to consciously recall either the process or the product. Once a pattern has been learned, however, the application of the generalizations to behavior (such as speech) is rapid and automatic (Ullman, 2004).

A complementary learning system, *declarative memory*, is responsible for *episodic learning*, "the rapid formation of comprehensive associations among the various elements of specific events and experiences, in a form sufficient to sustain an explicit…retrieval of the contents of the experience" (McClelland, McNaughton, and O'Reilly, 1995, p. 420), such as words and the contexts in which they were heard. The storage of speaker information as well as of phonetic detail that declarative memory makes possible has been shown to be operative within the first year (Houston and Jusczyk, 2000; cf. also Rovee-Collier, 1997), allowing infants to store individual linguistic experiences in toto for later analysis.

The procedural memory system processes information from declarative memory in addition to the distributional tallies that it has implicitly kept, and uses these two types of information to gradually generate abstract "rule-like relations" (Ullman, 2004, p. 237). In other words, procedural learning enables us to gradually discover relationships and regularities among events and experiences (McClelland et al., 1995). The results of procedural processing in turn influence later declarative learning, determining the salience of aspects of future linguistic experiences (Ellis, 2005).

In summary, both procedural and declarative learning are necessary: Procedural generalizations are evident in the rule-governedness of many aspects of phonological behavior. Young children systematize their phonologies, suggesting abstraction away from item learning. Even 7-month-olds appear to demonstrate rule-based learning (cf. Marcus, Vijayan, Bandi Rao, and Vishton, 1999). However, declarative learning is evident in the *token effects* (based upon specific items) that have been documented as well as *type effects* (based upon generalizations) in the phonological retrieval processes of older children (Beckman, Munson, & Edwards, 2004).

Because procedural learning includes both probabilistic and abstract processing, it is not necessary for a theory of language acquisition to choose between abstract linguistic structures (or formal grammar) and statistical learning (Pierrehumbert, 2001, 2003). In fact, several authors have proposed that probabilistic procedural learning induces more abstract procedural learning (e.g., Lotto, Kluender, and Holt, 2000; Pierrehumbert, 2001). For example, children with larger expressive vocabularies are better at repeating words that include low probability diphones (sequences of two sounds). Real words with high probability diphones (e.g., [ba]) are named more slowly, due to competition from other real words. Nonsense words are repeated more quickly if they contain high probability diphones, due to assistance from generalizations stored in procedural memory. Beckman et al. (2004) suggest that two levels of encoding are necessary to account for this: Stored fine-grained details facilitate the differentiation of systematic subphonemic variation from linguistically significant variation; this is *phonetic* learning. Coarser grained procedural generalizations about recurring phonological patterns in the words of the language constitute *phonological* learning. Phonological aspects of procedural processing may be primary for real word tasks, phonetic aspects for nonsense word tasks (Storkel & Morisette, 2002).

A two-component model of memory embraces the contradiction inherent in each individual's phonological system: The subphonemic details differ from person to person depending upon exposure while the overall patterns are shared across communities. Phonemes or other structures within individual lexical items have different production patterns depending upon the speaker's experience with that phoneme within that word. For example, as a result of many vacations in Canada the first author might tend to centralize [ɑʊ] in *out* and *about* but not in infrequent words like *grout* or *drought*. Individual tokens would induce stronger type as well as token effects in infants' phonologies; their limited linguistic experience affords each exposure a large impact on the whole system. Ironically, the paucity of cases in the child's declarative memory may contribute to both the relative accuracy of early word forms and their holistic nature: allophonic and sociocultural details cannot yet be filtered out; abstractions are, as yet, very gross.

The incorporation of stochastic learning into a model of phonological development as the pathway to linguistic abstractions also permits researchers to consider new perspectives on old ideas. One proposed hypothesis is that distributional data, not minimal pairs, enable children to distinguish phonemes from allophones in their languages (Peperkamp and Dupoux, 2004). Alternatively, childrens' learning of distributional allophonic patterns could be seen as evidence for a model of phonology in which the word is the primary unit of processing even for adults (Ferguson and Farwell, 1975; Vihman and Croft, in press), with distributional allophones secondarily induced from words (Pierrehumbert, 2003).

models of phonology

Given that abstract relationships are encoded in the developing phonological system, what should those relationships be called? How should we model their interactions? The models developed in the past 50 years share a focus on identifying patterns of phonological behavior rather than describing individual segments. Rules, processes, and constraints all operate at the level of feature classes rather than at the level of individual consonants and vowels.

