

INVITED REVIEW

Cracking the speech code: How infants learn language[1]

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1. CRACKING THE SPEECH CODE: EARLY PHONETIC PERCEPTION SHOWS HOW INFANTS LEARN LANGUAGE

The acquisition of language and speech looks deceptively simple. Young children learn to speak rapidly and effortlessly, from babbling at 6 months of age to full sentences by the age of 3, and follow the same developmental path regardless of culture (Fig. 1). Linguists, psychologists, and neuroscientists have struggled to explain *how* children do this, and why it is so regular across cultures. This puzzle, coupled with the failure of artificial intelligence approaches to build a computer that learns language, has produced the idea that speech is a deeply encrypted 'code.' Cracking the speech code is child's play for human infants but an unsolved problem for adult theorists and our machines. Why?

The last decade has witnessed an explosion of information about how infants tackle language learning. The new data help us to understand why computers have not cracked the 'code' and shed light on a long-standing debate on the origins of language in the child. Infants' strategies are surprising and are also unpredicted by the major historical theorists. Children approach language with a set of initial perceptual abilities that are necessary for language acquisition, though not unique to humans. Infants then rapidly learn from exposure to language, in ways that are unique to humans, combining pattern detection and computational abilities (often called statistical learning), with special social skills.

Recent neuropsychological and brain imaging work suggest that language acquisition involves a neural commitment of the brain's circuits. Early in development, the brain's neural networks code the properties of the native language, and these networks eventually make it difficult to learn a new language. The concept of neural commitment is linked to the long-standing issue of a "critical" or "sensitive" period for language acquisition. The idea is that initial coding of native-language patterns eventually interferes with the learning of new patterns (such as those of a foreign language).

1.1. Sorting out the Sounds

The world's languages contain many basic elements — around 600 consonants and 200 vowels [1]. However, each language uses a unique set of approximately 40 distinct elements, called phonemes, which change the meaning of a word (e.g., from *bat* to *pat*). But phonemes are actually groups of non-identical sounds, called phonetic units, which are functionally equivalent in the language. The infant's task is to learn the 40 phonemic categories before trying to acquire words which depend on these elementary units.

Categorical Perception

Infants bring innate skills to the task that assist phonetic learning. *Categorical perception* is the tendency for listeners of a particular language to classify the sounds used in their languages as one phoneme or another, showing no sensitivity to intermediate sounds. In adults, two tasks are used to show categorical perception, identification and discrimination (Fig. 2). Listeners are asked to identify each sound from a series generated by computer. Sounds in the series contain acoustic cues that vary in small, physically equal steps from one phonetic unit to another, for example, from /ra/ to /la/.

In one study, American and Japanese listeners were tested with a series of sounds ranging from /ra/ to /la/ [2]. Americans identified them as a sequence of /ra/ syllables that changed to a sequence of /la/ syllables. Even though the acoustic step size in the series was physically equal, American listeners did not hear a change until stimulus 6 on the continuum. When Japanese listeners were tested, they did not hear a change in the stimuli. All the sounds were identified as the same, Japanese /r/.

When pairs of stimuli from the series are presented, and listeners are asked to identify the sound pairs as "same" or "different," the results show that Americans are most

[1]The goal of this paper is to provide a summary of recent work on infant speech perception. It borrows heavily from recent reviews I have published elsewhere [28,68,79].

