MECHANISMS OF DEVELOPMENTAL CHANGE IN SPEECH AND LANGUAGE

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ABSTRACT

One of the most interesting aspects of language development is the transition that occurs in phonetic perception during the first year of life. At birth, infants are capable of distinguishing all phonetic contrasts in the world's languages. By adulthood, these abilities are severely restricted. This "language-general" to "language-specific" pattern of change is mirrored in speech production. This paper focuses on the role of early language experience on infants' perceptual and perceptual-motor systems in bringing this transition about. The data show that by the time infants begin to master the higher levels of language, such as sound-meaning correspondences, contrastive phonology, and grammatical rules, their perceptual and perceptual-motor systems are already tuned to a specific language. These results are described in a developmental theory at the phonetic level that holds promise for higher levels of language.

INTRODUCTION

Research on developmental speech perception and speech production has revealed an interesting pattern of change. Speech exhibits a language-general pattern that becomes language-specific by the end of the first year of life [1,2,3]. What accounts for the transition?

Early in life infants discern differences between all the phonetic units used in the world's languages, and demonstrate exquisite sensitivity to acoustic change in the region of the boundaries between phonetic categories [4]. By 12 months of age, infants fail to discriminate foreign contrasts they once discriminated [3]. As adults, our abilities are greatly reduced; we often find it difficult to perceive differences between sounds not used to distinguish words in our native language [3]. Adult native speakers of Japanese have difficulty discriminating American English /r/ and /l/ [5], though Japanese infants make the distinction [6].

Speech *production* follows a similar pattern. Regardless of culture, all infants progress through a set of universal stages during the first year [7]. By the end of the first year, however, the utterances of infants reared in different countries begin to diverge, reflecting the ambient language [8,9]. In adulthood, the speech motor patterns that contribute to one's "accent" are very difficult to alter [9].

Work in my laboratory focuses on the role of early linguistic experience in bringing about this language-general to language-specific change in speech perception and production. The thesis is that linguistic experience results in an interesting kind of learning. Given linguistic input, the perceptual and perceptual-motor systems underlying speech show self-organization accompanied by a loss in flexibility. The vehicle for change is argued to be *representations* stored in memory that capture the regularities of a specific language. These representations alter the perceptual and perceptual-motor skills of infants. The findings demonstrate that in the absence of formal language understanding or use, infants' perceptual and perceptual-motor systems are strongly biased towards the characteristics of the ambient language. A model is described at the phonetic level that shows how this structure accounts for the transition and aids the acquisition of phonology.

Language Experience Affects Speech Perception Early in Life

Research in my laboratory has uncovered an effect that helps explain how language experience affects speech perception and production. The effect shows that linguistic experience alters the perceived distances between speech stimuli. In effect, our results suggest that linguistic experience "warps" the perceptual space underlying speech. The result is that perceptual categories are formed, ones that begin to mirror the phonological categories of the ambient language. The experimental data that support these claims derive from a phenomenon I have called the *perceptual magnet effect*. It shows that phonetic "prototypes" (the best or most representative instances of phonetic categories) play a unique role in speech perception. They function like "perceptual magnets" for other sounds in the category [10] (Figure 1). When listeners hear a phonetic prototype and attempt to discriminate it from sounds that surround it in acoustic space (1A), the prototype displays an attractor effect on the surrounding sounds. It perceptually pulls other members of the category toward it, making it difficult to hear differences between the prototype and surrounding stimuli (1B). Poor instances from the category (nonprototypes) do not function in this way. A variety of experimental tasks produce this result [11,12]. Other studies confirm listeners' skills in identifying phonetic prototypes and show that they are language specific [13,14].

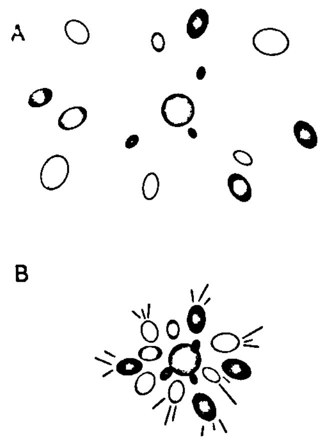

Figure 1. The perceptual magnet effect: When a variety of sounds in a category surround the category prototype (A), they are perceptually drawn toward the prototype (B). The prototype appears to function like a magnet for other stimuli in the category.

Developmental studies show that the perceptual magnet effect is exhibited by 6-month-old infants for the sounds of their native language [10]. Moreover, cross-language experiments show that the magnet effect is the product of linguistic experience [15]. The cross-language experiment was conducted with infants in America and Sweden. The infants from both countries were tested with two vowel prototypes, an American English vowel prototype, /i/ (as in "peep"), and a Swedish vowel prototype, /y/ (as in "fye"). Adults from both cultures perceived the foreign vowel as a nonprototype. The results demonstrated that the perceptual magnet effect was affected by exposure to a particular language as early as 6 months after birth. By the age of six months, American infants demonstrated the magnet effect only for the American English /i/; they treated the Swedish /y/ like a nonprototype. Swedish infants of the same age showed the opposite pattern, demonstrating the magnet effect for the Swedish /y/ and treating the American English /i/ as a nonprototype.

