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Early Speech Perception and Later Language Development: Implications for the "Critical Period"

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In this article, we present a summary of recent research linking speech perception in infancy to later language development, as well as a new empirical study examining that linkage. Infant phonetic discrimination is initially language universal, but a decline in phonetic discrimination occurs for nonnative phonemes by the end of the 1st year. Exploiting this transition in phonetic perception between 6 and 12 months of age, we tested the hypothesis that the decline in nonnative phonetic discrimination is associated with native-language phonetic learning. Using a standard behavioral measure of speech discrimination in infants at 7.5 months and measures of their language abilities at 14, 18, 24, and 30 months, we show (a) a negative correlation between infants' early native and nonnative phonetic discrimination skills and (b) that native- and nonnative-phonetic discrimination skills at 7.5 months differentially predict future language ability. Better native-language discrimination at 7.5 months predicts accelerated later language abilities, whereas better nonnative-language discrimination at 7.5 months predicts reduced later language abilities. The discussion focuses on (a) the theoretical connection between speech perception and language development and (b) the implications of these findings for the putative "critical period" for phonetic learning.

Work in my laboratory has recently been focused on two fundamental questions and their theoretical intersect. The first is the role that infant speech perception plays in the acquisition of language. The second is whether early speech perception can reveal the mechanism underlying the putative "critical period" in language acquisition.

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A theoretical position that links the two has been offered for debate and discussion (Kuhl, 2002, 2004). The proposed theory, Native Language Magnet, argues that early phonetic learning alters perception and changes future learning abilities. The underlying mechanism is “neural commitment” to the acoustic properties of native language phonetic units, a process that has bidirectional effects. Native language neural commitment (NLNC) enhances native-language learning while not supporting alternate phonetic patterns. NLNC may provide a clue to the mechanisms underlying a “critical period” at the phonetic level for language.

The goal of this article is twofold: (a) to discuss these issues and the NLNC hypothesis in the context of broader work in neurobiology on animal learning in vision and learning of species-typical communication systems and (b) to present new empirical data that support the NLNC hypothesis for human speech learning.

LINKING SPEECH TO LANGUAGE

Researchers focused on speech perception and language acquisition have traditionally worked in parallel, aware of their counterparts’ data and theorizing, but not linking the two. New data have begun to explain how infants’ early phonetic discrimination skills could affect the young child’s ability to acquire words, morphology, and syntax. The data suggest that infants’ abilities to discriminate the fine-grained acoustic events that underlie speech, shown early in development, play an important role in language acquisition.

An Association Between Early Speech Perception and Later Language

Only recently have prospective studies measured speech perception in typically developing infants and related this initial ability to future language skills. Tsao, Liu, and Kuhl (2004) tested 6-month-old infants’ performance on a standard measure of speech perception—the head-turn conditioning procedure—using a simple vowel contrast (the vowels in *tea* and *two*) and revealed a strong pattern of correlation between early speech perception skills and later language abilities. They tested the same infants’ language skills using the MacArthur-Bates Development Communicative Inventory (CDI; Fenson et al., 1993) at 13, 16, and 24 months of age and reported significant correlations between individual infants’ speech perception skills at 6 months and their language abilities—word understanding, word production, and phrase understanding—at 13, 16, and 24 months of age. The findings demonstrated, for the first time, that a standard measure of native-language speech perception at 6 months of age—the ability to discriminate two vowels as measured by the head-turn conditioning task—prospectively predicted language outcomes in typically developing infants at three ages over the next 18 months. Parental socioeconomic variables (education, profession, and income level) for both the mother and the father were measured and shown to be unrelated to either the infants' early speech perception skills or their later language abilities (Tsao et al., 2004). This is the first published study relating speech perception in infancy to later language acquisition in children under the age of 3.

Tsao et al. (2004) raised two alternative accounts for the association they observed between native-language speech perception and later language—infants' purely auditory abilities and their purely cognitive abilities. In the present experiment, we examine infants' native phonetic abilities, as well as their nonnative phonetic abilities, at 7.5 months of age and show that both native and nonnative phonetic perception predict future language, but in the opposite direction. These data allow us to address these alternative explanations.

Additional studies, retrospective in nature, suggest a connection between early speech and later language. Molfese and his colleagues showed, in children between the ages of 3 and 8, that classification into high- versus low-functioning language groups could be predicted by their event-related potential responses to speech syllables as newborns (Molfese, 2000; Molfese & Molfese, 1985, 1997). The authors' discriminant function analysis of the children's brain waves as newborns predicted their classification with about 80% accuracy into normal- and low-language performance groups, based on standardized tests.

Finally, indirect evidence provides support for the hypothesis that speech perception skill is related to language. Evidence can be adduced from the phonetic abilities of children diagnosed with reading disorders, learning disabilities, or language impairment in the form of specific language impairment (SLI). Children with learning disabilities or reading disabilities typically show deficits in speech perception. Children with reading disabilities were poorer than age-matched controls on the discrimination of consonants (Reed, 1989). Performance differences between children with dyslexia and controls were reported for tests of categorical perception with consonant sounds in several studies (Godfrey, Syrdal-Lasky, Millay, & Knox, 1981; Manis et al., 1997; Reed, 1989; Werker & Tees, 1987). Similar findings, using both brain and behavioral measures, have been reported for children with various forms of learning disabilities (Bradlow et al., 1999; Kraus et al., 1996).

Links between deficiencies in speech perception and poor language skills are particularly strong in school-age children with SLI (Leonard, McGregor, & Allen, 1992; Stark & Heinz, 1996; Sussman, 1993; Tallal & Piercy, 1974). Children with SLI perform significantly poorer than age-matched controls in the perception of consonantal acoustic cues such as formant transition, voice onset time, and frication noise (Leonard et al., 1992; Tallal & Piercy, 1974; Tallal & Stark, 1981).

To summarize, initial prospective longitudinal studies, in which typically developing children have been tested at 6 months and then followed until their 2nd year, indicate an association between early speech perception and later language (Tsao et al., 2004). Moreover, retrospective studies show that measures taken at birth can be used to sort children between 3 and 8 years of age with regard to normal versus low language skills (Molfese, 2000). Finally, as reviewed, when children with a variety of impairments that involve language are compared to age-matched controls, measures of speech perception show that children with language-related difficulties also have significant deficits in speech perception.

Linking Early Phonetic Learning to a "Critical Period" for Language

A second goal of the research reported here is to relate studies of infant speech perception, particularly our results, to the putative "critical period" for language acquisition. Knudsen (1999) distinguished a "sensitive" from a "critical" period, arguing that during a sensitive period, neuronal connections are particularly susceptible to environmental input, but later experience continues to influence neural development. In contrast, during a critical period, appropriate experience must occur to produce the neural connections necessary for normal function, and the resulting patterns are irreversible. During a critical period, the neural system "awaits specific instructional information … to continue to develop normally" (Knudsen, 1999, p. 637). Thus, in both sensitive and critical periods, young members of the species are highly responsive to experience, but sensitive periods are ones in which later experience can also affect the organism, whereas during critical periods, experience is required for learning to occur and learning produces durable effects (Knudsen, 2004; Linkenhoker & Knudsen, 2005). Although phonetic learning can be affected by experience past childhood, phonetic learning exhibits the two principles cited by Knudsen for a critical period: A lack of exposure early in development to natural language, speech, or sign results in the lack of normal language (e.g., Fromkin, Krashen, Curtiss, Rigler, & Rigler, 1974; Mayberry & Lock, 2003), and early experience with a particular language has indelible effects on speech perception (e.g., Flege, Yeni-Komshian, & Liu, 1999). Phonetic perception might therefore be thought of as exhibiting a critical period in development.