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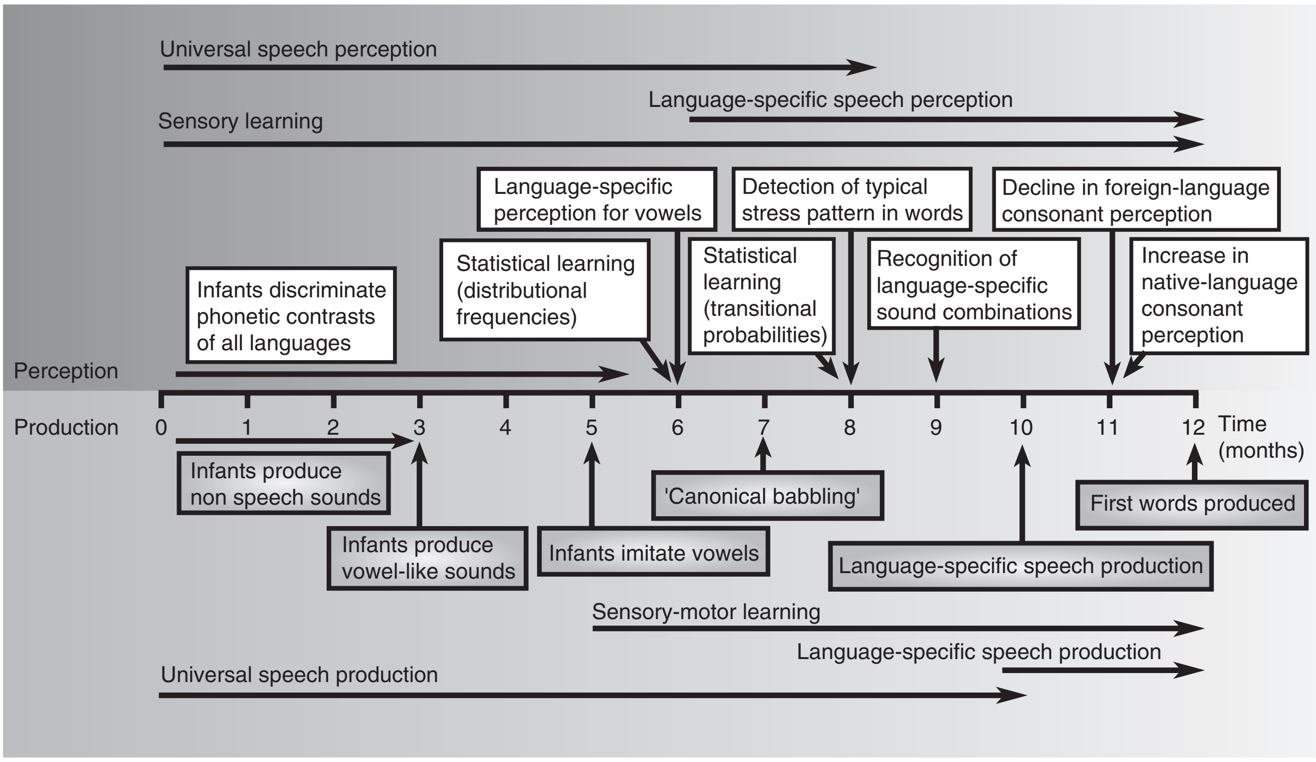

Fig. 1 Universal timeline of speech development in the first year of life. From Kuhl *et al.* [68].

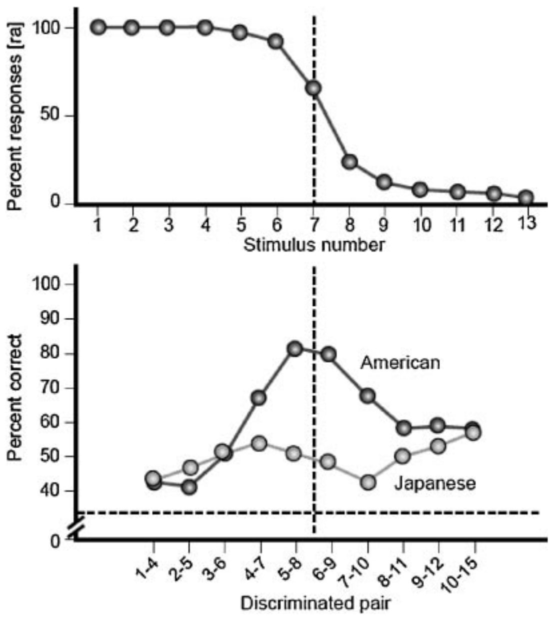

Fig. 2 The phenomenon of 'categorical perception.' American and Japanese adults show differential abilities to discriminate English /r/ and /l/ sounds; American listeners show a sharp increase in discrimination at the phonetic boundary between the /r/ and /l/ categories, whereas Japanese adults do not show this increase. From Kuhl [79].

sensitive to acoustic differences at the boundary between /r/ and /l/. Japanese adults' discrimination is near chance all along the continuum.

