Chapter • 4

Linguistic Experience and the "Perceptual Magnet Effect"

Patricia K. Kuhl and
Paul Iverson

Listening to a foreign speaker shows how extensively language experience alters perception. The sounds emitted are a jumble to us; however, they make perfect sense to a native speaker of that language. What differs in the two listeners? It is *not* how they process the signal at the level of the ear's basilar membrane. What differs is that one individual can recognize the signal, while the other cannot. The native listener hears familiar sounds and words; the other a stream of unrecognizable noises. In other words, what differs is the mind of the beholder.

The thesis of this chapter is that language experience alters the mechanisms underlying speech perception, and thus, the mind of the listener. Previous research provides ample evidence of the role of linguistic experience in speech processing (Strange this volume; Strange and Jenkins 1978; Werker and Polka 1993). Simple tests of our abilities to discern differences between the sounds used in different languages reveal a dramatic developmental change. At birth infants hear differences among all of the sounds of human language. However, by the time we reach adulthood, our abilities to differentiate the sounds of the worlds' languages is greatly reduced. The infant has been described as a "citizen of the world" and the adult as "culture-bound" in this regard (Kuhl 1993a). The questions are: What changes? What is the mechanism that underlies the change from a language-general to a language-specific listener?

New studies in our laboratory shed some light on the issue (see also Jusczyk, Hohne, and Mandel this volume). The studies suggest a mechanism by which language experience alters phonetic perception. The mechanism is exhibited in a phenomenon called the "perceptual magnet effect" (Kuhl 1991a). The magnet effect shows that exposure to a particular language results in a distortion of the perceived distances between stimuli; in a sense, language experience *warps* the acoustic space underlying phonetic perception. A model that incorporates these results—the "Native Language Magnet" (NLM) model—argues that exposure to language early in life produces a change in perceived distances in the acoustic space underlying phonetic distinctions, and this subsequently alters both the perception of spoken language and its production (Kuhl 1992a, 1993b, 1993c, 1994).

The impact of this on language processing is considerable, both for the infant learning a first language and for the adult attempting to learn a second language. Language is processed through a distorted lens; the lens acts as a filter through which language passes. Thus, what is perceived as a large difference between two sounds to an individual from one linguistic environment may not be perceived to differ at all by an individual from another. The theory being developed is that learning a primary language results in alterations of the underlying perceptual mechanisms that affect the processing of language from that time forward. The results and theory help explain a very old problem in speech perception: the fact that as adults we perceive speech sounds differently depending upon our native language. In the broadest sense, the results provide an example suggesting how experience can alter the mind.

The purpose of this chapter is to review the data that reveal this perceptual distortion and explore the implications of the resulting model of perception, including those that have been raised about the model's applicability to second-language learning. The model allows us to predict the kinds of results that should be obtained when we examine in detail the development of phonetic perception of infants in two different countries, and when we test adults from two different language environments on sounds not contained in their native language. The goal is to see how far the model takes us in terms of explaining the relevant developmental and cross-language phenomena.

The chapter is written in three parts. First, we review the phenomenon that has been uncovered in the studies—the "perceptual magnet effect." Next, we review two new studies that contribute further to the emerging story. The first study provides data on Motherese that explore the potential effects of language input on the child (Andruski et al. in preparation); the second provides new data from multidimensional scaling experiments that show the distortion of physical space in greater detail (Iverson and Kuhl 1995, in press). Finally, we describe the NLM model (Kuhl 1992a, 1993b, 1993c, 1994) that incorporates these data and explore its implications for speech perception.

PERCEPTUAL MAGNET EFFECT

The finding that led to the development of the NLM theory is that adults' and infants' phonetic perception is altered as a function of exposure to language. Our results provide strong experimental evidence that simply listening to the ambient language alters phonetic perception. We describe these results in detail. They suggest how experience can alter the perceptual systems of individuals.

Studies on Phonetic Prototypes

The underlying organization of phonetic categories is revealed when we test listeners with phonetic "prototypes." The notion of a prototype is attributable to Eleanor Rosch who defined prototypes as "good instances" of categories, instances that are representative of the category as a whole (Rosch 1975, 1978; see also Posner and Keele 1968). In the literature on psychological categories, it has been demonstrated that the prototypes of categories have a unique perceptual status. Good instances of categories (a collie, rather than a dachshund, of the category dog; a robin, as opposed to an ostrich, of the category bird) are easier to classify, easier to remember, and preferred over other members of a category (Mervis and Rosch 1981; Rosch 1975, 1977). It is important to note, however, that we use the term *prototype* narrowly, defining it as a good instance of a category without embracing what has been called "prototype theory" in the cognitive literature (e.g., Posner and Keele 1968). Prototype theory assumes that what people store in their heads to represent a category is an abstract statistical summary (also termed a *prototype*) of the category. The issue of the *form* that stored mental representations of speech might take is discussed later in the chapter.

Kuhl and her colleagues (Grieser and Kuhl 1989; Kuhl 1991a; see also Miller 1994) made two initial discoveries regarding phonetic prototypes. First, studies revealed that adult listeners of a particular language were adept at identifying best instances (prototypes) of phonetic categories in their native language. Second, the findings demonstrated that phonetic prototypes functioned in a special way in speech perception. Prototypes function as "perceptual magnets" for other sounds in the category, as illustrated conceptually in Figure 1. The tests demonstrated that when listeners hear a prototype of a phonetic category and are asked to compare it to sounds that surround it in an acoustic space (as shown in Figure 1A), the prototype displays an attractor effect on the sounds around it (as shown in Figure 1B). The prototype perceptually pulls other members of the category toward itself, thus the magnet metaphor. Poor instances from the same category (nonprototypes) do not function in this way. The magnet effect implies that the perceptual distance between outlying sounds and the prototype is reduced.

Vowel Tests and the Magnet Effect

The initial tests using phonetic prototypes were done on vowels (Grieser and Kuhl 1989; Kuhl 1991a). In pilot studies, over 100 /i/

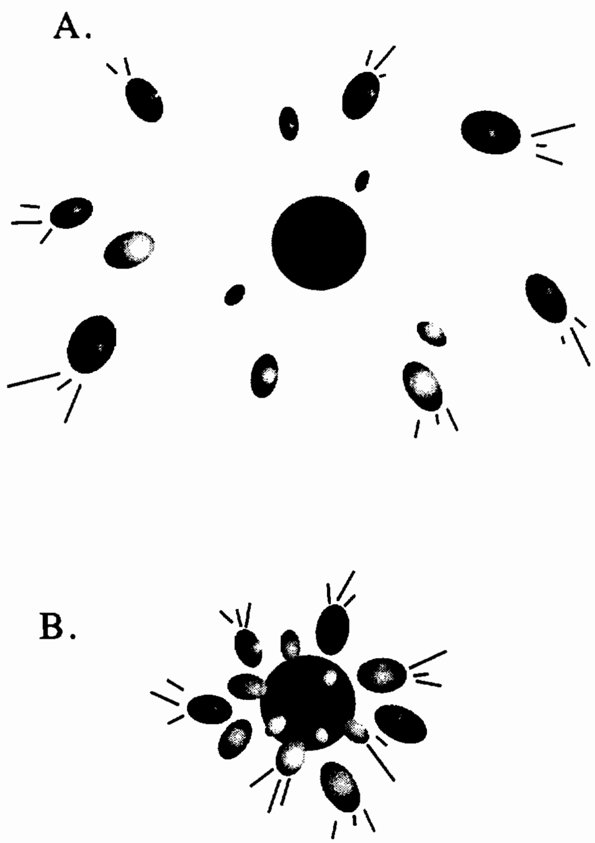

Figure 1. The perceptual magnet effect. Stimuli surrounding a phonetic prototype (A) are perceptually drawn toward the prototype (B), thereby shrinking the perceived distance between the prototype and other members of the category (from Kuhl 1993a).

vowels were synthesized. Speakers in the Pacific Northwest who spoke a general American dialect were asked to rate the vowels using a 7-point scale where a "7" was an excellent exemplar and a "1" was a poor exemplar. As a result of these tests, two vowels were identified, one that adult listeners thought was an excellent version of the /i/ vowel (referred to as the prototype, P) and one that adults thought was an /i/ but not a very good instance of the category (referred to as the nonprototype, NP).

To illustrate the magnet property of the prototype vowel, the first and second formant frequencies of the P and NP vowels were altered in small steps in a mel-scaled vowel space to create 32 variants that

surrounded each of them (formants three, four, and five were held constant). The variants orbiting the P and NP were scaled to be equally distant from their center vowel, as shown in Figure 2 (for further details, see Kuhl 1991a). Adults' and infants' ability to hear a difference between the P and its variants and the NP and its variants was tested. The magnet effect predicts that the prototype vowel will sound more similar to its variants than the nonprototype will sound in relation to its variants, even though acoustic distance is equated. In other words, the effect predicts that you must go further away from the prototype before you can hear a difference between the P and its variants when compared to the NP and its variants.

Adults and infants were tested similarly with only minor age-appropriate variations in technique. Six-month-old infants were tested using the head-turn preference procedure (HPP, see Polka, Jusczyk, and Rvachew this volume). Babies sat on a parent's lap while an assistant, located on the infant's right, moved silent toys to maintain the infant's attention. At the same time, a sound was repeated out of the loudspeaker located on the infant's left. The baby was taught to turn away from the assistant and toward the loudspeaker when the sound

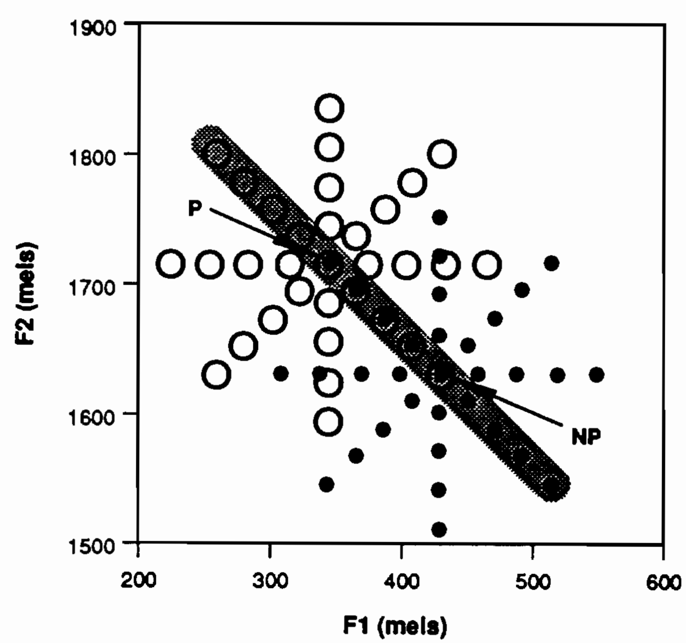

Figure 2. The prototype /i/ (P) and its 32 variants (open circles) and the nonprototype /i/ (NP) and its 32 variants (closed circles). The shaded area shows stimuli used in Iverson and Kuhl (1995).

coming from the loudspeaker changed. If the infant turned toward the loudspeaker at the appropriate time, a dark plexiglass box above the loudspeaker was lit up and a toy bear housed inside became visible and began pounding a drum. The parent holding the infant and the assistant wore headphones and listened to music so that they could not hear the stimuli and influence the infant's responses.