In many species, the young are particularly sensitive to environmental input at certain periods during development. The barn owl's ability to localize prey is calibrated by auditory-visual input during an early sensitive period in development; wearing prisms (or ear plugs) alters the mapping during this period (Knudsen, 2002). Binocular fusion is dependant on binocular visual input during a critical period early in development; rearing cats with one occluded eye irreversibly alters binocular representation in the visual centers of the cortex (Hubel & Wiesel, 1977; Shatz & Stryker, 1978). In songbirds, learning the species-typical song depends on experience during a critical temporal window; presentation of conspecific song during that time is essential for normal development (Konishi, 1985; Marler, 1970). Recent data and theorizing on the nature of "critical" periods—especially the factors that "open" and "close" them—are relevant to interpreting the phonetic perception data of this study. We argue that infants' abilities to discriminate native versus nonnative phonetic contrasts provide clues to the mechanism underlying a critical period for phonetic learning.

Regarding language, Lenneberg's (1967) influential Critical Period Hypothesis argued that there are maturational constraints on learning for primary language acquisition. Lenneberg hypothesized that first language acquisition relied on the plasticity of both hemispheres and that hemispheric specialization was complete at puberty. If language acquisition had not occurred by the time a child reached puberty, full mastery would never be attained. Evidence that these maturational effects include sign language was provided by Newport and Supalla (1987), who demonstrated a linear decline in performance with age of acquisition on aspects of American Sign Language in first language learners. Further work shows that deaf children born to hearing parents whose first exposure to sign language occurs after the age of 6 show a life-long attenuation in ability to learn language (Mayberry & Lock, 2003).

Lenneberg's maturational constraints proposal was adopted by researchers in second language acquisition to explain differences in the ultimate attainment of grammar in early, as opposed to late, bilinguals (Fathman, 1975; Johnson & Newport, 1989; Krashen, 1973; Long, 1990; Newport, 1990). Numerous studies have since demonstrated that late bilinguals with many years of experience with a second language typically do not acquire subtle aspects of grammar at the level reached by early bilinguals, even when the numbers of years of experience is controlled (Birdsong, 1992; Johnson & Newport, 1989; White & Genesee, 1996). Adults who learn their second language after puberty are more likely to make, and less likely to detect, grammatical errors than are those who learned the second language during childhood, even when the length of time speaking the second language is controlled (e.g., Coppieters, 1987; Johnson & Newport, 1989, 1991; but see also Birdsong, 1992; Flege et al., 1999, for a different finding).

Recent studies using neuroimaging techniques have also provided evidence for maturational constraints on language acquisition. Using functional magnetic resonance imaging, Kim, Relkin, Lee, and Hirsch (1997) demonstrated that separate but adjacent tissue in areas of the brain typically associated with grammatical processing (Broca's area) was activated for each language in late bilinguals, whereas overlapping areas were activated in early bilinguals. Other fMRI studies show the effects of amount of exposure (for reviews, see Abutalebi, Cappa, & Perani, 2001; Grosjean et al., 2003). For example, Perani and colleagues (2003) found that adults who acquired their second language early in childhood and had comparable levels of proficiency in the two languages, showed differences in brain activation for word production that was affected by both age of acquisition and levels of language exposure. Using event-related potentials (ERPs), Neville and colleagues have shown that longer latencies or durations of semantic ERP effects are noted for later versus early acquired second languages across individuals (Neville et al., 1997; Neville, Mills, & Lawson, 1992; Weber-Fox & Neville, 1996). In the syntactic domain, ERP effects typically elicited by syntactically anomalous sentences and closed- versus open-class words have been absent or attenuated for second languages acquired after infancy (Neville et al., 1997; Neville et al., 1992; Weber-Fox & Neville, 1996, 2001).

Phonology is known to be highly sensitive to age of second language aquisition effects (for review, see Bongaerts, Planken, & Schils, 1995). Flege et al. (1999) demonstrated that phonology is even more sensitive to age of acquisition effects than grammar. In a study of 240 native Korean-speaking learners of English, degree of foreign accent was positively correlated with age of arrival after variables confounded with age of arrival were controlled, whereas performance on a grammaticality judgment test was not.

Investigations in our laboratory have focused on the phonetic level and a potential explanation for the effects of age of acquisition on second-language phonetic learning. This view emphasizes learning rather than straightforward maturational constraints that govern a definitive "closing" of a "window of opportunity" (see also Elman et al., 1996). According to the NLNC hypothesis, native-language learning produces dedicated neural networks that code the patterns of native-language speech. NLNC affects learning bidirectionally. Early in development, learners commit the brain's neural networks to patterns that reflect natural language input. Initial coding of native-language patterns eventually interferes with the learning of new patterns (such as those of a new language), because they do not conform to the established "mental filter." Early learning thus promotes future learning that conforms to and builds on the patterns already learned but limits future learning of patterns that do not conform to the ones already learned.

Evidence for the effects of NLNC in adults come from measures of neural efficiency obtained using Magnetoencephalography: When processing foreign-language speech sounds, the adult brain is activated for longer and over a larger area than when processing native-language sounds (Zhang, Kuhl, Imada, Kotani, & Tohkura, in press). The neural inefficiency observed in brain measures of foreign-language speech processing can be traced to the fact that listeners use native-language listening strategies when processing foreign speech, strategies that do not allow accurate phonetic categorization of the foreign language (e.g., Iverson et al., 2003). Training with appropriate phonetic materials improves behavioral performance and increases neural efficiency, though not to the levels shown by native speakers (McClelland, Fiez, & McCandliss, 2002; Pisoni, Aslin, Perey, & Hennessy, 1994; Zhang et al., in press).

MOTIVATION FOR THIS STUDY

As reviewed, previous studies relating speech to language, either prospective (Tsao et al., 2004) or retrospective (Molfese, 2000), examine the relation between early speech perception and language using native-language phonetic contrasts. This study differs from previous work by testing infants' native and nonnative phonetic abilities and examining how performance on each predicts future language.

NLNC makes a specific prediction regarding how nonnative perception relates to future language abilities. It predicts that language acquisition depends on native-language phonetic learning and that the degree to which infants remain able to detect nonnative phonetic contrasts reflects the degree to which the brain remains open or uncommitted to native-language speech patterns. Moreover, because early native-language speech perception is required for later language learning, the degree to which an infant remains good at discriminating nonnative phonetic contrasts is predicted to correlate negatively with later language learning. NLNC's prediction is straight forward—an open system reflects uncommitted circuitry. Skill at discriminating nonnative-language phonetic units provides an indirect measure of the brain's degree of commitment to native-language patterns. It is a marker of the degree to which native-language phonetic learning has occurred.