Generative Phonology (Chomsky and Halle, 1968) was unique in its time for its rule-based account of phonology. The rules described how phonemes or classes of phonemes were produced under specified circumstances. For example, the fact that underlyingly voiced stops become voiceless in final position in German can be stated as a rule:

[+obs +voice] → [-voice] /____# e.g., *weg* ('way') → [vɛk]

As applied to child phonology, generative rules were used to describe children's simplifications of adult phonemes, such as [+ continuant] segments (fricatives) becoming [- continuant] (stops) in certain word positions (Smith, 1973), e.g., [dɪp] 'zip'.

A problem with this approach was that it assumed that the child's underlying representations (phonemic targets) matched the adults' and were changed only to accommodate immature physiology or inappropriately organized phonology (Smith, 1973). Many authors have questioned this assumption (e.g., Menn and Matthei, 1992; see Vihman, 1996). Another problem was the focus on errors (e.g., substitutions) rather than on advances in phonological development. For example, the fact that a child could produce fricatives, although not in the appropriate contexts, could not be captured. A third problem was the difficulty of writing word-level rules within a system that was, by nature, segmental and linear. Recognition of this problem led to the application of *nonlinear phonology* to child data, which expanded the formal rule system of Generative Phonology to capture hierarchical relationships such as those between coda and syllable, syllable and word, and word and phrase (Goldsmith, 1990).

The inability of the theory of Generative Phonology as originally conceived to handle variability was seen as a further major drawback by sociolinguists as well as child phonologists. In response, *variable rules*, or generative rules with associated frequencies of occurrence, were proposed by Labov (1969). A final formal shortcoming of Generative Phonology was that it did not appropriately constrain the rules. Using the formalisms of the theory, phonological rules that are highly unnatural phonetically (neither attested in languages nor explicable based upon physiological principles) could be generated as easily as natural, commonly occurring rules.[5]

Natural Phonology (Stampe, 1972; Donegan and Stampe, 1979) was one response to this last issue. This theory was based upon the idea that perceptual and articulatory physiology constrains human phonologies in predictable ways. In order to communicate effectively, a child must overcome some of these physiological limitations – specifically, those that do not constrain the patterns of their language. A child English-learner, for example, must not apply consonant cluster simplification (or reduction) – i.e., must learn to produce consonant clusters. A Hawaiian-learner, on the other hand, need not "suppress" the process of consonant cluster reduction because the language includes no clusters.

In Natural Phonology all processes were required to have a physiological basis. However, over time this requirement was lost in practice as physiologically unnatural patterns were identified in both adult and child phonologies. Natural Phonology shared with Generative Phonology the assumption that the child's underlying representations or target forms are the same as the adult's. This theory also focuses on the child's errors (inappropriate processes) rather than on capabilities. In many cases the theory provided a label but no explanation for phonological behavior; e.g., labeling metathesis as such does not explain why it occurs. Finally, Natural Phonology, like Generative Phonology, had to deal with variability in a post hoc manner. Frequencies of occurrence could be associated with particular processes, but no mechanism predicted them.[6]

The focus of Optimality Theory (OT) is the notion that phonologies are organized in such a way as to optimize certain output forms. Rather than being process-oriented, like the models described above, OT is outcome-oriented (McCarthy and Prince, 1996; Archangeli, 1997). Thus, OT has the advantage for child phonologists of focusing on what the system does do, and on what is achieved by nonadult changes in the output, rather than on errors. In this approach, the child's phonology can be modeled as a dynamic developing system rather than as an inadequately realized adult system.

Within OT, two main forces are contrasted: *Markedness* (the preference for certain elements and structures, often but not always based upon ease of production or perception) and *Faithfulness* (the need to achieve communicative effectiveness by producing word forms that are true to the common lexicon). Faithfulness can only be judged with respect to the language of the speaker and the specific word targeted for production. Markedness occurs in both universal and language specific forms: physiologically based markedness constraints, especially, are reflected in the distributions of elements and structures in all languages, but other elements or structures are marked (avoided) in only a subset of languages. Markedness and Faithfulness are reflected in sets of *constraints* that specify, first, those output forms that are preferred or avoided and, second, the aspects of an individual word that must be maintained in production. Typical Markedness constraints identify preferred patterns such as the CV syllable, in the constraints Onset, which specifies that a word must begin with a consonant, and NoCoda, which prohibits a word final consonant. A typical example of a Faithfulness constraint is IDENT(labial), which states that if a word has a labial in the underlying representation, it must be produced with a labial.