Infants listened to either P or NP, which was repeated as the background sound over the loudspeaker. The background sound (either P or NP) was changed to one of its variants during 6-sec. *test trials* to see whether infants responded to the change in the sound by turning their heads. An equal number of *control trials* were interspersed in which the sound was not changed, but infant headturns were monitored to ensure that infants were not producing false positive responses (for further details, see Kuhl 1985, 1991a; see also Polka, Jusczyk and Rvachew this volume). When adults were tested, they pressed a response button rather than producing a head-turn response. The test was identical in all other respects.

The results showed that both adults and infants demonstrated a strong magnet effect (Kuhl 1991a). The infant data are displayed in Figure 3, which plots the average results of two studies on infants (Grieser and Kuhl 1989; Kuhl 1991a). A greater percentage of the variants were equated to the prototype (the solid line) than to the nonprototype (the dashed line) at each distance. Infants did not distinguish many of the variants from the prototype. Infants in the nonprototype group were better able to distinguish variants. Adults tested in the same task also equated significantly more variants to the P than to the NP (Kuhl 1991a).

To test the species specificity of this behavior, Kuhl (1991a) tested rhesus monkeys in the same basic task, with only minor modifications. The reason monkeys were of interest was that previous work in Kuhl's laboratories had shown that monkeys share certain speech perception abilities with human infants. For example, monkeys demonstrate "categorical perception" (for review, see Kuhl 1987, 1991b). The categorical perception ability is demonstrated in young human infants in the absence of linguistic experience (e.g., Streeter 1976). Coupled with the results on animals, this finding led Kuhl (1991a) to conclude that the categorical perception phenomenon in infants was attributable to general auditory processing mechanisms, and that this ability was very deeply embedded in our phylogenetic history (Kuhl and Miller 1975, 1978; Kuhl 1988, 1991b). Kuhl argued that the categorical perception phenomenon was exploited in the evolution of the sound system used in language (Kuhl 1987, 1988). Testing the perceptual magnet effect with monkeys was designed to answer whether the prototype phenomenon is similar to categorical perception, with monkeys ex-

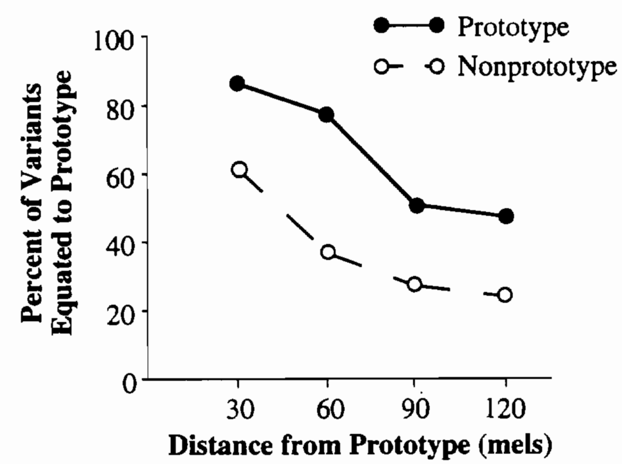

Figure 3. Results showing that the prototype is equated to its variants more often than is the case for the nonprototype, and thus, that it exhibits a stronger perceptual magnet effect.

hibiting it as well, or whether the magnet effect is species specific.

Monkeys lifted a response key to indicate the detection of a difference rather than producing a head-turn response, and they were reinforced with applesauce rather than a visible toy. The task was identical in all other respects. Interestingly, the results showed that monkeys displayed no magnet effect. Monkeys equated variants to the prototype and to the nonprototype to the same degree (Kuhl 1991a).

Linguistic Experience and the Magnet Effect

The data thus revealed an ability exhibited by infants early in life—by 6 months—and one that was not replicated in monkeys. The next question was the degree to which the magnet effect, as exhibited by 6-month olds, was the product of linguistic experience. Would the magnet effect be demonstrated by all 6-month-old infants regardless of language experience? If so, we could argue that it constituted part of infants' innate biological endowment for language. Stevens (1989) has shown that certain vowels, primarily the "point" vowels /i/, /a/, and /u/, are particularly stable from an acoustic standpoint. This suggested that the American /i/ might be a particularly likely candidate for early demonstration of the magnet effect, irrespective of language experience.

On the other hand, by 6 months of age, the magnet phenomenon could differ in infants being reared in different language environments. By 6 months of age, infants have heard a considerable amount of native-language input, and this might be sufficient to alter perception. Perhaps by simply listening to language, infants have already learned something about its properties (see also Jusczyk, Hohne, and Mandel this volume). This alternative would suggest that learning contributes in a profound way, even before infants can speak.

The method used to test these two developmental alternatives was to conduct a cross-language experiment (Kuhl et al. 1992). The goal of the study was to test infants from two different language environments, English and Swedish, using vowel prototypes from both languages. Kuhl et al. (1992) reasoned that if the magnet effect was unaffected by linguistic experience then both groups of infants would behave identically, either by exhibiting the magnet effect for both vowel prototypes, or by both groups showing the effect for only one of the two vowels. Alternatively, if the magnet effect was due to linguistic experience, then it should be observed only for the native-language vowel prototype.

The Swedish language allowed us the better test of the hypothesis. Infants in Sweden hear many /i/ vowels, but none is identical to the American English unrounded /i/. Tests showed that adult Swedes considered the American English /i/ a poor member of the Swedish /e/ category (for details see Kuhl 1992b). The Swedish vowel we chose to test was the front rounded /y/, a vowel not produced by American adults and thus never heard by American babies. The Swedish /y/ prototype vowel and its 32 variants (shown in Figure 4) were synthesized using the same techniques used to create the American English /i/ and its variants (for details see Kuhl et al. 1992). To conduct these tests, the entire laboratory and research team was moved to Stockholm, Sweden. This ensured that all aspects of the tests in the two countries were identical except the language experience of the infants who were tested in the two countries.

The results clearly showed that the perceptual magnet effect in 6-month-old infants was affected by exposure to a particular language (Figure 5). American infants showed a significantly stronger perceptual magnet effect for the American English /i/ when compared to the Swedish /y/. Swedish infants showed the opposite pattern, demonstrating the perceptual magnet effect significantly more strongly for the Swedish /y/ vowel. Figure 5 shows the mean number of trials in which infants treated the variants from each of the four rings surrounding English /i/ and Swedish /y/ as identical to the prototype vowel. American infants' data are shown at the top; Swedish infants' data are shown at the bottom. When American infants listened to the American /i/ vowel, they treated significantly more of the variants as identical to the prototype than when they listened to the Swedish /y/ vowel. When the Swedish infants listened to the very same stimuli, they reversed the effect. They showed a greater tendency to treat the

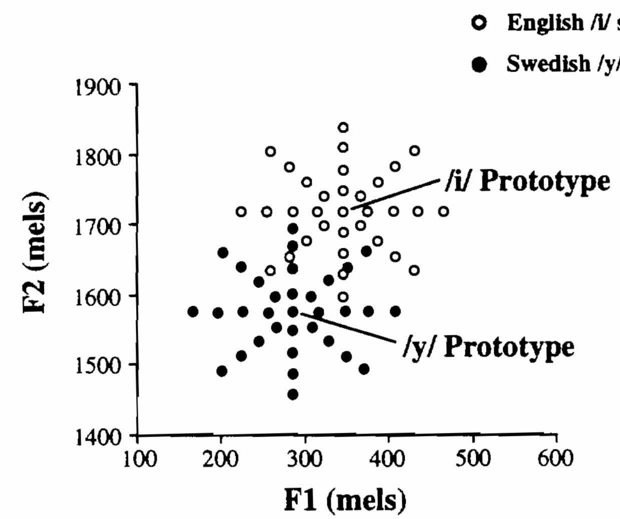

Figure 4. Two vowel prototypes, American English /i/ and Swedish /y/, each with 32 vowel variants, used in a cross-language study on 6-month-old infants in the United States and Sweden.

variants around the Swedish /y/ vowel as identical to it, when compared to the American /i/ vowel. The data indicate a highly reliable statistical interaction between the language environment of the infant and the sound tested. No other effects were significant. American infants did not differ overall from Swedish infants, and overall performance on the two sounds did not differ. Only the interaction of the two factors was significant. In both cases, infants heard fewer variations in their native-language prototype when compared to the foreign-language prototype; the variants in the native-language category were perceptually pulled toward the prototype to a greater degree.

The results revealed an effect of language experience that was measurable by 6 months of age, clearly demonstrating that infants' exposure to ambient language alters their perception of the phonetic units of language. This is the earliest age at which linguistic experience has been found to affect phonetic perception.

NEW DATA ON PERCEIVED GOODNESS AND THE MAGNET EFFECT

Language Input to the Child: Motherese and "Good" Vowels

The cross-language results indicated that infants listen to speech, and that something is altered in their perceptual systems as a result of that listening experience. Infants are bathed in language from the time they are born, and this early language experience affects infants, high-

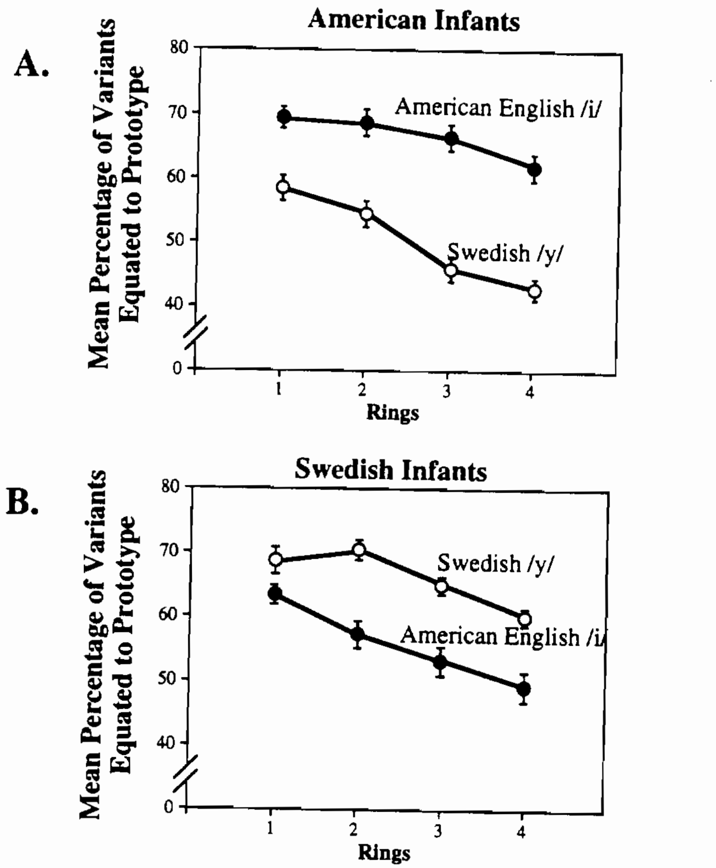

Figure 5. Results on American (A) and Swedish (B) 6-month-old infants tested on two vowel prototypes, American English /i/ and Swedish /y/. Infants from both countries equated variants to their native-language vowel prototype more often than for the foreign-language vowel prototype, producing a stronger magnet effect for their native-language sound.

lighting the importance of the speech addressed to them. To learn something about the nature of language input to the child, we undertook a large study that examines the amount and phonetic content of infant-directed speech, specifically looking at "motherese," the special speech-style used by caregivers when addressing infants (Fernald 1985).