The goal of this study was to examine the predictive value of native and nonnative speech perception abilities on later language skills. Using a standard behavioral measure of speech perception, we tested infants at 7.5 months of age—at this age, infants are at the cusp of phonetic learning. The behavioral task used in this study provides a sensitive measure of individual infants' speech perception skill, head turn (HT) conditioning; it has been used in many studies of infant phonetic perception (Kuhl, 1985; Lalonde & Werker, 1995; Polka, Jusczyk, & Rvachew, 1995; Werker, Polka, & Pegg, 1997) and provides an absolute performance measure in individual infants. The MacArthur Communicative Development Inventories (CDIs), well-established measures of language development, were used to measure language outcomes at 14, 18, 24, and 30 months of age (Fenson et al., 2000; Fenson et al., 1994). The major goal of the study was to test the hypothesis that both native and nonnative speech perception ability in infancy is predictive of subsequent language development in the 2nd and 3rd years of life, but differentially so. Native phonetic perception was predicted to show a positive correlation with future language abilities, whereas nonnative phonetic perception was predicted to show a negative correlation with future language. Our hypothesis is driven by the argument that native-language phonetic learning reflects neural commitment and is necessary for language acquisition and that nonnative perception reflects the degree to which the system remains uncommitted.

METHOD

Participants

The participants were 20 full-term infants (10 girls), first tested at 7 months of age (*M* age = 7.34 months, *SD* = 0.16, range = 6.74 to 7.46 months) and followed longitudinally to 30 months of age. Criteria for participants included (a) English as the only language spoken in the home; (b) no known physical, sensory, or mental handicap; (c) gestational age at birth at 40 ± 3 weeks; and (d) birth weight between 6 and 10 lbs.

Stimuli

Infants were tested on two phonetic contrasts: a native English place contrast (/ta/, /pa/), and a nonnative Mandarin Chinese fricative–affricate contrast at a place of articulation that does not occur in English (/çi/, /tçʰi/). Previous studies have indicated that Mandarin speakers attend to different cues than English speakers who do not speak Mandarin when processing this contrast (Tsao, 2001). The American English stimuli were synthesized using Delta speech-synthesis software (Eloquent Technology, Inc., Ithaca, NY). Sounds were created based on characteristic formant transitions, which are distinct frequency regions of high acoustic energy caused by differences in vocal tract configuration. The syllables differed in the second through fourth transitions (F2, F3, and F4) from the consonant onset; both syllables had a first formant (F1) of 350 Hz at the consonant release. Beginning F2, F3, and F4 values for /pa/ were 850, 2400, and 3150 Hz, respectively; values for /ta/ were 2300, 3550, and 4500 Hz, respectively. Thus, the formant transitions for F2, F3, and F4 for /pa/ were rising toward the vowel, and these formants were falling toward the vowel for /ta/. Total syllable duration was 300 msec; steady state vowel formant frequencies were 710, 1200, 2545, and 3290 Hz, respectively; bandwidths were 110, 80, 175, and 360 Hz, respectively; and pitch contours were identical, with a fundamental frequency of 135 Hz at the beginning of the vowel and tapering down to 95 Hz. The tokens were correctly identified and judged to be good exemplars of the intended consonants by native American English speaking adults.

The Mandarin Chinese stimuli were synthesized using HLsyn speech-synthesis software (Sensimetrics Corp., Somerville, MA). They were matched on all acoustic parameters except for the amplitude rise time during the initial 130 msec frication portion, which is the critical parameter for distinguishing affricate and fricative consonants by Mandarin Chinese listeners (Tsao, 2001). The amplitude rose 3 dB sound pressure level (SPL) over the first 30 msec for /tçʰi/ and over the first 100 msec for /çi/. Total syllable duration for each syllable was 375 msec; steady-state vowel formant frequencies were 293, 2274, 3186, and 3755 Hz, respectively; bandwidth was 80, 90, 150, and 350 Hz, respectively; and fundamental frequency was 120 Hz (high-flat tone, Tone 1 in Mandarin). All stimuli were equalized in root mean square (RMS) amplitude and played to infants at a comfortable listening level of 68 dBA.

Phonetic Perception Tests at 7.5 Months

Infants were tested using the HT conditioning procedure (Kuhl, 1985; Polka et al., 1995; Werker et al., 1997). Order of testing of the native contrast (/ta/ background, /pa/ target) and the nonnative contrast (/çi/ background, /tçʰi/ target) was counterbalanced across participants. Participants sat on their parent's lap during testing. An assistant, seated to the right, manipulated silent toys to attract the infant's attention. Infants were trained to turn away from the assistant and toward a loudspeaker on their left when they detected a change from the repeating background sound to the target sound. An experimenter observed the infants on a video monitor in a control room during testing and judged HT responses. Correct HT responses were reinforced with a 5-sec presentation of a mechanical toy (e.g., bear tapping on a drum). Several measures were taken to control bias: (a) All contingencies and trial selection were under computer control; (b) the parent and assistant wore headphones and listened to music that masked the speech sounds and prevented them from influencing the infants’ responses; and (c) the experimenter’s headphones, which allowed monitoring of the experimental room, were deactivated during trials so that the experimenter could not hear the stimuli during the trial. These controls effectively protect against bias.

The HT procedure consists of two phases: conditioning and test. In the conditioning phase, all trials were change trials, allowing the infant to learn the association between target sound and visual reinforcement. During initial conditioning, the target sound was presented at a louder level (+4 dB) than the background sound to draw the infant’s attention to the stimulus change. Following two consecutive correct HT responses to the target sound in anticipation of the visual reinforcer, the intensity cue was removed. When infants produced three additional consecutive correct HT responses to the target syllable, the conditioning phase was complete and the test phase began. Infants were required to meet the conditioning criteria within 60 trials for inclusion in the study. Typical infants required 4 days to complete the tests on both contrasts, which were scheduled within a week’s time.

In the test phase, change (sound change) and control (no sound change) trials occurred with equal probability, and consecutive trials of one type were restricted to 3. During change trials, the background sound changed to the target sound for three repetitions and HT responses during this period were reinforced with a 5-sec presentation of a mechanical toy. During control trials, the background sound was unchanged and infants’ HT responses were recorded. The test phase continued until 30 trials were complete. For change trials, HTs were scored as “hits” and failure to turn as “misses”; for control trials, HTs were scored as “false alarms” and failure to turn as “correct rejections.” Using signal-detection analysis methods, the data were used to calculate a percentage correct measure [= (%hit + %correct rejection)/2] and a sensitivity index, d' [= z (hit) – z (false alarm)].