Young infants show categorical perception—they are especially sensitive to acoustic changes at the phonetic boundaries between categories, including those of languages they have never heard [3,4]. Infants can discriminate among virtually all the phonetic units used in languages, whereas adults cannot. The acoustic differences on which this depends are very small. A change of 10 ms in the time domain changes /b/ to /p/. From birth, infants can discriminate these subtle differences, which is essential for the acquisition of language. Categorical perception also shows that infant perception is constrained. Infants do not discriminate all physically equal acoustic differences; they show heightened sensitivity to those that are important for language.

Although categorical perception is a building block for language, it is not unique to humans. Non-human mammals—such as chinchillas and monkeys—also partition sounds where languages place phonetic boundaries [5–7]. Non-speech sounds that mimic the acoustic properties of speech are partitioned in this way as well [8,9]. I have argued that the match between basic auditory perception and the acoustic boundaries that separate phonetic categories in human languages is not fortuitous: general auditory perceptual abilities provided 'basic cuts' that influenced the choice of sounds included in the phonetic repertoire [10,11]. Languages capitalized on natural auditory discontinuities. These basic cuts provided by audition are primitive, and partition sounds only roughly. The exact locations of phonetic boundaries differ across languages and exposure to a specific language sharpens infants' perception of stimuli near phonetic boundaries in that language [12,13]. According to this argument, a domain-general skill, auditory perception, initially constrained choices at the phonetic level of language during its evolution. This ensured that infants at birth are capable of hearing the differences between phonetic contrasts in any natural language [10,11].

Infants' initial universal abilities to distinguish among phonetic units must eventually become a language-specific pattern of listening. In Japanese, the phonetic units /r/ and /l/ are combined into a single phonemic category (Japanese /r/), whereas in English, the difference is preserved (*rake* and *lake*); similarly, in English, two Spanish phonetic units (distinguishing *bano* from *pano*) are united into a single phonemic category. Infants can initially distinguish these sounds, but must eventually learn to perceptually group sounds they initially hear as distinct—they must learn to *categorize* sounds [14].

Werker and colleagues investigated when infants fail to discriminate nonnative contrasts that they initially could discriminate [15]. They showed that infant perception changes between 6 and 12 months of age; by 12 months, nonnative discrimination declines substantially. English-learning infants at 12 months have difficulty in distinguishing between sounds that are not used in English [15,16]. Japanese infants find the English /r–l/ distinction more difficult [17,18], and American infants' discrimination declines for both a Spanish [19] and a Mandarin distinction [20] that are not used in English. At the same time, infants' ability to discriminate native-language phonetic units improves [18–21]. For example, American infants' discrimination of /r/ and /l/ improves between 6 and 12 months of age, while that of Japanese infants declines [18] (Fig. 3).

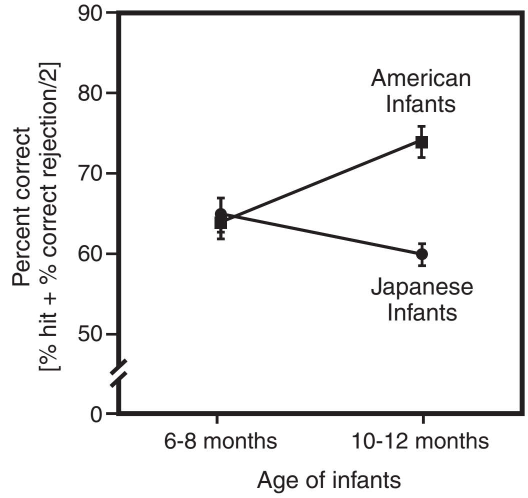

Fig. 3 The effects of age on speech perception performance in American and Japanese infants' discrimination of the American English /r–l/ sounds. Both groups show above-chance discrimination at 6–8 months; at 10–12 months, American infants show a significant increase while Japanese infants show a decline. From Kuhl *et al.* [18].