We know that the prosodic characteristics of motherese are unique: it has a higher pitch, a slower tempo, and exaggerated intonation contours. We also know that this speaking style is near universal in the speech of caregivers worldwide when addressing infants (e.g.,

Grieser and Kuhl 1988). Motherese is socially pleasing and attention getting, and parents from almost all cultures use it when speaking to their infants. Research in Kuhl's laboratory also has shown that infants prefer to listen to Motherese over speech directed toward another adult (Fernald 1985; Fernald and Kuhl 1987). In other words, Motherese attracts infants' attention. It is also "vowel-drenched."

In ongoing work, we show that the vowels contained in Motherese are perceived as better instances than the same vowels spoken by the same women when addressing an adult. In the study, 32 women were recorded speaking naturally to their 2-month-old infants and to an adult. They were told to use three words containing the vowel /i/ in both conversations: "bead," "keys," and "sheep." The three words were edited out of these dialogues and rated by adults using the 7-point rating scale. The results showed that Motherese vowels were rated significantly higher than adult-directed vowels. We also found that mothers prolong vowels when they speak to infants. As shown in Figure 6, the word "bead" spoken to an infant is nearly three times longer than when spoken to an adult. Longer vowels were rated as significantly better instances than shorter vowels, regardless of whether they were contained in adult-directed or infant-directed speech. In other words, Motherese contains a large number of vowels that tend to be prolonged, and prolonged vowels are perceived as better instances of vowel categories. Thus, infants may find it easier to focus on the vowels of Motherese. The important theoretical point is that in addition to its social-affective role, Motherese may play another role in language development—it may "tutor" infants on the sound patterns of their native language.

The Magnet Effect in Adults: Analysis Using Signal Detection Theory and Multidimensional Scaling

The magnet effect implies that the area around a phonetic prototype is associated with reduced discrimination sensitivity when compared to areas around nonprototypic members of the category. This, in turn, suggests that the perceptual space underlying a phonetic category is distorted so that the perceptual distance around a prototype is reduced. Our next goal was to examine these implications in greater detail using adult speakers of English (Iverson and Kuhl 1995).

For these experiments, 13 tokens (highlighted in Figure 1) were selected from the set employed by Kuhl (1991a). To address the issue of absolute sensitivity, we applied signal detection methods and theory to calculate d′ (a measure of sensitivity), thus assessing the magnet

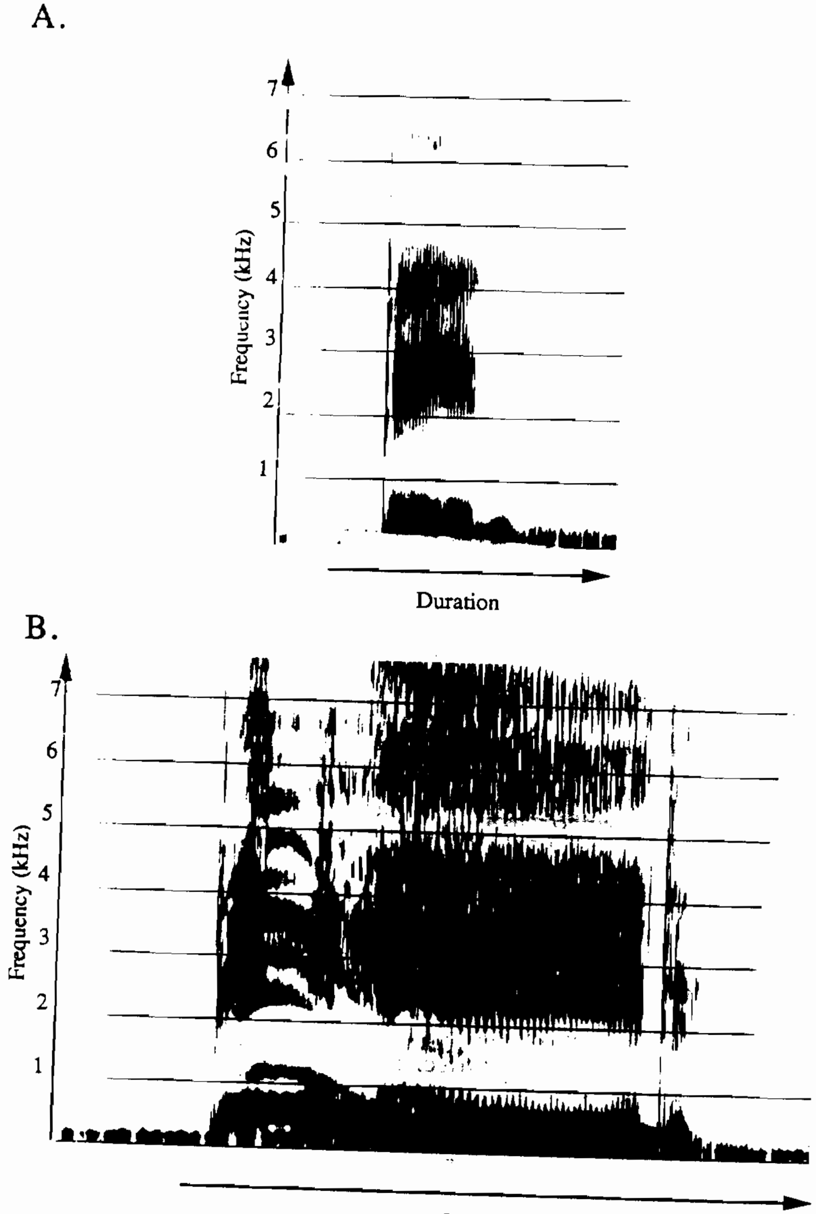

Figure 6. Spectrograms of the word "bead" spoken by the same woman when addressing an adult (A) and her 2-month-old infant (B). The vowel portion of the infant-directed utterance is over three times longer than the comparable portion of the adult-directed utterance, and is rated as a better instance of the /i/ vowel category.

effect using a bias-free measure (Green and Swets 1966; Macmillan, Kaplan, and Creelman 1977; Macmillan and Creelman 1991). To examine the influence of the magnet effect on the underlying perceptual space, we used multidimensional scaling (MDS) to model reaction times in a discrimination task (a measure of similarity). Multidimensional scaling assigns stimuli to locations in a geometric space so that distances in the space correspond to perceived similarity (Shepard 1962a, 1962b). Geometrically modeling the similarity of tokens allowed us to examine whether there is distortion of the perceptual space near the category prototype, as suggested by the magnet effect.

Three experiments were conducted. The first experiment gathered goodness and identification judgments for the 13 stimuli. The second experiment employed a discrimination task to measure sensitivity along the continuum using a bias-free measure (d′). Finally, the third experiment employed MDS to map the distortion of the perceptual space due to the magnet effect.

In the first experiment, subjects were asked to identify the 13 stimuli as either the vowel in "he" or the vowel in "hay." Subjects had not been given a choice between two vowels in Kuhl (1991a); they had simply been asked to rate each stimulus as a member of the category /i/. Figure 7 displays the average identification and goodness ratings from Iverson and Kuhl (1995). Nine tokens were identified as /i/ ("he") greater than 50% of the time, and the four tokens on the right end of the continuum were more often identified as /e/ ("hay"). Although the subjects in this experiment heard some tokens as belonging to the /e/ rather than the /i/ category, the goodness ratings indicated that none of the tokens most often categorized as /e/ were particularly good exemplars of that category. For the tokens most often identified as /i/, tokens near the Kuhl (1991a) P stimulus received consistently higher goodness ratings than those near the Kuhl (1991a) NP, supporting the earlier findings. However, the tokens to the left of the P on the continuum received higher goodness ratings than the tokens to the right of the P, suggesting that the prototype for these subjects may have been in a somewhat more extreme region of the vowel space.

The second experiment by Iverson and Kuhl (1995) was designed for analysis within the framework of signal detection theory (Green and Swets 1966) as extended to the same–different discrimination paradigm commonly used in speech perception research (Macmillan, Kaplan, and Creelman 1977; Macmillan and Creelman 1991). Subjects heard two stimuli on each trial and judged if they were same or different. A comparison of the percentage of hits ("different" responses when the stimuli were different) and false alarms ("different" responses when the stimuli were the same) allowed for orthogonal measurement of the

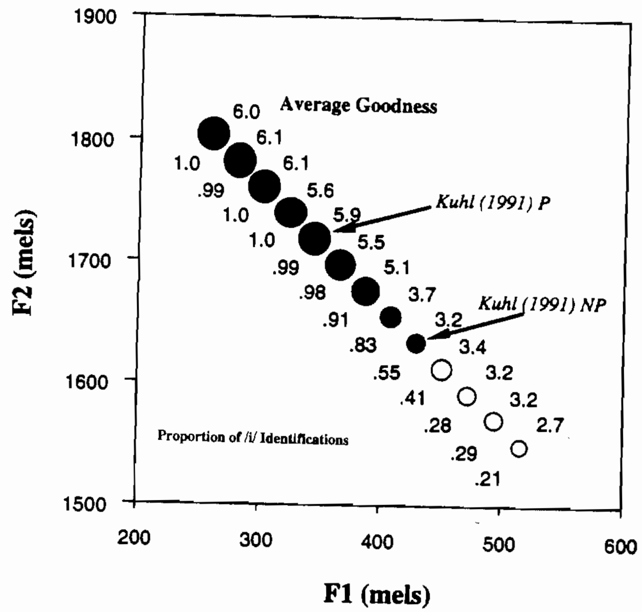

Figure 7. Stimuli on a single vector from Kuhl (1991a) used in Iverson and Kuhl (1995) in discrimination and multidimensional scaling experiments. Stimuli were identified as /i/ or /e/ and then rated on a 7-point scale indicating its perceived quality as a member of that vowel category ("1" = "poor," and "7" = "excellent").

sensitivity (d') and response bias for each pair of tokens (Macmillan, Kaplan, and Creelman 1977; Macmillan and Creelman 1991).[1]

Subjects heard two stimuli on each trial and judged whether the stimuli were the same or different. In one block of trials, subjects were presented with a random ordering of the Kuhl (1991a) P stimulus paired with the tokens 30, 60, or 90 mels away in both directions on