Recent work by Polka and Werker [16] both support and extend these findings. They tested Canadian English infants in a discrimination task involving two German phonetic contrasts. Their results confirm the presence of the magnet effect in 6-month-old infants and show a decline in the discrimination of foreign-language vowel contrasts between 4 months and 6 months, earlier for vowels than for consonants but following the same pattern.

Studies conducted on adult listeners by Iverson and Kuhl have begun to suggest the mechanism underlying the magnet effect. These studies employ multidimensional scaling (MDS) techniques to examine how the magnet effect distorts perception [17,18] (Figure 2). The studies show that the best instances of phonetic categories yield increased perceptual clustering while the category's worst instances yield reduced perceptual clustering. For example, Iverson and Kuhl [17] computer synthesized a set of syllables beginning with /r/ and /l/. The syllables were created by varying critical acoustic components of the signals, the second (F2) and third (F3) formant frequencies. The syllables were spaced at equal intervals in a 2-dimensional grid (2A). Listeners identified each syllable as beginning with either /r/ or /l/, rated its category goodness, and estimated the perceived similarity for all possible pairs of stimuli using a scale from "1" (very dissimilar) to "7" (very similar). Similarity ratings were scaled using MDS techniques.

The results revealed that *perceived* distances differed from *real physical* distances. The physical (acoustic) differences between pairs of stimuli were equal (2A); however, perceived distance was not equal, it was "warped" (2B). The perceptual space around the best /r/ and the best /l/ was greatly reduced, while the space near the boundary between the two categories was expanded (see [19] for similar findings on cognitive categories outside the domain of speech).

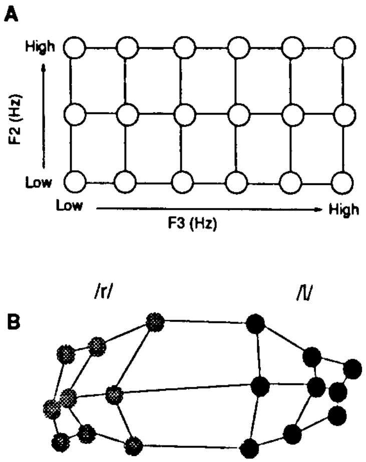

Figure 2. Consonant tokens of /r/ (gray dots) and /l/ (black dots) were generated to be equally distant from one another in acoustic space (A). However, when listeners perceive them, distance is distorted (B). Perceptual space is reduced near the best instances of /r/ and /l/ and expanded at the boundary between the two. The resulting "perceptual map" (B) differs for speakers of different languages.

The results suggest that linguistic experience results in the formation of *perceptual maps* specifying the perceived distances between stimuli. These maps increase internal category cohesion while maximizing the distinction between categories. The critical point for theory is the hypothesis that the map is defined differently for speakers of different languages [18]. Native speakers of Japanese tested with the same American /r/ and /l/ stimuli show a different perceptual map, one without perceptual clusters around the American /r/ and /l/ prototypes.

NATIVE LANGUAGE MAGNET (NLM) THEORY

I have proposed a 3-step theory of speech development, called the Native Language Magnet (NLM) theory [1,2]. NLM describes infants' initial state as well as changes brought about by experience with language. It explains how infants' developing native-language speech representations alter both speech perception and production. The schematic illustration provided here presents the hypothetical case for vowels, but the same principles and theory applies to consonant perception.

Phase 1 describes the initial state of infants' speech perception abilities (Fig. 3). At birth, infants partition the sound stream into gross categories separated by natural auditory-perceptual boundaries. The lines in Figure 3 show these hypothesized perceptual boundaries. The lines separate the vowels of all languages. According to NLM, these perceptual boundaries are innately specified in auditory processing and do not depend on specific language experience. The boundaries initially structure perception in a phonetically-relevant way, which is extremely helpful for infants. However, they are not due to a "language module" or other language-specific device but to more basic auditory perceptual processing mechanisms. This is argued to be the case because experiments on animals show that they exhibit boundary effects in the same places in acoustic space [20].

The data on human infants supporting this initial stage in the model stems from two kinds of studies: first those showing that early in life infants discriminate natural native- and foreign-language vowel and consonant contrasts, and second, those on "categorical perception" showing that infants exhibit increased sensitivity to change in the region of phonetic boundaries for both consonants and vowels [21]. Both show that at birth infants are capable of distinguishing among the consonants and vowels of the world's languages.