Language Abilities at 14, 18, 24, and 30 Months

Language abilities were assessed with the MacArthur-Bates CDI, a reliable and valid parent survey for assessing language and communication development from 8 to 30 months (Fenson et al., 1993). Two forms of the CDI — Infant and Toddler—were used in this study. The Infant form (CDI: Words and Gestures) assesses vocabulary comprehension, vocabulary production, and gesture production in children from 8 to 16 months. The vocabulary production section was used in this study. The Toddler form (CDI: Words and Sentences) is designed to measure language production in children from 16 to 30 months of age. This form divides language production into two parts. Part 1 contains a 680-word vocabulary production checklist. Part 2 includes five sections designed to assess morphological and syntactic development. Three of these sections were used in this study: vocabulary production, sentence complexity, and mean length of the longest three utterances.

One week before children reached a target age, the appropriate MacArthur-Bates CDI form was sent to parents. Parents were instructed to complete the CDI on the day their child reached the target age and return the form. Parents received $10 for each completed CDI.

RESULTS

Phonetic perception HT data were obtained for both the native and nonnative contrast for 16 participants; 18 participants completed the test phase for the native contrast only and 17 participants for the nonnative contrast only (1 participant failed to condition to either contrast, and 1 participant experienced an equipment problem during the test phase for the nonnative contrast). Completed CDI forms were received from all participants for at least one age: 18 (9 girls) participants at 14 months, 19 (9 girls) participants at 18 months, 19 (9 girls) participants at 24 months, and 15 (6 girls) participants at 30 months.

The first goal was to examine the relation between native and nonnative speech perception skill in 7.5-month-old infants. As predicted, a significant negative correlation was obtained between *d* prime for the native and nonnative contrasts ($r = -.481$, $p = .030$, $n = 16$): Infants with higher *d*-prime scores for the English native contrast tended to have lower *d*-prime scores for the Mandarin Chinese nonnative contrast (see Figure 1).

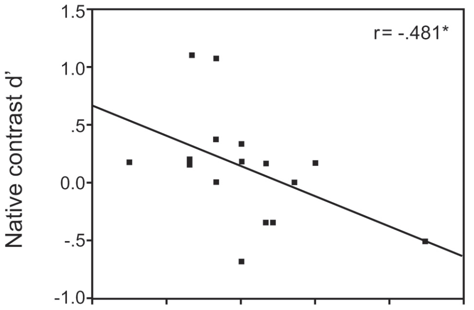

FIGURE 1 Scatterplot showing the relation between native and nonnative phonetic perception measured behaviorally at 7.5 months of age. As shown, a significant negative correlation was obtained.

The second goal was to determine whether either native or nonnative phonetic perception predicts future language ability and, if so, to explore the nature of the relation. As hypothesized, the results showed that both native and nonnative *d*-prime measures of speech discrimination at 7.5 months predict later language, but differentially. Percentage correct scores produced the same pattern of results. Early native-language phonetic discrimination was positively correlated with word production at 18 months ($r = .503$, $p = .020$, $n = 17$), sentence complexity at 24 months ($r = .423$, $p = .046$, $n = 17$), and mean length of the longest three utterances at 24 months ($r = .492$, $p = .023$, $n = 17$; see Figure 2, left scatterplots). In contrast, early nonnative-language phonetic discrimination was negatively correlated with word production at 18 months ($r = –.507$, $p = .023$, $n = 16$), word production at 24 months ($r = –.532$, $p = .017$, $n = 16$), and sentence complexity at 24 months ($r = –.699$, $p = .001$, $n = 16$; Figure 2, right scatterplots).

One of the language measures, number of words produced, was available for all four CDI test ages, allowing examination of the growth patterns in number of words produced over time and comparison of growth patterns based on a median split of the participants tested. The differential relation between native and nonnative phonetic discrimination and vocabulary growth can be seen by comparing vocabulary growth in infants whose *d*-prime scores are at or above the median with vocabulary growth in infants whose *d*-prime scores are below the median. The growth curves demonstrate that perception of native (see Figure 3a) and nonnative phonetic contrasts (see Figure 3b) at 7.5 months of age differentially affects the pattern of later vocabulary growth. Infants with *d*-prime values for the native-language contrast at or above the median showed faster vocabulary growth than infants with *d*-prime values below the median. The pattern is reversed for the nonnative contrast: Infants with *d* primes at or above the median for nonnative sounds showed slower growth in the number of words produced. The pattern is particularly pronounced for the nonnative contrast.

Differences between groups were most pronounced at 18 and 24 months of age. As shown in Figure 4a, participants with higher *d*-prime values above the median for the native-language contrast produced more words at 18 and 24 months than participants with *d*-prime values below the median. The group difference approached significance at 18 months, $t(15) = –2.045$, $p = .059$, but is not significant at 24 months, $t(15) = –.411$, $p = .687$). In contrast, participants with *d*-prime values above the median for the nonnative-language contrast produced fewer words at 18 and 24 months than participants with *d*-prime values below the median (see Figure 4b). The group effect was not significant at 18 months, $t(14) = 1.494$, $p = .157$, but was significant at 24 months, $t(14) = 2.858$, $p = .013$. Repeated measures analysis of variance revealed the expected significant age effect for number of words produced, $F(1, 13)= 76.653$, $p = .000$. In addition, the group effect was significant for the nonnative contrast, $F(1, 13) = 5.046$, $p = .043$, and the group by age interaction approached significance, $F(1, 13) = 4.600$, $p = .051$.

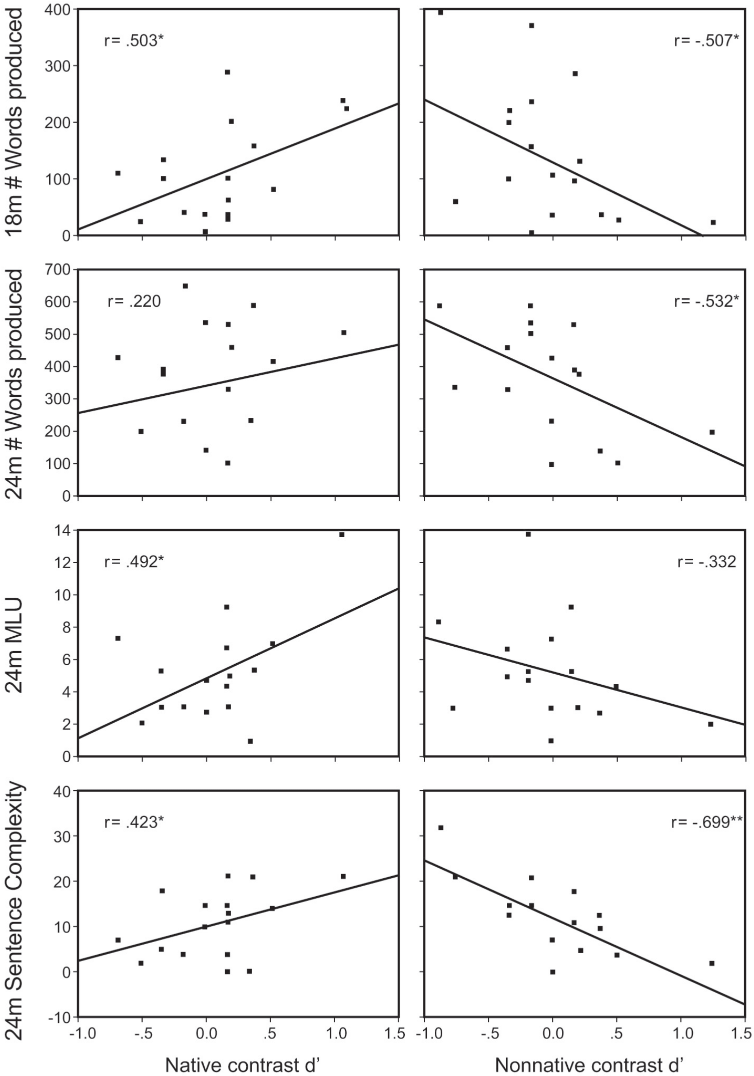

FIGURE 2 Scatterplots showing the relation between native (left) and nonnative (right) phonetic perception at 7.5 months and language measures taken in the 2nd and 3rd year of life.