[1]In Kuhl's (1991a) initial tests of the magnet effect, a "go/no-go" psychophysical technique was selected so that adults, 6-month-old infants, and rhesus monkeys could be tested with only minor adjustments to procedures. With this technique, subjects listened to a constantly repeating background stimulus while monitoring the stimulus for a change in the sound. In tests on all three populations, there were 50% test trials and 50% control trials. On test trials, the stimulus was changed during a 4.5-sec. observation interval, and subjects were rewarded for detecting the change (adults and infants with a visual stimulus; monkeys with applesauce). On control trials, the stimulus was not changed, and subjects were monitored to assess the probability of false positive responses (see Kuhl 1991a for further details). The "go/no-go" technique measured the four trial outcomes of discrimination experiments ("hits," "correct rejections," "misses," and "false alarms") and allowed calculation of an overall percent correct measure based both on test and control trials ("hits" + "correct rejections"/2). However, the decision criteria of the "go/no-go" technique have not been studied systematically, making it difficult to evaluate sensitivity and response bias reliably within the context of signal detection theory.

the continuum. In another block, subjects were presented with a random ordering of trials composed of the Kuhl (1991a) NP stimulus, also paired with tokens 30, 60, or 90 mels away in both directions on the continuum. Measures of d' (Kaplan, Macmillan, and Creelman 1978; Macmillan and Creelman 1991) were calculated for each subject. Figure 8 displays the d' data. As shown, subjects were significantly worse at discriminating stimuli from the P than from the NP, supporting the findings of Kuhl (1991a). Additionally, discrimination was significantly lower to the left of the P than to the right of the P. This establishes the magnet effect for stimuli that are all clearly within the /i/ vowel category, and supports the assertion of a correspondence between goodness judgments and discrimination, because goodness ratings were also higher to the left of the P than to the right of P. There was no significant difference between discrimination to the left of the NP and to the right of the NP, even though tokens to the right of the NP were more often judged as belonging to a different phonetic category (/e/). Taken together, the data show that the perceptual magnet effect reduces sensitivity to acoustic differences near prototypic stimuli independent of response bias. This result has now been replicated by Sussman and Lauckner-Morano (1995).

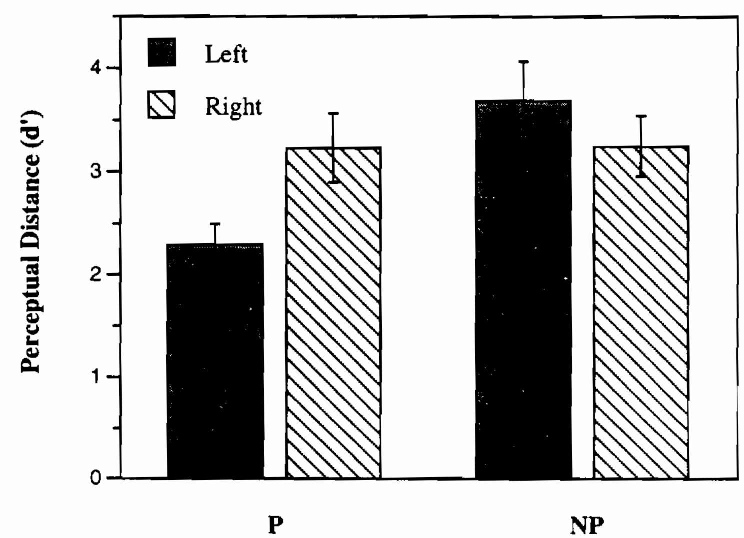

Figure 8. Signal detection analysis of the results of a vowel discrimination experiment. The bias-free estimate of sensitivity (d') is reduced around the prototype (P) when compared to the nonprototype (NP), and sensitivity is poorer to the left of P than to the right of P, as predicted by the magnet effect (from Iverson and Kuhl 1995).

Iverson and Kuhl's (1995) third experiment employed multidimensional scaling (Shepard 1962a; 1962b) to examine whether the perceptual space underlying the vowel category is distorted, as suggested by the magnet effect. Most previous MDS experiments on vowels have employed tokens from different phonetic categories, and they have revealed a high correspondence between acoustic differences and distances in MDS solutions based on measures of perceptual similarity (Pols, van der Kamp, and Plomp 1969; Shepard 1972; Terbeek 1977; Fox 1982, 1983, 1985). Dimensions in MDS spaces have corresponded quite closely to acoustic measurements of vowels (F1, F2, and F3), so that MDS solutions tend to match traditional acoustic maps of vowel inventories. Additionally, Kewley-Port and Atal (1989) demonstrated that subphonemic differences between vowels are effectively mapped using MDS. Acoustic differences between stimuli of the same phonetic category were represented in MDS solutions as well as acoustic differences between stimuli of different phonetic categories.

A related technique has also been used by Nosofsky (1984; 1986) to examine distortions of perceptual similarity due to attention. When subjects classify multidimensional stimuli into categories, subjects pay more attention to dimensions that are relevant to the categorization task and less attention to irrelevant dimensions. This influence of attention can be modeled as distortions in a multidimensional space, so that the distance between tokens along attended dimensions is "stretched," while the distance between tokens along unattended dimensions is "shrunk."

Iverson and Kuhl (1995) similarly used MDS to assess potential shrinking and stretching of the perceptual space underlying vowels. Additionally, the interstimulus interval (ISI) was varied in an initial attempt to evaluate the influence of memory on the magnet effect. Subjects heard all possible pairs of the 13 tokens at three different ISIs (25, 250, and 2500 ms) and judged whether the tokens in each pair were the same or different. Listeners initiated a trial by pressing a response key, and they continued to press the key during the presentation of stimuli. If they thought the tokens were different, they immediately stopped pressing the key. If they thought the tokens were the same, they continued to press the key until the computer signaled the trial was over (2 sec. after the onset of the second token). Their response ("same" or "different") and reaction time (RT) on different responses was recorded for each trial. Trials were blocked by ISI, with the order of blocks counterbalanced among subjects.

Each subject's responses were put into the form of three triangular matrices (one matrix for each ISI) listing the log average RT for each pair of tokens. Intersubject correlations demonstrated that RTs were highly consistent among subjects. These ratings were then averaged across subjects to form three triangular matrices (one for each ISI), and these average matrices were analyzed separately using the Kruskal (1964a, 1964b) MDS technique. All three matrices were fit with one-dimensional solutions, displayed in Figure 9. Reaction times were modeled with MDS so that tokens with long RTs (high similarity) were placed close together on the dimension, and tokens with short RTs (low similarity) were placed far apart.

The perceptual magnet effect was apparent at all three ISIs. The /i/ tokens with the highest goodness ratings were clustered more tightly than the /i/ tokens with lower goodness ratings, supporting the findings of Kuhl (1991a). The prototype acted as a perceptual magnet by drawing tokens toward the prototype in the perceptual space. Additionally, tokens most often identified as /e/ were clustered more tightly than the worst /i/ tokens, although the clustering was not as tight as for the best /i/ tokens. This suggests that tokens on the right end of the continuum may have been approaching a prototypic location in the vowel space for the /e/ category, although none of these tokens was an excellent exemplar of that category. The MDS solutions were similar for all three ISIs. Additional statistical analyses revealed that subjects were slower with longer ISIs; however, there was no significant interaction between ISI and the magnet effect, suggesting that the influence of the prototype did not become greater with the increased memory load (for discussion, see Iverson and Kuhl 1995).

The three experiments reported by Iverson and Kuhl (1995) thus provide additional support for Kuhl's (1991a) finding of a perceptual magnet effect for phonetic prototypes. The use of a bias-free measure revealed reduced sensitivity to stimulus differences around the phonetic prototype, as suggested by the perceptual magnet effect. In addition, the use of MDS showed that the magnet effect causes a distortion of the perceptual space in the region of the prototype. Specifically, perceptual distance appears to be shrunk in the region where the best instances occur, while it is stretched in the regions where the worst instances occur. Taken together, the results suggest that perception within a speech category is not equivalent over the entire category (Grieser and Kuhl 1989; Kuhl, 1991a). The best instances of the category are associated with reduced discrimination and perceptual clustering.

It will now be important to extend these findings on the magnet effect to other phonetic units. Ongoing studies in our laboratory are now focused on consonants. One line of studies examines the acoustic cues that correlate with perceived category goodness for the voicing contrast /k/ versus /g/ (Davis and Kuhl 1992, 1993, 1994; Davis, Iverson, and Kuhl in preparation). In addition, preliminary tests with synthesized consonants indicate that the magnet effect will effectively characterize both the perception of consonant voicing, as in the /k–g/

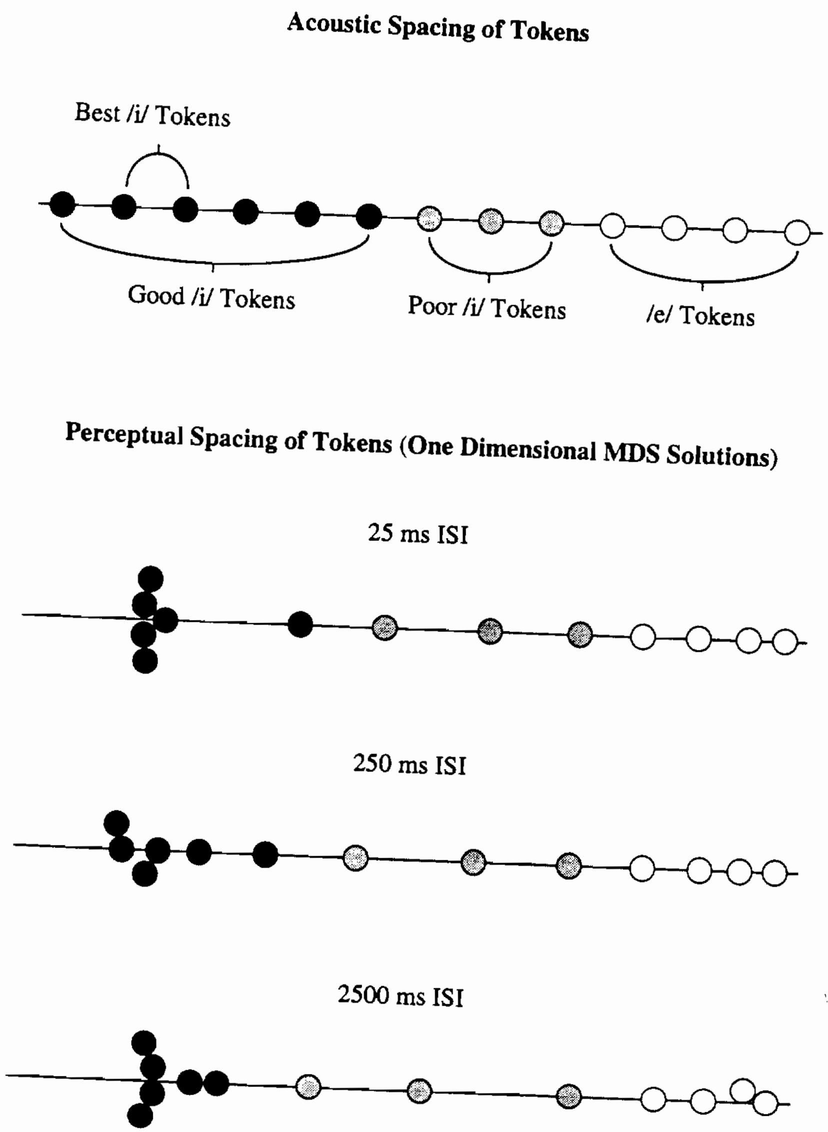

Figure 9. Results of a multidimensional scaling (MDS) experiment plotting the perceived distance between vowel stimuli. While the acoustic space was divided equally across the set of stimuli (top), perceptual space was distorted (bottom). Perceptual space is shrunk in the region of best instances of the category and stretched in the region of the poorest instances. This occurred at all three interstimulus intervals (ISI) (from Iverson and Kuhl 1995).

consonant contrast (Davis and Kuhl 1994) and perception of the liquid /ɹ–l/ consonant contrast (Iverson and Kuhl in press; Kuhl 1994, 1995).