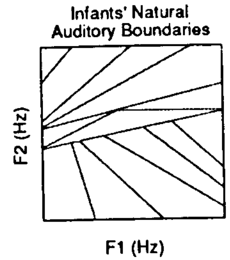

Figure 3. At birth, infants perceptually partition the acoustic space underlying phonetic distinctions in a language-universal way. These "boundaries" allow them to discriminate all phonetically relevant differences in language.

Phase 2 in the model illustrates hypothetical vowel spaces that exist at 6 months of age for infants reared in three very different language environments, Swedish, English, and Japanese (Fig. 4). According to the model, infants at this age show more than the innate boundaries exhibited in Phase 1. Our data indicate that by 6 months, infants have heard hundreds of thousands of instances of particular vowels. According to NLM, infants represent this information in memory in some form. This is illustrated in Figure 4. These diagrams show infants' stored representations, which reflect the distributional characteristics of the vowels infants have heard. Infants being raised in Sweden, America, and Japan hear different vowels. Thus, their stored representations differ. In each case, linguistic experience has produced stored representations that reflect the vowel system of the ambient language. According to NLM, in Phase 2 language-specific magnet effects are exhibited by infants.

Phase 3 shows how magnet effects recursively alter the initial state of speech perception. Magnet effects cause certain perceptual distinctions to be minimized (those near the magnet attractors) while others are maximized (those near the boundaries between two magnets). The consequence is that some of the boundaries that initially divided the space perceptually "disappear" as the space is reconfigured to incorporate a language's particular magnet placement. This is schematically illustrated in Figure 5 in which certain boundaries that existed in Phase 1 have been erased. It is important to note, however, that even though these boundaries have been erased, the model does not hold that sensory perception has changed. Instead, it is argued that higher order memory and representational systems have altered infants' abilities. In other words, magnet effects *functionally* erase certain boundaries — those relevant to foreign but not native languages. By Phase 3, a perceptual space once characterized by simple boundaries has been replaced by a warped space dominated by magnets.

The important point for theory is that infants at 6 months of age have no awareness of phonemes or the fact that sound units are used contrastively in language to name things. Yet the infant's perceptual system has organized itself to reflect language-specific phonetic categories. At the next stage in linguistic development, when infants acquire word meanings by relating sounds to objects

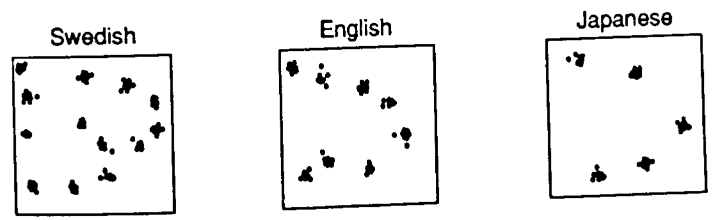

Figure 4. By 6 months of age, infants reared in different linguistic environments show an effect of language experience. Infants store incoming vowel information in memory in some form. The resulting representations are language-specific, and reflect the distributional properties of vowels in the three different languages.

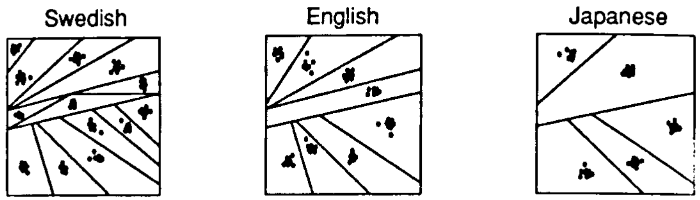

Figure 5. After language-specific magnet effects appear (shown by the dots), some of the natural boundaries that existed at birth 'disappear.' Infants now fail to discriminate foreign-language contrasts they once discriminated.

and events in the world, the language-specific mapping that has already occurred in their perceptual systems will greatly assist this process.

NLM theory offers a potential explanation for the reorganization in speech perception observed by Werker [3]. A developing magnet pulls sounds that were once discriminable towards it, making them less discriminable. Magnet effects should therefore developmentally precede changes in infants' perception of foreign-language contrasts; preliminary data indicate that they do [16]. The magnet effect also helps account for the results of studies on the perception of sounds from a foreign language by adults [3,5,9]. For example, NLM theory explains Japanese listeners' difficulty with American /r/ and /l/ by predicting that the magnet effect for their category prototype (which is neither American /r/ nor /l/) will attract both /r/ and /l/, making the two sounds difficult for native-speaking Japanese people to discriminate. Best [5] has made predictions about the relative discriminability of foreign-language contrasts by examining the relationship of specific foreign sounds to native-language categories; these predictions are consistent with NLM.