The median-split data (see Figures 3 and 4) indicate that after 24 months the effects dissipate. This is not surprising, given the fact that the infant participants in the study are all typically developing infants who are expected to achieve normal language skills.

These results document a dissociation between speech discrimination ability for native versus nonnative contrasts and differential predictions for native ver-

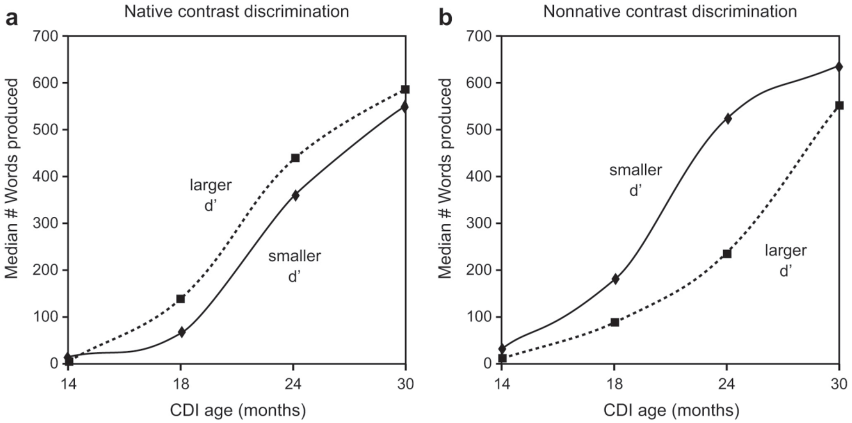

FIGURE 3 Vocabulary growth curves (median number of words produced) for participants with phonetic discrimination at or above versus below the median for the native-language contrast (a) and the nonnative-language contrast (b).

sus nonnative speech perception and later language. Kuhl et al. (submitted) reported similar relations when the Mismatch Negativity (MMN), a negative-going ERP effect elicited in auditory oddball paradigms in both infants and adults (Cheour-Luhtanen et al., 1996), was used to assess native and nonnative perception at 7.5 months. As with the behavioral results reported here, MMNs for native and nonnative contrasts were negatively correlated ($r = -.631$, $p = .002$, $n = 21$), and neural discrimination of native and nonnative contrasts differentially predicted later productive language scores. The participants in this experiment

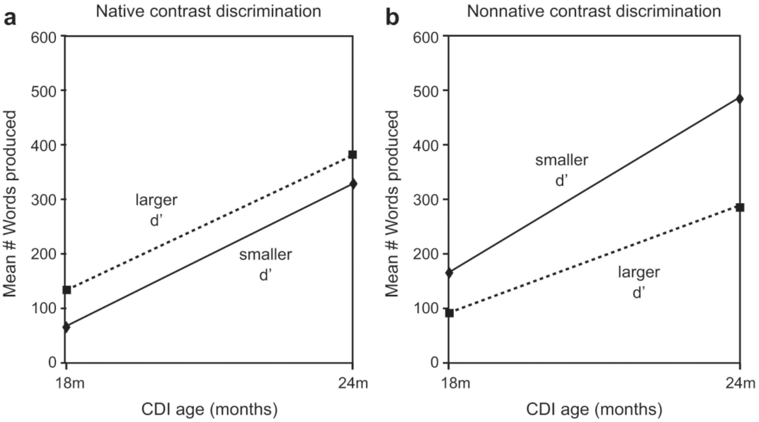

FIGURE 4 Vocabulary growth (mean number of words produced) between 18 and 24 months for participants with phonetic discrimination at or above versus below the median for the native-language contrast (a) and the nonnative-language contrast (b).

are a subset of those studied by Kuhl et al., allowing examination of the relation between behavioral discrimination (*d* prime) and MMN for the same native and nonnative contrasts in the same infants (see Figure 5).

Examining first the correlation between the native contrast measured behaviorally and neurally, the data reveal the expected relation between behavioral (*d*-prime) measures of discrimination and MMNs observed independently in the same infants. Infants with good behavioral discrimination of the phonetic contrast, as evidenced by higher *d*-prime values, showed greater discrimination of the same contrast, as evidenced by more negative MMNs. This produced the expected negative correlation, which was significant, $r = -.445$, $p = .042$, $n = 16$ (see Figure 5a). When behavioral performance on the native contrast was related to neural discrimination of the nonnative contrast, the expected correlation was positive—better behavioral discrimination of the native contrast should correlate with poorer neural discrimination. The results conformed to this prediction (see Figure 5b). Infants with good behavioral discrimination of the native contrast (high *d*-prime values) showed less discrimination of the nonnative contrast as evidenced by less negative MMNs, $r = .513$, $p = .030$, $n = 14$. Similarly, examining the nonnative contrast, good behavioral discrimination of the nonnative contrast was correlated with poor discrimination of the native contrast (see Figure 5c), producing a positive correlation, $r = .568$, $p =$

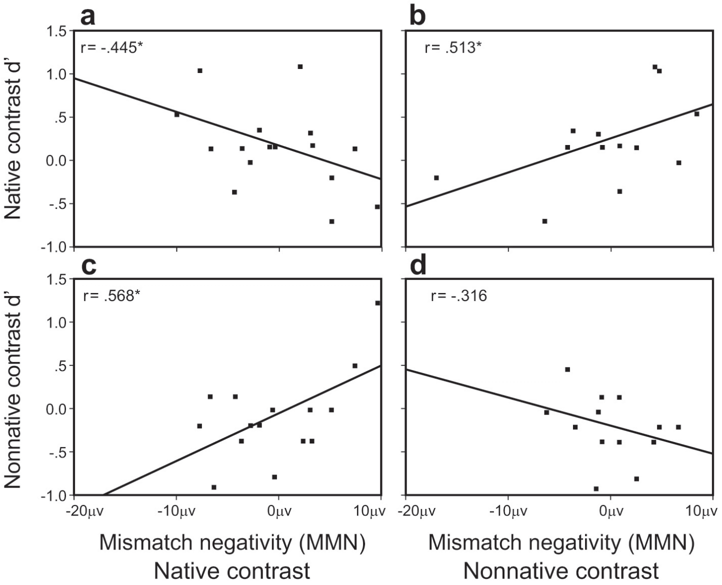

FIGURE 5 Scatterplots showing the relation between behavioral discrimination (*d* prime) and measures of neural discrimination of native and nonnative contrasts. The correlations are complementary, negative within the native or nonnative contrast, and positive across native and nonnative contrasts.