NATIVE LANGUAGE MAGNET MODEL

The studies just described have led to a new theory of the development of speech perception, called the native language magnet theory (Kuhl 1992a, 1993b, 1993c, 1994). The theory accounts for the early period of speech perception covering roughly the first year of life, prior to the time that infants acquire word meaning and contrastive phonology. The theory holds that infants' early exposure to language spoken by their caretakers results in the formation of speech representations that constitute the beginnings of language-specific speech perception. These early speech representations are argued to play a critical role in infants' perception of native- and foreign-language sounds and also to play a critical role in guiding their initial attempts at speech production.

A model of speech perception development has to account for infants' early speech perception abilities as well as changes in those abilities that accompany language experience in the first year. What constitutes the biological endowment at the phonetic level of language? What, on the other hand, is acquired in ontogeny? The NLM theory holds that what is "given by nature" is the ability to partition the sound stream into gross categories separated by natural boundaries, as schematically illustrated in Figure 10A. These boundaries, shown here as divisions in a two-formant vowel space, convey the fact that infants are born with a capacity to resolve the acoustic differences between sounds that belong to different phonetic categories. In tests of categorical perception, infants have shown that they are sensitive to the acoustic cues that underlie phonetic distinctions in language. Their abilities to discriminate speech sounds are particularly keen at the boundaries between phonetic categories. Infants discriminate phonetic units that straddle the boundaries between two phonetic categories, while failing to discriminate phonetic units that fall within a single phonetic category. This is true both for consonants (Eimas et al. 1971; Eimas 1974, 1975) and for vowels (Swoboda et al. 1978). These divisions do not indicate that discrimination ability between and within categories is as categorical as the initial adult studies suggested (e.g., Liberman et al. 1967); they merely suggest that infants show better discrimination for pairs of stimuli that straddle these boundaries than for pairs of stimuli that do not. The ability to resolve fine differences in speech that signal changes in phonetic categories is extremely helpful for the infant and, as described later, plays a role in infants' abilities to organize their initial category representations.

It is important to note, however, that the boundary effects shown in Figure 10A are not entirely unique to humans; some are also displayed by nonhuman animals (Kuhl and Miller 1975, 1978; Kuhl and Padden 1982, 1983). The theory Kuhl is developing thus claims that the infant's ability to hear the relevant differences between phonetic units is innate and attributable to general auditory processing mechanisms. Perceptual boundaries are not argued to be attributable to special processing mechanisms that evolved in humans especially for language. According to this account, these "basic cuts" in auditory

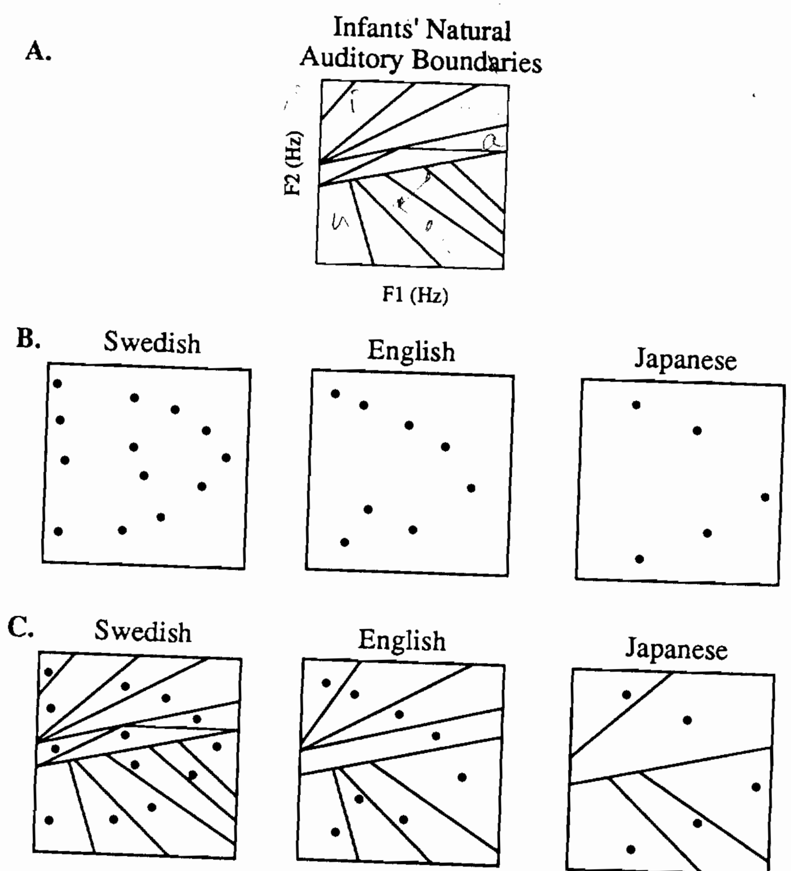

Figure 10. A. NLM Theory: Phase 1. At birth infants perceptually partition the acoustic space underlying phonetic distinctions in a language-general way. B. Phase 2. By 6 months of age, infants reared in different linguistic environments show an effect of language experience. They exhibit language-specific magnet effects induced by ambient language input. C. Phase 3. After language-specific magnet effects are observed, certain phonetic boundaries "disappear." Magnet effects alter the perceived distance between stimuli causing certain distinctions to be less well discriminated than they were prior to specific language experience for each group of infants.

perception helped guide the initial selection of stimuli for a phonetic inventory (for review and discussion, see Kuhl 1987, 1988).

Given that the acoustic space is initially divided by natural psychophysical boundaries that are shared by certain nonhuman animals, what is acquired in human ontogeny? Based on the data gathered in the perceptual magnet studies reported here, NLM claims that by 6 months of age, infants have something more than the basic cuts they were born with. By 6 months of age, infants show evidence of language-specific magnet effects. This is illustrated in the plots shown in Figure 10B. Here the centers of the acquired magnet effects in vowel space are schematically portrayed for infants being raised in three different countries: Sweden, America, and Japan. The graphs are not meant to be precise with regard to the locations of magnet effects. They convey in conceptual terms the idea that linguistic experience in the three different cultures has resulted in magnet effects that differ in number and location for infants growing up listening to the three different languages.

Where do the magnet effects come from? According to NLM, magnet effects are the result of infants' analysis of language input. They are derived from infants' representations of the distributional properties of vowels produced by native speakers of the language. Infants' perceptual boundaries help this process of magnet acquisition. The boundaries set limits on what the infants' representations must organize. Thus, infants' analysis of language input results in category representations (magnets) that summarize a restricted area rather than the entire vowel space. To complete this description, additional work on Motherese will be helpful. We plan to analyze language input to the child in the three languages of interest, Swedish, American English, and Japanese. Our hypothesis is that the distribution of vowels in the three languages will be very different, and that these differences in language input will account for infants' varying perceptual representations by 6 months of age.

Native Language Magnets and the Perception of Foreign Language Sounds

What about infants' perception of foreign-language sounds? NLM theory holds that acquisition of native-language magnet effects subsequently alters the perception of differences in phonetic space. Perceptual magnets warp the acoustic space underlying phonetic distinctions by shrinking the perceived distance between good instances and surrounding stimuli, and stretching the perceived distance in the region of the phonetic boundary. This will cause certain perceptual distinctions to be maximized (those near the boundaries between two magnets), while others are minimized (those near the magnet attractors themselves). The effects of infants' acquisition of perceptual magnets on the underlying phonetic space is shown in the schematic diagrams of Figure 10C. In essence, magnets cause certain boundaries to "recede" as the perceptual space is reconfigured to incorporate a language's particular magnet placement. Work on adults suggests that the boundaries do not literally disappear; that is, it is possible to increase performance on the discrimination of foreign-language contrasts in adults with extensive training (e.g., Logan, Lively, and Pisoni 1991; MacKain, Best, and Strange 1981; Flege this volume). These training data suggest that the alterations in perception that occur as a result of linguistic experience do not alter the sensory ability to discriminate a contrast. Rather, the data suggest that the change occurs at a higher level, one that involves memory and/or attention. The point being made in Figure 10C is that exposure to a given language results in the development of a speech representational system that alters the underlying perceptual system, as suggested by the magnet effect, reducing the prominence of certain distinctions when compared to the language-general initial state (Figure 10A).

We know from the data obtained by Werker and her colleagues (Werker and Polka 1993; Werker this volume) that infants aged 10–12 months exhibit a failure to discriminate foreign-language sounds that they had discriminated earlier. According to NLM, developing magnets pull sounds that were once discriminable toward a single magnet, making the sounds no longer discriminable. According to the theory, magnet effects developmentally *precede* and underlie the changes in infants' perception of foreign-language contrasts. Data gathered in vowel studies by Werker and Polka (1993) are in line with this hypothesis. The NLM theory thus offers a *mechanism* that explains the "reorganization" in phonetic perception that Werker observed.

The magnet effect may help account for the results of studies on the perception of sounds from a foreign language by adults. These studies suggest that phonetic units from a foreign language that are similar to a category in the adult's own native language are particularly difficult to perceive as different from the native-language sound; sounds that are not similar to a native-language category are relatively easy to discriminate (Best, McRoberts, and Sithole 1988; Best 1993, this volume). The classic example of /ɹ–l/ discrimination by native speakers of Japanese could be accounted for by this model. The segments /ɹ/ and /l/ are not phonemically contrastive in Japanese, and native speakers have difficulty with the contrast even after considerable training (Yamada and Tohkura 1992; Yamada this volume). The NLM suggests that native language Japanese prototypes may distort the perception of Japanese listeners such that the /ɹ-l/ contrast becomes less distinctive (Kuhl 1994, 1995).

Kuhl is currently conducting developmental studies in Japan that will help clarify whether the NLM's prediction about the relationship between the magnet effect and foreign-language consonant discrimination is correct. In collaboration with Shigeru Kiritani and Toshisada Deguchi in Japan, the plan is to do three experiments with infants residing in the United States and Japan. In the first, the discrimination of /ɹ/ and /l/ will be tested in both groups at 6 months of age, an age argued to be prior to the point at which magnet effects develop for consonants, based on Werker's data. The prediction is that both the American and the Japanese 6-month-old infants will initially show the ability to discriminate the /ɹ/ and /l/ sounds. (Eimas [1975] demonstrated that 2- to 3-month-old American infants discriminate /ɹ/ and /l/. Japanese infants have not previously been tested on the English /ɹ/ and /l/ consonants.) Next, studies will establish the age at which the magnet effect for the /ɹ/ and /l/ consonants occurs in American infants; Japanese infants will also be tested on the magnet effect for /ɹ/ and /l/, but the theory predicts that they will *not* show a magnet effect for these consonants. Finally, once the age at which American infants exhibit the magnet effect for /ɹ/ and /l/ has been established, American and Japanese infants older than the established age will be tested on the same /ɹ/ and /l/ stimuli used previously. The NLM predicts that at this later age, Japanese infants will fail to show discrimination of English /ɹ/ and /l/, while American infants tested at the same age will continue to succeed in discriminating the two sounds.