Unlike the rules of Generative Phonology, these constraints are not present or absent ("on" or "off"). Rather, they are ranked. Those at the top of the ranking are obeyed under all conditions; lower constraints are respected only if that is possible without violating a higher ranked constraint. Because the ranking is not "all or none," it is possible to accommodate variability. Constraints may be equally ranked, yielding a variable output (e.g., 50–50, if two constraints are both relevant to the same case and are unranked with respect to each other). In more elaborated versions or modified theories built on the basic insights of OT, variability may be attributed to random ranking of mutually unranked constraints on each relevant occasion (Anttila, 1997); constraints with overlapping, normally distributed ranges of ranking values (Boersma, 1997; Boersma and Hayes, 2001); or constraints that select a set of "best" outputs that are implemented with frequencies reflecting the relative rankings of the constraints (Coetzee, 2004).

Initially, Optimality Theory assumed that all languages shared the full constraint set; the power of the theory was purported to lie in its formal simplicity and universality. In child phonology, an OT perspective has generally included the assumption that the constraints are given in the form of innate knowledge; in this view only the ranking remains to be achieved through learning. This assumption has been weakened over time as ever more language-specific constraints are identified, leaving open the question of how such a set of partially universal, partially language-specific constraints might be acquired by learners.

The neurocognitive findings discussed above suggest such a mechanism. The child's relatively systematic output patterns may result from the influence of familiar patterns (from prior perception and production experience) on the process of generalizing and inducing abstractions (Vihman and Kunnari, in press). The frequencies of occurrence of these patterns in the child's experience, possibly along with sociolinguistic factors like the status of the speaker of each exemplar (Docherty, Foulkes, Tillotson, and Watt, 2006), will determine its use by the child. The constraints may reflect abstraction over the two types of phonological data that the child gains through experience: (i) physiological (perceptual and articulatory) parameters, and (ii) the distributional characteristics and relationships of the ambient language. Implicit learning means that children will have collected, and generalized over, a great deal of data regarding the distributional frequencies found in the ambient language and in their own articulatory routines. Rule-based relations are induced from these patterns and some of these may begin to be evident in the child's productions even prelinguistically. Once a child has a minimal lexicon, it is possible to begin gathering information about the types of morphological and phonetic variability allowed within the language.[7]

Once children have productive vocabularies of about 50 words they begin to abstract away from particular target word patterns and rely instead on the production routines or templates that they have induced from experience of both target words and their own word forms. As the child not only selects words for production based on matches to the template but also adapts other words to respect the idiosyncratic constraint set reflected in that template, output forms now become less accurate.

conclusion: towards a pattern induction model for phonology

In contrast to the theories reviewed above (Generative Phonology, Natural Phonology, and Optimality Theory), the pattern induction model proposed here claims no innate phonological knowledge. Rather, it specifies the learning processes by which phonological information is gathered, analyzed, and acted upon. The outcomes are not universal; variability both within and between speakers is expected. The means of developing a phonological system are presumed to be available to all humans by virtue of shared neurological, sensory and motor capacities. Most structures of the eventual phonological system are also shared, given their rootedness in neuromotor, perceptual, and learning capacities acting upon human experience.

Certain patterns, such as the avoidance or favoring of language-particular elements or structures and complex interactions between these constraints on output, are expected. These constraints are induced via phonologization of human language processing limitations, of patterns and associations learned implicitly and abstracted via the coarse (procedural) memory system, and of individual child responses to experience. Less fine-grained responses to phonological challenges, such as consonant harmony and metathesis, are to be expected of children whose abstract generalizations are based upon few exemplars and whose cognitive processing systems are not yet finely tuned.

In adults as well as children the constraints are gradiently influenced in their applications to particular words or contexts by grammar-external factors such as sociolinguistic variables. Thus, the lines between grammar and an associative cognitive system are substantially blurred within this model. This is a desirable result; it reflects an increase in psycholinguistic reality and a deeper grounding in known brain structures and processes.

notes

1. Editor's note: see also Chapter. 1, this volume.
2. Editor's note: Chapter 5, this volume, presents a complementary view of perception and input-driven learning for L2 acquisition.
3. Editor's note: sound sequence composed of vowel-consonant-vowel such as [ada] or [ama].
4. Editor's note: repeated sequences of consonant-vowel [dada] or [mama].
5. Editor's note: Chapter 3, this volume, includes other relevant discussions.
6. Editor's note: for another perspective on the handling of variation in Natural Phonology, see Chapter 3, this volume.
7. Editor's note: this pattern-induction model is similar to that proposed in Chapter 5, this volume, for L2 acquisition; also see Chapter 3, this volume, for further discussion of the acquisition of variable phonological patterns.

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