.014, $n = 15$. Finally, when neural discrimination of the nonnative contrast was correlated with behavioral discrimination of the nonnative, the pattern of response was in the appropriate direction, though it was not significant, $r = -.316$, $p = .147$, $n = 13$, perhaps due to the smaller N in this condition (see Figure 5d).

DISCUSSION

This study tested the hypothesis that infants’ performance on native and nonnative phonetic discrimination tasks would each significantly predict children’s language abilities 2 years later. Moreover, we tested the hypothesis that native and nonnative speech perception would predict language development differentially—we hypothesized that better native phonetic abilities would predict greater advancement in language, whereas better nonnative phonetic abilities would predict less advancement. The basis of our predictions was the NLNC hypothesis, which argues that early native-language phonetic skill is necessary for language acquisition and that the degree to which infants remain good at nonnative phonetic perception indirectly reflects uncommitted circuitry. As learning ensues, alternative phonetic mapping schemes, such as those appropriate for other languages, are suppressed because they do not conform to the native-language pattern.

The results provide strong support for our hypotheses. Our findings show that at 7.5 months of age, a time in development when phonetic learning from ambient language exposure begins to be noted, infants’ native and nonnative phonetic perception skills are negatively correlated with one another. The better an individual infant is on native-language phonetic perception, the worse his or her performance on nonnative phonetic perception. Moreover, our results show that the trajectory of language development from 7.5 months to 30 months depends on infants’ native versus nonnative abilities. A 7.5-month-old infant’s skill at native-language phonetic perception is a strong positive predictor of that child’s speed of advancement in language acquisition, whereas a 7.5-month-old infant’s skill at nonnative-language phonetic perception is an equally strong predictor of slower language growth. Infants’ early phonetic perception predicted language at many levels—the number of words produced, the degree of sentence complexity, and the mean length of utterance were all predicted by infants’ early phonetic abilities. These results are buttressed by additional studies from our laboratory showing the same pattern of prediction for a variety of native and nonnative contrasts and tests involving both brain (Kuhl et al., 2005; Rivera-Gaxiola, Klarman, Garcia-Sierra, & Kuhl, 2005) and behavioral (Conboy, Rivera-Gaxiola, Klarman, Aksoylu, & Kuhl, 2005) measures. In all cases, native phonetic perception predicts the rapidity of language development, whereas nonnative phonetic perception predicts the reverse.

NLNC asserts that the native and nonnative results are attributable to a common cause—phonetic learning, which commits neural tissue to the acoustic patterns represented in native-language phonetic units. Our data suggest that for language acquisition to ensue, the state of equipotentiality that characterizes all infants initially (their “citizen of the world” status as phonetic listeners at birth) must give way to NLNC. NLNC has two consequences—it reinforces native-language phonetic listening, which furthers language development (see the following sections and Figure 6) and reduces the capacity to respond to nonnative contrasts and subsequent learning based on nonnative contrasts. As native-language phonetic learning occurs, and neural networks become committed to the experienced acoustic properties, patterns that do not conform to those learned (such as those of a nonnative language) are no longer detected with equal accuracy.

The results raise three issues. First, why does early native-language speech perception predict language? Can we explain why the two are related? Second, is it speech perception per se that predicts language acquisition or some other mediating factor? Third, can the negative correlation between native and nonnative speech perception, both at 7.5 months and predictively to 30 months, be helpful in understanding the critical period in language acquisition?

Why Does Speech Perception Predict Language Development?

The results of three experiments from our laboratory now suggest that native-language speech perception predicts future language development. Tsao et al. (2004) provided the first data indicating a connection between speech perception and later language development. Tsao et al. measured native-language phonetic perception using vowel stimuli and showed correlations between infants’ phonetic perception and language development measured at 13, 16, and 24 months of age. Kuhl et al. (2005) confirmed this result for native-language speech perception in infants using

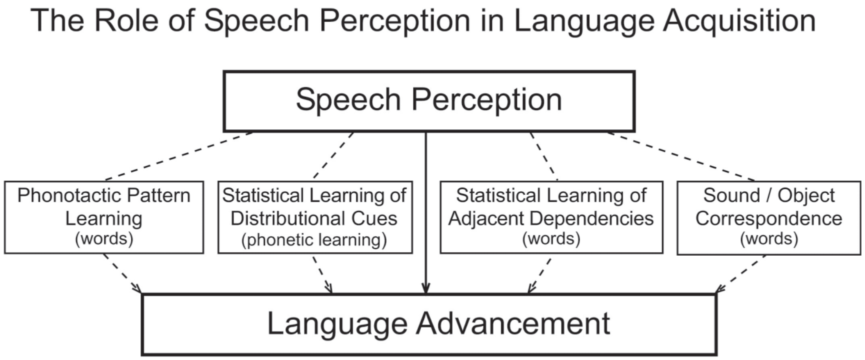

FIGURE 6 Diagram showing the hypothesized links between infant speech perception and language acquisition.

consonants, testing them at 7.5 months of age using a brain measure, the Mismatch Negativity (MMN), an ERP effect elicited in response to a syllable change. These data confirm that early native-language phonetic abilities predict future language using the same behavioral measure used by Tsao et al. and extend the data to show that behavioral and neural measures taken on the same infants are correlated. The results provide strong support for the association between early native-language speech perception and later language. Although these data establish an associative, rather than a causative relation, they are consistent with the idea that speech perception plays an important role in language acquisition. Why should this be the case?

Figure 6 provides a theoretical explanation for the observed associations between speech perception and language acquisition. The diagram indicates four possible factors that are likely to link speech and language. None of these proposed links have been tested experimentally; nonetheless, the theoretical threads can now be described.

First, better speech perception skills could assist infants’ detection of phonotactic patterns, patterns that describe combinations of phonemes that are legal in the child’s native language and that characterize words in that language. Phonotactic patterns assist the identification of words, and between 6 and 9 months of age, infants have been shown to use phonotactic patterns to segment words from running speech (Friederici & Wessels, 1993; Mattys, Jusczyk, Luce, & Morgan, 1999).

Second, studies show that by 6 months of age, infants respond to the distributional properties of sounds contained in the language they hear and that this alters perception to produce more native-like phonetic processing of both vowels (Grieser & Kuhl, 1989; Kuhl, 1991; Kuhl, Williams, Lacerda, Stevens, & Lindblom, 1992) and consonants (Maye, Werker, & Gerken, 2002). Perceiving speech through a native-language lens would assist word recognition. Infants’ sensitivity to the distributional properties of sounds, as shown in these experiments, requires the ability to discriminate phonetic units. Infants whose phonetic discrimination skills are enhanced may therefore show advanced skill at detecting the distributional properties of sounds, which in turn promotes the development of native-language listening.