This same argument about the role of language experience in infancy on the discrimination of foreign-language contrasts can be applied to adults learning a second language. Studies on second-language learning suggest that the acquisition of a new language by adults poses difficulty at the level of phonology (Flege 1987, this volume; Bohn this volume; Rochet this volume). In particular, it has been suggested that the native-language categories of the listener somehow interfere with the ability to perceive the phonetic distinctions in the new language. The theory Kuhl has put forward argues that the magnet effect contributes to this difficulty. As shown in the studies reviewed here, native-language magnets distort the underlying perceptual space, and this results in the "attraction" of similar sounds. This, in turn, makes certain foreign-language distinctions difficult to perceive, such as the segments /ɹ/ and /l/ for native speakers of Japanese. The prediction that stems from the theory is that the difficulty posed by a given foreign-language unit will depend on its proximity to a native-language magnet. The nearer it is to a magnet, the more it will be assimilated to the native-language category, making it indistinguishable from the native-language sound (see also Best 1993, Flege this volume, for arguments about which cross-language contrasts will be difficult and which easy to discriminate). Phonologists interested in second-language learning have developed an analogy that is consistent with the hypothesized magnet effect. The phonetic categories of one's native language have been described as forming a "sieve" through which the phonetic units of the newly acquired language must pass (Trubetzkoy 1939). The idea developed here, that good instances of native-language categories act as magnets that filter the new language's phonetic units, provides a mechanism that explains this phenomenon.

While we currently have no data that address this issue, the topic of second-language learning raises an interesting developmental issue, that of bilingual exposure to language early in life. We have yet to conduct experiments on infants reared in a bilingual home in which the infant is regularly exposed to two different languages. Our interest would be in tracking the development of the magnet effect in infants reared in bilingual homes using as test stimuli the sounds of both languages. The hypothesis would be that infants would show magnet effects for the sounds of both languages.

Unanswered Questions: Are Speech Representations Being Formed?

The NLM theory has argued that infants are beginning to form speech representations, some type of memory for the sounds of their native language (Kuhl 1994, 1995). It is possible, of course, that there are no *representations*, per se, being formed, and that the alterations seen in perception are the result of changes in perceptual networks independent of memory for specific sounds (see Jenkins and Yeni-Komshian this volume, for discussion). Studies in Finland (Aaltonen and Eerola 1993) that independently replicate the magnet effect in Finnish subjects listening to good versus poor instances of their /i/ and /y/ vowels, suggest that event related potentials (ERP) correlate very well with the perceptual magnet effect. These brain potentials are considered "preperceptual" and occur early in the processing of auditory information. These findings thus lead to the suggestion that the magnet effect is operating at an earlier level than we might have supposed. Future studies will have to be done using this technique. The ERP approach may prove helpful, for example, in mapping the development of the magnet effect in infants between birth and 6 months. This would allow us to examine the level at which the perceptual magnet effect is present and the age at which it develops.

The Finnish data also provide some indication of the robustness of the perceptual magnet effect. The magnet effect was replicated in three studies in our laboratory (Grieser and Kuhl 1989; Kuhl 1991a; Iverson and Kuhl 1995), and also cross-linguistically in America and

our laboratory in Stockholm (Kuhl et al. 1992). It was also replicated in studies completed in other laboratories (Sussman and Lauckner-Morano 1995), in addition to the studies being done in Finland (Aaltonen and Eerola 1993). Such results indicate that the effect is robust.

What Form Might Speech Representations Take?

If speech representations are being formed, there are three issues with regard to representation that must be addressed in future studies. All have to do with the exact form that speech representations take (see also Pisoni and Lively this volume). Specific questions are: (1) whether speech representations consist of individual exemplars or abstract summaries; (2) how the effects of context are reflected in speech representations; and (3) whether speech representations are solely perceptual as opposed to polymodal in nature.

Considering the first issue, early theorists studying good stimuli assumed, because representative instances of categories were associated with special effects, that this meant that people mentally calculated and stored some abstract version that characterized the category as a whole (Posner and Keele 1968; see Pisoni and Lively this volume for further discussion). It was assumed that as people experienced new items from a category, a generalization about those items as a group was formed, such as an average of all the experienced exemplars. As the number of instances grew, the details of individual stimuli that generated the average were not as prominent in memory as the average itself. Category decisions were thought to be made by comparing newly encountered items to this summary representation. Prototype abstraction thus reduced memory load.

An alternative, "exemplar-based" model of categorization, has recently gained support (Hintzman 1986; Medin and Barsalou 1987; Nosofsky 1987; Estes 1993). According to this model, classification can be accounted for by the storage and retrieval of individual exemplars. Exemplar theories maintain that newly encountered items act as retrieval cues to allow access to stored individual exemplars from a category. Because the most representative stimuli (prototypic) are similar to a large number of individual exemplars, they are more likely to be retrieved quickly, thus the exemplar model offers an alternative explanation for the results of studies showing superior or more efficient recognition of prototypic items from a category.

As Estes (1993) and others have pointed out, both models account for the typical "prototype" effect wherein best instances of categories show special perceptual effects. In the case of speech, it is unclear what form the underlying representation of phonetic categories might take. Typicality effects, such as the magnet effect shown in these studies for speech, can be accounted for by either type of representation. In regard to speech, therefore, we do not thus far take a position as to whether speech category information might be stored in terms of an abstract summary or as individual instances. The perceptual magnet effect, as tested thus far, does not distinguish between the two alternatives in this debate and is not substantially affected by the debate (see Kuhl 1993b, 1993c for further discussion). We underscore an additional point, namely that nothing precludes people from having access to both kinds of memory systems, one that stores information about individual exemplars and a separate system that stores general category information derived from individual exemplars.

Recent studies show that category composites are not only attractive to subjects, but are formed in an amazingly short time. Human newborns have been shown to react to composites of individual faces within 1 min. of exposure to the individual faces (Walton and Bower 1993). These findings buttress earlier results on faces and other complex visual stimuli showing that at an early age, infants have the ability to abstract a central category representation (for review, see Quinn and Eimas 1986). Thus, whatever form category representations take, we will have to account for the fact that composites are attractive to infants and readily formed in a very short time.

Another issue with regard to representation is the effect of context. There are data to suggest that the location of best instances of the category shifts with changes in such variables as the rate of speech (Miller and Volaitis 1989; Volaitis and Miller 1992; Miller 1994). Similarly, we would expect that the location of the best instance of /i/ would shift with the gender of the speaker. What we do not yet know is whether a good instance produced by a male talker has an effect on perception of instances spoken by a female talker. In other words, we do not know whether the magnet's attractor effect is restricted to variants that share certain basic parameters with the tested stimulus (such as the gender of the speaker) or whether the effect extends to tokens in which these basic parameters have been changed. These questions will be answered in future studies.

A final issue with regard to representation is whether or not phonetic category information is solely auditory or whether information regarding the production of speech is also contained in the representation. Kuhl's NLM is not a modality-specific nor an exclusively perceptual model of infants' speech development (Kuhl 1992a, 1993b, 1993c, 1994, 1995). The results of experiments on both adults (Green and Kuhl 1989, 1991; Green et al. 1991; Massaro 1987) and infants (Kuhl and Meltzoff 1982, 1984; Kuhl, Williams, and Meltzoff 1991; MacKain et al. 1983) show that people's perception of speech is neither modality-specific nor confined to perception. At a very young age, infants recognize the visual concomitants of an auditory speech signal (Kuhl and Meltzoff 1982, 1984; MacKain et al. 1983). Moreover, there are data to suggest that infants have the capacity to imitate speech vocally very early in life; as early as 12 weeks of age, they hear speech and move their own articulators to replicate certain features of the sounds that they hear (Kuhl 1994; Kuhl and Meltzoff 1982, 1988, in press; Meltzoff and Kuhl 1994).

These kinds of data demonstrate that the speech representational system is "polymodally mapped" very early in life. The NLM theory holds that speech representations are initially auditory, but that they become polymodal as infants acquire information (both visual and motor) about the production of speech. Infants relate auditory information to the visual information that accompanies speech, and also relate it to how they must move their own articulators in order to produce speech. Thus, as a result of their experiences in listening to, watching, and attempting to produce speech, infants' speech representations become polymodal in nature.

Much as a memory of species-specific song is formed in birds prior to the time that production of song begins (for review see Konishi 1989), NLM holds that speech representations initially shaped by auditory input eventually guide motor learning. Data on vocal imitation in 12- to 20-week-old infants indicates that infants have the ability to store auditory information that subsequently influences their production of sound (Kuhl and Meltzoff in press). Thus, the NLM argues that infants' perceptual representations serve as targets for the acquisition of phonetically relevant gestures (for data showing an early influence of ambient language on infants' speech production see de Boysson-Bardies et al. 1989).

DEVELOPMENTAL NEUROSCIENCE AND THE MAGNET EFFECT

Finally, it is interesting to contemplate the neural mechanisms that underlie the kind of alteration in perception that results from experience. It is tempting to speculate that the development of language-specific speech representations is, in Greenough's terms, an "experience-expectant" process (Greenough and Black 1992). These authors have argued that certain developmental changes are underlain by an overproduction of synaptic connections, which are subsequently pruned to achieve a more efficient neural organization. Synaptic overproduction is seen in situations in which a certain kind of experience is highly reliable in the environment of the organism. They explain: "Our terminology for this synapse overproduction process reflects the apparent fact that the synapses are produced in the evolutionarily-based *expectation* that appropriate experience will provide the information that the nervous system needs in order to select the appropriate subset of synaptic connections" (p. 163).

The idea that these magnet effects are built up through an experience-expectant process is attractive. Native language phonetic input is a reliable feature of infants' prenatal and postnatal experience, and other data on infants confirm the fact that they can learn many regularities of their native language. The earliest effects have to do with learning the prosodic properties of sound—ones learned in utero—as evidenced by newborns' preference for mother's voice (DeCasper and Fifer 1980) and their preference for the stress pattern typical of their mother's language (Mehler et al. 1988). In work conducted on infants in the second half-year of life, Jusczyk and his colleagues (1992, 1993, this volume) have shown that infants learn the regularities that govern larger units of speech, such as the prosodic patterns and phonotactic constraints that govern words, phrases, and clauses.