Effects of Linguistic Experience on Speech Production

As adults, we produce speech motor patterns that are difficult to alter. When do infants acquire these life-long speech-motor patterns? When do they forge the initial link between the perception and production of speech? Data can be adduced by the earliest age at which ambient language affects spontaneous speech production. It is known that by 1 year of age language-specific patterns of speech production appear in infants' spontaneous utterances [8,9]; by 30 months, detailed patterns that differentiate sounds in two different languages are observed [22].

Recent studies, however, suggest that the initial perceptual-motor link is in place much earlier. In another paper in this volume, Kuhl and Meltzoff describe research showing that infants can imitate the gross spectral forms of vowels at 12-, 16-, and 20-weeks of age. This indicates the presence of an auditory-articulatory link very early in life. In the Kuhl and Meltzoff studies [23], infants watched a video of a woman articulating either /i/, /a/, or /u/ for 5 minutes on each of three consecutive days. Infants' utterances were analyzed both perceptually (phonetic transcription) and instrumentally (spectrographic analysis). Two findings emerged. There was developmental change in infants' vowel productions between 12- and 20-weeks of age. The areas of vowel space occupied by infants' /a/, /i/, and /u/ vowels become progressively more tightly clustered at each age. Second, the data suggest that infants attempted to imitate the vowels they heard. The total amount of exposure was only 15 minutes; yet this appeared to be sufficient to alter infants' productions. If 15 minutes of laboratory exposure to a vowel is sufficient to influence infants' vocalizations, then listening to ambient language for weeks would be expected to provide a powerful influence on infants' production of speech. Kuhl and Meltzoff interpret the data as suggesting that infants' stored representations of speech alter not only infant perception, but speech production as well. Infants' representations serve as targets that guide motor production. Stored representations are thus viewed as the common cause for both the tighter clustering observed in infant vowel production and the tighter

clustering observed in infant vowel perception. Additional data on infants' and adults' auditory-visual perception of speech, also support this conclusion (see [23] for further discussion)

This pattern of learning and self-organization, in which perceptual patterns stored in memory serve as guides for production, is strikingly similar to that seen in other domains involving auditory-perceptual learning, such as birdsong [24], visual-motor learning, such as gestural imitation of articulatory movements in the absence of sound [25], and imitation from memory [26]. In each of these cases, perceptual experience establishes a representation that guides sensory-motor learning. In the case of infants and speech, perception affects production in the earliest stages of language learning, reinforcing the idea that the perceptual-motor link is in place early in life [2,23,27,28,29].

Learning Prosodic Regularities

Infants' abilities to learn do not begin the day they are born. Learning commences prenatally with the more global, prosodic aspects of language. By the time infants are born, exposure to sound *in utero* has resulted in a preference for native-language over foreign-language utterances [30,31]. The mother's voice [32] and simple stories she read during the last trimester [33] are also recognized by infants at birth. Studies on the acoustics of speech and the intrauterine environment suggest that intense (above 80dB), low-frequency sounds (particularly below 300 Hz, but as high as 1000 Hz with some attenuation) penetrate the womb [34]. This means that the prosodic patterns of speech, including voice pitch and the stress and intonation characteristics of a particular language and speaker, are transmitted to the fetus, while the sound patterns that allow phonetic units and words to be identified are greatly attenuated. (This can be compared to listening to speech through the wall of a room — a human voice can be identified, but words cannot be made out.)

Postnatally, infants' learning of the prosodic aspects of speech provides additional information about language-specific sound patterns. Jusczyk and his colleagues have focused on infant learning of the sound patterns typical of native-language words, phrases, and sentences [35]. This work shows that between 6 and 9 months of age, infants develop listening preferences for sound patterns typical of the native language. In one study [36], both American and Dutch infants listened significantly longer to native- as opposed to foreign-language words. At 6 months of age, infants showed no listening preferences. Other work shows listening preferences at 9 months, but not at 6 months, for words that follow the predominant stress pattern of the language [37]. These studies indicate that prior to the time that infants learn the meanings of individual words or phrases, they recognize general perceptual characteristics that describe such units in their native language.

CONCLUSIONS

In the first year of life infants learn much about the perceptual characteristics of their native language. Perceptual learning subsequently alters the perception and production of speech. According to the *Native Language Magnet* theory, perceptual learning early in life results in the formation of stored representations that capture native-language regularities. These stored representations act like *perceptual magnets* for similar patterns of sound. Magnet effects distort physical distance, creating perceptual maps in which distance has been altered. Perceptual maps shrink distances near a category's most typical instances and stretch distances between categories. Perceptual maps differ in adults who speak different languages. The magnet effects and the perceptual maps they produce also affect speech production. This helps explain why, as adults, we do not hear or produce foreign-language sounds very well. During the language-learning period, our perceptual maps are tuned to our native language. The model ascribes an important role for language input. Future work will be aimed at testing and refining the model.

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