Third, infants use transitional probabilities between segments and syllables to segment words from running speech (Goodsitt, Morgan, & Kuhl, 1993; Newport & Aslin, 2004; Saffran, Aslin, & Newport, 1996). Recent data suggest that segments may be more critical than syllables in the detection of these adjacent dependencies (Newport, Weiss, Wonnacott, & Aslin, 2004). Resolving differences between phonetic units would thus assist this form of statistical learning. Individual differences in the ability to discriminate phonetic cues could therefore modulate the detection of likely word candidates.

Fourth, to learn words, infants have to associate sound patterns with objects. Werker and her colleagues (Mills et al., 2004; Stager & Werker, 1997; Werker, Fennell, Corcoran, & Stager, 2002) showed that infants’ phonetic abilities are challenged under these conditions. When infants attempt to learn new words using phonetically similar syllable pairs, the task is sufficiently difficult that infants at 14 months of age do not succeed unless the phonetic units being used are very different from one another; they do not fully succeed at the task until 24 months of age (however, see Swingley & Aslin, 2002, for evidence that 14-month-olds can attend to fine phonetic-level detail at the word level in a different type of task). Children thus depend on their abilities to perceive phonetic distinctions to successfully associate a sound pattern with a lexical item. An individual infant with advanced speech perception skills should therefore show advanced word learning skills.

These four links could potentially explain why a relation is observed between early phonetic perception skill and later language ability, but these four factors have not been related to language empirically. Focusing on the connections between speech and language will likely prompt the appropriate experimental tests.

Is It Speech Perception per se That Predicts Language, or Some Other Factor?

As mentioned, Tsao et al. (2004) raised two alternative possibilities that might account for the observed association between speech perception and later language, infants' purely auditory abilities and their purely cognitive abilities. Our data now allow us to rule out these two alternative explanations.

The alternative views argue that it is not infants' phonetic skills per se that explain the observed association between early speech and later language but some other factor. Two in particular, infants' general cognitive skills and infants' general auditory skills, merit consideration. Infants' general cognitive skills could be argued to play a role, especially when speech perception is measured using complex tasks such as HT conditioning as in this study, a task that taps general cognitive abilities (Kuhl, 1985; Polka et al., 1995). HT conditioning requires infants to learn a complex contingency between two independent events, a change in a sound and the presentation of a reward. Infants with higher cognitive skills may therefore perform better in the HT task, independent of their phonetic abilities. Cognitive factors may also play a role in learning the arbitrary pairing of sound patterns and words.

Infants' general auditory capabilities might similarly be argued to explain the observed association between phonetic perception and later language. Group studies suggest that poor auditory perceptual skills, when measured using nonspeech signals, are a significant factor in children who have difficulty with language and reading (Tallal, 1980; Tallal, Stark, & Mellits, 1985). Children with SLI utilize fewer spectral cues to segregate a target tone from a masking noise when compared to normal controls (Wright et al., 1997). In a recent study of 6-month-old infants with and without positive histories of language impairment, auditory temporal resolution thresholds of individual infants for nonspeech stimuli were associated with language comprehension and production scores at the age of 2 (Benasich & Tallal, 2002). These results suggest that infants’ phonetic processing abilities could be influenced by variation in infants’ auditory skills.

The set of results reported here and in other studies in our laboratory (Conboy et al., 2004; Kuhl et al., 2005; Rivera-Gaxiola et al., 2005) effectively rule out both possibilities in explaining the present results because the findings show that the associative relation between speech and language depends on whether one is measuring native-language phonetic perception or nonnative-language phonetic perception. Individual variation in infants’ general auditory or general cognitive abilities should influence native- and nonnative-phonetic perception equally. Therefore, the relation between speech perception and language development cannot be reduced to variations in infants’ auditory or cognitive skills. Moreover, the fact that brain and behavioral measures on the same infants are highly correlated suggests that general cognitive skills—perhaps important in the HT task but not in the preattentive MMN brain measure—could not be responsible for the observed association. This is not to say that infants’ auditory and cognitive skills do not play a role in language development. We agree with the position that multiple attentional, social, and linguistic cues contribute to infants’ word understanding and production in early language development (Hirsh-Pasek & Golinkoff, 1996; Hollich, Hirsh-Pasek, & Golinkoff, 2000). Our data simply show that the associations we have observed between early speech perception and later language development cannot be explained by differences in infants’ basic sensory or cognitive skills. Our working hypothesis is that speech perception skills play a direct role in the acquisition of language.

It is also important to mention that our studies establish an association between environmental language input and infants’ speech perception abilities. Specifically, our studies indicate an association between the clarity of a mother’s speech and her infant’s speech perception skills. Liu, Kuhl, and Tsao (2003) examined the degree of individual mother’s speech clarity using a measure previously shown to provide a valid and reliable index of speech intelligibility, the degree of acoustic “stretching” seen in the mother’s vowel sounds. Mothers’ expansion of the acoustic cues that code phonetic differences is robust across languages in infant-directed speech (Kuhl et al., 1997). This increases the acoustic differences between phonetic units, making them more discriminable in speech. The acoustic stretching has been shown to be unique to language used to address infants, as opposed to language used to address household pets (Burnham, Kitamura, & Vollmer-Conner, 2002). Liu et al. (2003) examined the hypothesis that mothers’ increased clarity during infant-directed speech was associated with infants’ ability to distinguish phonetic differences. The study showed that the degree to which an individual mother stretches the acoustic cues of speech during infant-directed speech is strongly correlated to her infant’s speech perception abilities as measured by the HT technique. Liu et al. reported this result for two independent samples of mother–infant pairs, mothers with 6- to 8-month-old infants and mothers with 10- to 12-month-old infants.

This associative relation between language input to the infant and infants’ speech perception skills provides some support for the idea that “motherese” plays a role in infant speech perception. Other work in our laboratory suggests that mothers expand all phonetically relevant features in infant-directed speech; for example, Mandarin-speaking mothers expand the range of pitches used to convey the four phonemic tones in infant-directed speech (Liu, 2002). NLNC argues that the acoustic stretching of phonetically relevant information in infant-directed speech focuses infants' attention on the appropriate acoustic cues in speech and that this plays an important role in infants' general speech discrimination skills (see also Merzenich et al., 1996; Tallal et al., 1996, for similar speech modifications used to assist children with dyslexia). Although the studies supporting this claim only establish an associative, rather than causative, relation, we argue that infants' increased attention to the critical differences in speech is a viable explanation for a potential causative relation between "motherese" language input and infant phonetic learning, and this could directly affect language acquisition.

Does Early Speech Perception Reveal a Potential Critical Period Mechanism?

We observed a dissociation between native and nonnative speech perception at 7.5 months, and this pattern of dissociation persisted until 30 months, when many aspects of language are still developing. We argue that nonnative phonetic perception provides a measure of the degree to which infants at the earliest stages of phonetic learning have uncommitted neural circuitry. Infants who remain good at nonnative phonetic perception at 7.5 months are still in the equipotential open stage of phonetic perception, in which all phonetic distinctions are discriminated, and this slows advancement toward language.