The data presented here showing infants' early learning of the phonetic properties of language indicate that infants' abilities to perceive and store information are broad based, and not limited to prosodic patterns. Infants are apparently able to learn specific spectral patterns, such as those that would typify a particular vowel. Taken together, these studies show that experience with ones' native language early in life results in learning quite specific aspects of the sound patterns of the language. What we have shown uniquely in the studies reported here is that learning is accompanied by dramatic changes in perception. From a neuroscience perspective, infants' early automatic learning may be attributable to an evolutionarily-based expectation that infants of the species will experience patterned auditory input beginning as early as the onset of auditory function in utero (Kuhl 1994).

SUMMARY AND CONCLUSIONS

Studies on the perceptual magnet effect in speech perception show that linguistic experience results in a distortion of the perceptual space underlying speech. The effect shows that a phonetic prototype perceptually attracts surrounding stimuli. More specifically, studies confirm the appropriateness of the magnet analogy. The region surrounding a good instance or "prototype" of the category exhibits reduced sensitivity and perceptual clustering. Perceptual distance between the prototype and its surrounding stimuli is shrunk, while the region near the phonetic boundary is perceptually stretched. This distortion of the perceptual space underlying phonetic categories is attributable to language experience. Infants at 6 months of age growing up in two different countries, the United States and Sweden, listening to English and Swedish, respectively, exhibited the perceptual magnet effect only for their native-language vowel. Thus, by 6 months of life, well before they utter or understand their first words, infants demonstrate an ability to learn simply by listening to ambient language. This suggests a powerful linguistic representational system that responds automatically given proper input. These data are incorporated into a new model of the development of speech perception, the native language magnet (NLM) theory, which describes how innate abilities interact with infants' early experience to produce a language-specific and species-specific pattern of speech perception. The model holds that nature's initial structuring in the form of natural boundaries, combined with the role experience plays in defining language-specific phonetic categories, results in the development of native-language speech representations that subsequently alter both the perception of speech and its production. This view accounts for a large set of available data in infant speech perception. The model also helps explain the perception of foreign-language sounds by infants and adults. The magnet effects exhibited by prototypes of native-language categories render certain foreign-language contrasts less discriminable, making the acquisition of a second language in adulthood more difficult than the acquisition of a primary language. The perceptual magnet effect thus illustrates how exposure to language alters perception and may generally reflect a mechanism by which experience can alter the mind of an individual.

ACKNOWLEDGEMENTS

The research described in this chapter is supported by grants to PKK from the NIH (DC00520 and HD18286). The authors thank E. Stevens for assistance in conducting the research described here and in preparation of the manuscript.

REFERENCES

Aaltonen, O., and Eerola, O. 1993, August. Do event related brain potentials reflect the perceptual magnet effect of vowel prototypes? Paper presented at the VIIth International Conference on Event Perception and Action, Vancouver, BC, Canada.

Andruski, J. A., Kuhl, P. K., Gustafson, K. T., and Stevens, E. B. In preparation. Language input to the child: Studies on the phonetic content of Motherese.

Best, C. T. 1993. Language-specific developmental changes in non-native speech perception: A window on early phonological development. In *Developmental Neurocognition: Speech and Face Processing in the First Year of Life*, eds. B. de Boysson-Bardies, S. de Schonen, P. Jusczyk, P. MacNeilage, and J. Morton. The Netherlands: Kluwer Academic Publishers B.V.

Best, C. T., McRoberts, G. W., and Sithole, N. M. 1988. Examination of perceptual reorganization for nonnative speech contrasts: Zulu click discrimination by English-speaking adults and infants. *Journal of Experimental Psychology: Human Perception and Performance* 14:345–60.

Chomsky, N. 1982. On the representation of form and function. In *Perspectives on Mental Representation*, eds. J. Mehler, E. C. T. Walker, and M. Garrett. Hillsdale, NJ: Erlbaum.

Davis, K., and Kuhl, P. K. 1992. Best exemplars of English velar stops: A first report. In *Proceedings of the International Conference on Spoken Language Processing*, eds. J. J. Ohala, T. M. Nearey, B. L. Derwing, M. M. Hodge, and G. E. Wiebe. Edmonton, Alberta: University of Alberta.

Davis, K., and Kuhl, P. K. 1993. Acoustic correlates of phonetic prototypes: Velar stops. *Journal of the Acoustical Society of America* 93:2392.

Davis K., and Kuhl, P.K. 1994. Tests of the perceptual magnet effect for American English /k/ and /g/. Paper presented at the 127th meeting of the Acoustical Society of America, Boston, MA.

Davis, K., Kuhl, P. K., and Iverson, P. In preparation. Within category perception of velar stops. *Journal of the Acoustical Society of America* 95:2976.

de Boysson-Bardies, B., Halle, P., Sagart, L., and Durand, C. 1989. A cross-linguistic investigation of vowel formants in babbling. *Journal of Child Language* 16:1–17.

DeCasper, A. J., and Fifer, W. P. 1980. Of human bonding: Newborns prefer their mothers' voices. *Science* 208:1174–76.

Eimas, P. D. 1974. Auditory and linguistic processing of cues for place of articulation by infants. *Perception & Psychophysics* 16:513–21.

Eimas, P. D. 1975. Auditory and phonetic coding of the cues for speech: Discrimination of the /r-l/ distinction by young infants. *Perception & Psychophysics* 18:341–47.

Eimas, P. D., Siqueland, E. R., Jusczyk, P., and Vigorito, J. 1971. Speech perception in infants. *Science* 171:303–306.

Estes, W. K. 1993. Concepts, categories, and psychological science. *Psychological Science* 4:143–53.

Fernald, A. 1985. Four-month-old infants prefer to listen to motherese. *Infant Behavior and Development* 8:181–95.

Fernald, A., and Kuhl, P. 1987. Acoustic determinants of infant preference for Motherese speech. *Infant Behavior and Development* 10:279–93.

Flege, J. E. 1987. The production of "new" and "similar" phones in a foreign language: Evidence for the effect of equivalence classification. *Journal of Phonetics* 15:47–65.

Fox, R. A. 1982. Individual variation in the perception of vowels: Implications for a perception-production link. *Phonetica* 39:1–22.

Fox, R. A. 1983. Perceptual structure of monophthongs and diphthongs in English. *Language and Speech* 26:21–60.

Fox, R. A. 1985. Auditory contrast and speaker quality variation in vowel perception. *Journal of the Acoustical Society of America* 77:1552–59.

Green, D. M., and Swets, J. A. 1966. *Signal Detection Theory and Psychophysics*. New York: Wiley.

Green, K. P., and Kuhl, P. K. 1989. The role of visual information in the processing of place and manner features in speech perception. *Perception and Psychophysics* 45:34–42.

Green, K. P., and Kuhl, P. K. 1991. Integral processing of visual place and auditory voicing information during phonetic perception. *Journal of Experimental Psychology: Human Perception and Performance* 17:278–88.

Green, K. P., Kuhl, P. K., Meltzoff, A. N., and Stevens, E. B. 1991. Integrating speech information across talkers, gender, and sensory modality: Female faces and male voices in the McGurk effect. *Perception & Psychophysics*, 50:524–36.

Greenough, W. T., and Black, J. E. 1992. Induction of brain structure by experience: Substrates for cognitive development. In *The Minnesota Symposia on Child Psychology, Vol. 24: Developmental Behavioral Neuroscience*, eds. M. Gunnar and C. Nelson. Hillsdale, NJ: Erlbaum.

Grieser, D., and Kuhl, P. K. 1989. Categorization of speech by infants: Support for speech-sound prototypes. *Developmental Psychology* 25:577–88.

Grieser, D. L., and Kuhl, P. K. 1988. Maternal speech to infants in a tonal language: Support for universal prosodic features in motherese. *Developmental Psychology* 24:14–20.

Hintzman, D. L. 1986. "Schema abstraction" in a multiple-trace memory model. *Psychological Review* 93:411–28.

Iverson, P., and Kuhl, P. K. In press. Influences of phonetic identification and category goodness on American listeners perception of /r/ and /l/. *Journal of the Acoustical Society of America* 95:2976.

Iverson, P., and Kuhl, P. K. 1995. Mapping the perceptual magnet effect for speech using signal detection theory and multidimensional scaling. *Journal of the Acoustical Society of America* 97:553–62.

Jusczyk, P. W. 1992. Developing phonological categories from the speech signal. In *Phonological Development: Models, Research, Implications*, eds. C. A. Ferguson, L. Menn, and C. Stoel-Gammon. Timonium, MD: York Press.

Jusczyk, P. W. 1993. Sometimes it pays to look back before you leap ahead. In *Developmental Neurocognition: Speech and Face Processing in the First Year of Life*, eds. B. de Boysson-Bardies, S. de Schonen, P. Jusczyk, P. MacNeilage, and J. Morton. The Netherlands: Kluwer Academic Publishers B.V.

Kaplan, H. L., Macmillan, N. A., and Creelman, C. D. 1978. Tables of d' for variable-standard discrimination paradigms. *Behavior Research Methods, Instruments and Computers* 10:796–813.

Kewley-Port, D., and Atal, B. S. 1989. Perceptual differences between vowels located in a limited phonetic space. *Journal of the Acoustical Society of America* 85:1726–40.

Konishi, M. 1989. Birdsong for neurobiologists. *Neuron* 3:541–49.

Kruskal, J. B. 1964a. Multidimensional scaling by optimizing goodness of fit to a nonmetric hypothesis. *Psychometrika* 29:1–27.

Kruskal, J. B. 1964b. Nonmetric multidimensional scaling: A numerical method. *Psychometrika* 29:115–29.

Kuhl, P. K. 1985. Methods in the study of infant speech perception. In *Measurement of Audition and Vision in the First Year of Postnatal Life: A Methodological Overview*, eds. G. Gottlieb and N. Krasnegor. Norwood, NJ: Ablex.

Kuhl, P. K. 1987. The special-mechanisms debate in speech research: Categorization tests on animals and infants. In *Categorical Perception: The Groundwork of Cognition*, ed. S. Harnad. New York: Cambridge University Press.

Kuhl, P. K. 1988. Auditory perception and the evolution of speech. *Human Evolution* 3:19–43.

Kuhl, P. K. 1991a. Human adults and human infants show a "perceptual magnet effect" for the prototypes of speech categories, monkeys do not. *Perception & Psychophysics* 50:93–107.

Kuhl, P. K. 1991b. Perception, cognition, and the ontogenetic and phylogenetic emergence of human speech. In *Plasticity of Development*, eds. S. E. Brauth, W. S. Hall, and R. J. Dooling. Cambridge, MA: MIT Press.

Kuhl, P. K. 1992a. Infants' perception and representation of speech: Development of a new theory. In *Proceedings of the International Conference on Spoken Language Processing*, eds. J. J. Ohala, T. M. Nearey, B. L. Derwing, M. M. Hodge, and G. E. Wiebe. Edmonton, Alberta: University of Alberta.

Kuhl, P. K. 1992b. Psychoacoustics and speech perception: Internal standards, perceptual anchors, and prototypes. In *Developmental Psychoacoustics*, eds. L. A. Werner and E. W. Rubel. Washington, DC: American Psychological Association.

Kuhl, P. K. 1993a. Early linguistic experience and phonetic perception: Implications for theories of developmental speech perception. *Journal of Phonetics* 21:125–39.

Kuhl, P. K. 1993b. Infant speech perception: A window on psycholinguistic development. *International Journal of Psycholinguistics* 9:33–56.

Kuhl, P. K. 1993c. Innate predispositions and the effects of experience in speech perception: The Native Language Magnet Theory. In *Developmental Neurocognition: Speech and Face Processing in the First Year of Life*, eds. B. de Boysson-Bardies, S. de Schonen, P. Jusczyk, P. MacNeilage, and J. Morton. The Netherlands: Kluwer Academic Publishers.

Kuhl, P. K. 1994. Learning and representation in speech and language. *Current Opinion in Neurobiology* 4:812–22.

Kuhl, P. K. 1995. Speech perception, memory, and cognition: *Journal of the Acoustical Society of America* 97:3260.

Kuhl, P. K., and Meltzoff, A. N. 1982. The bimodal perception of speech in infancy. *Science* 218:1138–41.

Kuhl, P. K., and Meltzoff, A. N. 1984. The intermodal representation of speech in infants. *Infant Behavior and Development* 7:361–81.

Kuhl, P. K., and Meltzoff, A. N. 1988. Speech as an intermodal object of perception. In *Perceptual Development in Infancy: The Minnesota Symposia on Child Psychology*, vol. 20, ed. A. Yonas. Hillsdale, NJ: Erlbaum.

Kuhl, P. K., and Meltzoff, A. N. In press. Infant vocalizations in response to speech: Vocal imitation and developmental change. *Journal of the Acoustical Society of America*.

Kuhl, P. K., and Miller, J. D. 1975. Speech perception by the chinchilla: Voiced–voiceless distinction in alveolar plosive consonants. *Science* 190:69–72.

Kuhl, P. K., and Miller, J. D. 1978. Speech perception by the chinchilla: Identification functions for synthetic VOT stimuli. *Journal of the Acoustical Society of America* 63:905–17.

Kuhl, P. K., and Padden, D. M. 1982. Enhanced discriminability at the phonetic boundaries for the voicing feature in macaques. *Perception & Psychophysics* 32:542–50.

Kuhl, P. K., and Padden, D. M. 1983. Enhanced discriminability at the phonetic boundaries for the place feature in macaques. *Journal of the Acoustical Society of America* 73:1003–10.

Kuhl, P. K., Williams, K. A., Lacerda, F., Stevens, K. N., and Lindblom, B. 1992. Linguistic experience alters phonetic perception in infants by 6 months of age. *Science* 255:606–608.

Kuhl, P. K., Williams, K. A., and Meltzoff, A. N. 1991. Cross-modal speech perception in adults and infants using nonspeech auditory stimuli. *Journal of Experimental Psychology: Human Perception and Performance* 17:829–40.

Liberman, A. M., Cooper, F. S., Shankweiler, D. P., and Studdert-Kennedy, M. 1967. Perception of the speech code. *Psychological Review* 74:431–61.

Logan, J. S., Lively, S. E., and Pisoni, D. B. 1991. Training Japanese listeners to identify English /r/ and /l/: A first report. *Journal of the Acoustical Society of America* 89:874–86.

MacKain, K., Studdert-Kennedy, M., Spieker, S., and Stern, D. 1983. Infant intermodal speech perception is a left-hemisphere function. *Science* 219:1347–49.

MacKain, K. S., Best, C. T., and Strange, W. 1981. Categorical perception of English /r/ and /l/ by Japanese bilinguals. *Applied Psycholinguistics* 2:369–90.

Macmillan, N. A., and Creelman, D. 1991. *Detection Theory: A User's Guide*. New York: Cambridge.

Macmillan, N. A., Kaplan, H. L., and Creelman, C. D. 1977. The psychophysics of categorical perception. *Psychological Review* 84:452–71.

Massaro, D. W. 1987. Psychophysics versus specialized processes in speech perception: An alternative perspective. In *The Psychophysics of Speech Perception*, ed. M. E. H. Schouten. Boston: Nijhoff.

Medin, D. L., and Barsalou, L. W. 1987. Categorization processes and categorical perception. In *Categorical Perception: The Groundwork of Cognition*, ed. S. Harnad. New York: Cambridge University Press.

Mehler, J., Jusczyk, P., Lambertz, G., Halsted, N., Bertoncini, J., and Amiel-Tison, C. 1988. A precursor of language acquisition in young infants. *Cognition* 29:143–78.

Meltzoff, A. N., and Kuhl, P. K. 1994. Intermodal processing of biologically relevant signals: Faces and speech in infants and adults. In *The Development of Intermodal Perception*, eds. D. Lewkowicz and R. Lickliter. Hillsdale, NJ: Erlbaum.

Mervis, C. B., and Rosch, E. 1981. Categorization of natural objects. *Annual Review of Psychology* 32:89–115.

Miller, J. L. 1994. On the internal structure of phonetic categories: A progress report. *Cognition* 50:271–85.

Miller, J. L., and Volaitis, L. E. 1989. Effect of speaking rate on the perceptual structure of a phonetic category. *Perception & Psychophysics* 46:505–12.

Nosofsky, R. 1987. Attention and learning processes in the identification and categorization of integral stimuli. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 15:87–108.

Nosofsky, R. M. 1984. Choice, similarity, and the context theory of classification. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 10:104–14.

Nosofsky, R. M. 1986. Attention, similarity, and the identification-categorization relationship. *Journal of Experimental Psychology: General* 115:39–57.

Pols, L. C. W., van der Kamp, L. J. T., and Plomp, R. 1969. Perceptual and physical space of vowel sounds. *Journal of the Acoustical Society of America* 46:458–67.

Posner, M. I., and Keele, S. W. 1968. On the genesis of abstract ideas. *Journal of Experimental Psychology* 77:353–63.

Quinn, P. C., and Eimas, P. D. 1986. On categorization in early infancy. *Merrill-Palmer Quarterly* 32:331–63.

Rosch, E. 1975. Cognitive reference points. *Cognitive Psychology* 7:532–47.

Rosch, E. 1978. Principles of categorization. In *Cognition and Categorization*, eds. E. Rosch and B. Lloyd. Hillsdale, NJ: Erlbaum.

Rosch, E. H. 1977. Human categorization. In *Studies in Cross-Cultural Psychology*, vol. 1, ed. N. Warren. San Francisco: Academic Press.

Shepard, R. N. 1962a. The analysis of proximities: Multidimensional scaling with an unknown distance function. I. *Psychometrika* 27:125–40.
Shepard, R. N. 1962b. The analysis of proximities: Multidimensional scaling with an unknown distance function. II. *Psychometrika* 27:219–46.
Shepard, R. N. 1972. Psychological representation of speech sounds. In *Human Communication: A Unified View*, eds. E. E. David and P. B. Denes. New York: McGraw Hill.
Stevens, K. N. 1989. On the quantal nature of speech. *Journal of Phonetics* 17:3–45.
Strange, W., and Jenkins, J. J. 1978. Role of linguistic experience in the perception of speech. In *Perception and Experience*, eds. R. D. Walk and H. L. Pick Jr. New York: Plenum.
Streeter, L. A. 1976. Language perception of 2-month-old infants shows effects of both innate mechanisms and experience. *Nature* 259:39–41.
Sussman, J. E., and Lauckner-Morano, V. J. 1995. Further tests of the "perceptual magnet effect" in the perception of [i]: Identification and change/no-change discrimination. *Journal of the Acoustical Society of America* 97:539–52.
Swoboda, P. J., Kass, J., Morse, P. A., and Leavitt, L. A. 1978. Memory factors in vowel discrimination of normal and at-risk infants. *Child Development* 49:332–39.
Terbeek, D. 1977. A cross-language multi-dimensional scaling of vowel perception 37:1–271.
Trubetzkoy, N. S. 1939/1969. *Principles of Phonology*. Originally published in German (Grundzüge der Phonologie) as *Travaux du cercle linguistique de Prague 7*. C. A. M. Baltaxe, Translator. Berkeley: University of California.
Volaitis, L. E., and Miller, J. L. 1992. Phonetic prototypes: Influence of place of articulation and speaking rate on the internal structure of voicing categories. *Journal of the Acoustical Society of America* 92:723–35.
Walton, G. E., and Bower, T. G. R. 1993. Newborns form "prototypes" in less than 1 minute. *Psychological Science* 4:203–205.
Werker, J. F., and Polka, L. 1993. The ontogeny and developmental significance of language-specific phonetic perception. In *Developmental Neurocognition: Speech and Face Processing in the First Year of Life*, eds. B. de Boysson-Bardies, S. de Schonen, P. Jusczyk, P. MacNeilage, and J. Morton. The Netherlands: Kluwer Academic Publishers B.V.
Yamada, R. A., and Tohkura, Y. 1992. The effects of experimental variables on the perception of American English /r/ and /l/ by Japanese listeners. *Perception & Psychophysics* 52:376–92.

Chapter • 5

Age-Related Changes in Cross-Language Speech Perception *Standing at the Crossroads*

Janet F. Werker

One of the characteristics of scientific progress is the movement between what appears to be a consistent story and the emergence of new data that demand alternative explanations. It is my sense that we are currently at such a crossroads in our understanding of the meaning of experiential influences on infant speech perception. In this chapter, I develop this thesis. I first present a very brief summary of previous research on cross-language phonetic perception in infancy, in particular, our finding of language-specific influence on phonetic discrimination evident by 10–12 months of age. I then briefly outline some of the early interpretations given to this work, present some of the reasons those early interpretations were dismissed, and briefly outline a more recent descriptive framework we proposed. Finally, I review some newer evidence that again presents a challenge to the models that have been offered and attempt to point the reader in the direction where I think a new synthesis can be found.

EARLY RESEARCH IN CROSS-LANGUAGE SPEECH PERCEPTION

When I first became interested in the area of cross-language speech perception, there was a suggestion in the literature (which had not yet been adequately tested) that although adults sometimes have difficulty discriminating non-native phonetic contrasts, infants can discriminate native and non-native contrasts with equal ease (for a review of the early work see Strange and Jenkins 1978). Richard Tees and I conducted a number of studies to test the validity of this conclusion, and if it

This book was manufactured in the United States of America.

Typography by The Type Shoppe, Inc.
Printing and binding by BookCrafters.
Cover design by Joseph Dieter, Jr.
Book design by Sheila Stoneham.

Library of Congress Cataloging-in-Publication Data

Speech perception and linguistic experience : issues in cross-language research / edited by Winifred Strange.
p. cm.
Experiences of participants in a conference entitled "Workshop on Cross-Language Speech Perception", held at the University of South Florida in 1992.
Includes bibliographical references and index.
ISBN 0-912752-36-X
1. Speech perception—Congresses. 2. Second language acquisition—Congresses. 3. Psycholinguistics—Methodology—Congresses. I. Strange, Winifred. II. Workshop on Cross-Language Speech Perception (1992 : University of South Florida)
P37.5.S68S68 1995 95-43317
401'.93—dc20 CIP

YORK PRESS BALTIMORE

CONTENTS