The data raise a question: Does native-language phonetic learning actively "suppress" nonnative phonetic learning? Suppression suggests an opponent phonological system, and such a view was proposed (Eimas, 1975; see Best & McRoberts, 2003, for a comparison of recent theories). On the other hand, if the underlying neural system simply awaits experience at a particular point in development and commits neurally only to what is experienced, our results would still obtain, and this would not require active suppression. Tests that would allow us to choose between the two alternatives require that we determine whether our effects depend on the similarity between the native and nonnative phonetic contrasts. Is performance on native phonetic contrasts negatively correlated with all nonnative contrasts or only those that are very similar? In this study, a native place of articulation contrast was pitted against a nonnative fricative–affricate contrast at a place of articulation that does not occur in English, and a negative correlation was observed. Further work needs to be done to determine whether this relation holds for native and nonnative contrasts that involve different phonetic features.

Either pattern of results could potentially provide an explanation for the critical period in phonetic learning. Under one alternative, phonetic learning of native-language patterns actively suppresses nonnative learning (because it is an innately specified opponent system); under the other, the neural system awaits phonetic input at a particular point in development and only codes patterns that are experienced—either alternative would make it more difficult to perceive nonnative phonetic categories once learning ensues. English and Japanese phonetic categories, for example, require different perceptual schemes for accurate phonetic sorting—Japanese listeners must learn to combine the /r/ and /l/ categories (Iverson & Kuhl, 1996), which as infants they perceive as distinct (Kuhl et al., 2005). Adult brain (Zhang et al., in press) and behavioral (Iverson et al., 2003) studies suggest that to achieve these different perceptual sorting schemes, listeners attend to different acoustic aspects of the same stimuli; Japanese adults attend to variations in the second formant, whereas American adults attend to variations in the third formant (Iverson et al., 2003). Our working hypothesis is that infant attention is directed to the relevant native-language features of speech by the acoustic stretching contained in infant-directed speech. We also note that one's primary language affects other forms of information, such as the coding of exact mathematical terms, and that this coding affects mathematical processing in bilinguals using their second language (Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999; Spelke & Tsivkin, 2001).

As in all other species, particular events must open and close the critical period during which infants are particularly sensitive to environmental input. A variety of factors suggest that initial phonetic learning is triggered on a maturational timetable, likely between 6 and 12 months of age. It is during this period that infants show the decline in nonnative perception (Best & McRoberts, 2003; Best, McRoberts, LaFleur, & Silver-Isenstadt, 1995; Werker & Tees, 1984). More important, it is at this time that increases in infants' neural responses to native-language speech have been observed (Cheour et al., 1998; Rivera-Gaxiola, Silva-Pereyra, & Kuhl, 2005), and increases in behavioral HT measures of speech perception have been demonstrated (Kuhl et al., 2001; Tsao, 2001). Other evidence can be adduced from the fact that at 9 months, infants readily learn phonetically when exposed to a new language for the first time after only 12 exposure sessions taking place over a month's time (Kuhl, Tsao, & Liu, 2003).

Greenough and Black (1992) proposed that "experience-expectant" processes prepare animals for environmental stimulation that is reliably available. Similarly, we argue that neural preparation for phonetic learning in humans is guided maturationally because evolution has led to the expectancy of reliable environmental stimulation critical to learning. Infants, normally exposed to language from birth (even in utero, see Moon & Fifer, 2000), have a reliable source of language information from which to learn—infant-directed speech—a signal that is phonetically enriched by the acoustic stretching that occurs across languages.

Little is known about the physiological underpinning of "neural readiness" in humans and the subsequent changes brought about by experience, but these processes are well understood in animal species (Knudsen, 2004). The animal data indicate that critical period learning is realized in neural circuits whose architecture is modified by experience. Architectural shifts change the patterns of conductivity among circuits, making them stable and preferred. Regarding language, according to NLNC, exposure to spoken (or signed) language during a critical period enabled by maturation instigates a mapping process during which the brain's circuits are altered, creating networks that become committed to the basic statistical and prosodic features of ambient language. Changes in the pattern of connectivity promote native-language speech perception and enable further learning of native-language patterns. Native language learning commits neural tissue, and alternative schemes—such as those represented by nonnative phonetic distinctions—are not represented in the neural architecture.

If maturation opens the critical period, and learning ensues, what closes the period for phonetic learning? The NLNC view is that learning continues until stability is achieved. It has been argued elsewhere (Kuhl, 2000, 2004) that the closing of the critical period may be a statistical process whereby the underlying networks continue to change until the amount and variability (represented by the distribution of acoustic cues) for a particular category (the formant frequencies of vowels, for example) reach stability. In other words, the networks stay flexible and continue to learn until the number and variability of occurrences of a particular vowel (like the /ah/ in *pot*) have produced a distribution that predicts new instances of the vowel; new instances no longer significantly shift the underlying distribution. This view is consistent with connectionist accounts of critical period effects, such as that put forth by Elman et al. (1996) and others. According to this view, critical period phenomena arise not from a genetically determined change in learning capacity at a particular age, but from entrenchment, which is the direct outcome of learning. Furthermore, this view seems to be consistent with dynamic systems views of development (see Munakata & McClelland, 2003).

We are a long way from understanding how these mathematical principles might be realized physiologically in humans. However, it is clear that in animal species, closure of the critical period is affected by the quality and quantity of relevant input. In the visual system, rearing animals in the dark prolongs the period during which binocular fusion can occur, in effect extending the critical period (Cynader & Mitchell, 1980; Mower & Christen, 1985). In songbirds, the quality of input determines how quickly learning occurs and the length of time before learning declines (Eales, 1987; Petrinovich & Baptista, 1987). NLNC argues that closure of the period of phonetic learning will also be affected by the statistical stability, the quality, and the quantity of linguistic input. Studies that test these hypotheses are now underway in our laboratory.

In summary, we have shown that young infants' native-language phonetic perception predicts future language and that nonnative phonetic perception produces the opposite result—it predicts a slower path toward language acquisition. We interpret these findings as consistent with the NLNC hypothesis. The findings of this study, and those of other studies from our laboratory, suggest that it is speech perception, and not some other mediating factor, that predicts language acquisition. Finally, we speculate that infants' perception of speech will reveal mechanisms of phonetic learning that are opened by a maturational process and closed by experience. Maturation opens the period of learning, and if experience does not occur, the ability to learn from experience may be permanently altered. For example, deaf children born to hearing parents whose first exposure to sign language occurs after the age of 6 show a life-long attenuation in ability to learn language (Mayberry & Locke, 2003); moreover, in children who are socially isolated and not exposed to language, language is never fully learned (Fromkin et al., 1974). If language experience (either speech or sign, see Petitto, Holowka, Sergio, Levy, & Ostry, 2004) occurs as expected, learning ensues, modifying neural circuitry and architecture, and this alters our future ability to learn new phonetic patterns, reducing the ability to learn alternate schemes. Closure of the most sensitive period for learning, we argue, may be a mathematical process, and one that is affected by the quality and quantity of language input.

In summary, a combination of maturation and learning, as observed in other species, is posited to govern the critical period for phonetic learning in human infants. Infants' early abilities to differentiate the sounds of human speech (or sign—the underlying mechanisms are posited to be identical) may not only be the gateway to language but may also provide important insights into the long-standing issue of the critical period for language learning.

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