1.2. Computational Strategies

What mechanism is responsible for the developmental change in phonetic perception between 6 and 12 months? One hypothesis is that infants analyze the frequency distributions of sounds they hear in ambient language and that this alters perception. American infants hear frequent repetitions of /r/ and /l/ while Japanese infants hear frequent repetitions of Japanese /r/. When the frequency of phonetic units is measured across languages, modal values occur where languages place phonemic categories; distributional frequencies are low at the borders between categories. Distributional patterns of sounds thus provide clues about the phonemic structure of a language. Can infants detect the relative distributional frequencies of phonetic segments in the language they hear? If infants group sounds near modal values, it would help them learn the phonetic categories of their language.

Kuhl and colleagues [22] tested this hypothesis with 6-month-old American and Swedish infants using prototype vowel sounds (modal values) from both languages (Fig. 4A). Both the American English vowel and the Swedish vowel were synthesized by computer and, by varying the critical acoustic components in small steps, 32 variants of each vowel prototype were created. The infants listened to the prototype vowel (either English or Swedish) presented as a 'background' stimulus, and responded with a head-turn when the prototype vowel changed to one of its 'variants' (Fig. 4B). The hypothesis was that infants would show a 'perceptual magnet effect' for native-language sounds, because prototypical (modal) sounds function like magnets for surrounding sounds—in other words, infants categorize sounds around a prototype as identical [23]. The results confirmed this prediction (Fig. 4C). American infants perceptually grouped the American vowel variants together, but treated the Swedish vowels as less unified. Swedish infants reversed the pattern, perceptually grouping the Swedish variants more than the American vowel stimuli. The results reflect infants' sensitivity to the distributional properties of sounds in their language [24]. Interestingly, monkeys did not show a prototype magnet effect for vowels [23], suggesting that the effect in humans is attributable to linguistic experience.

Additional laboratory studies show that infants are affected by short-term exposure to the distributional frequencies of the sounds they hear. Maye and colleagues [25] exposed 6- and 8-month-old infants for about 2 min to 8 sounds that formed a series. Infants were familiarized

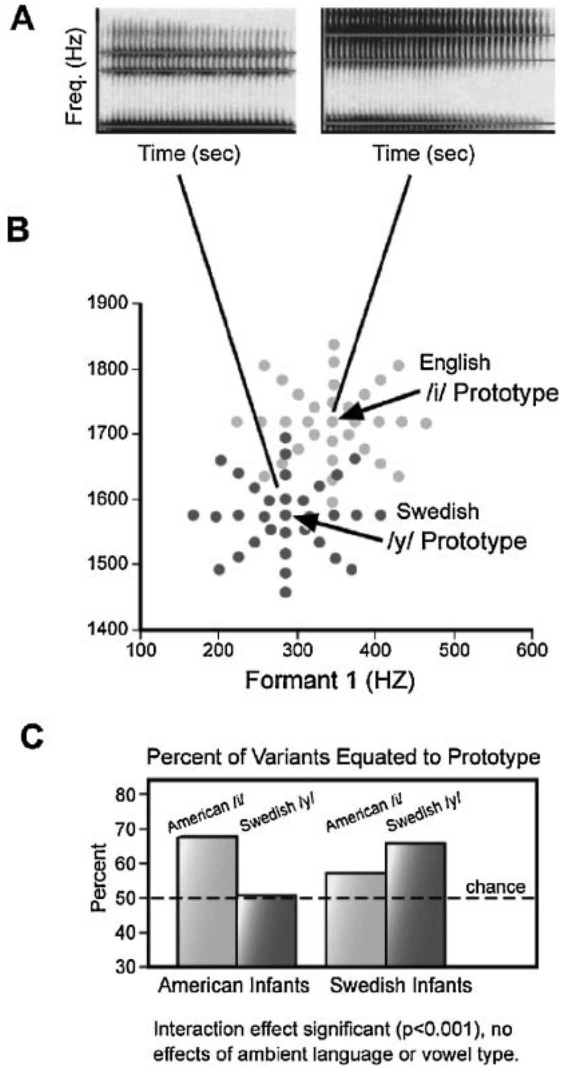

Fig. 4 Infants show an effect of learning by 6 months of age. American and Swedish 6-month-olds were tested with an English vowel prototype (/i/) and a Swedish vowel prototype (/y/) and 32 variants of each vowel. Spectrograms show the frequency components of each prototype (A). Variants of each prototype were computer-synthesized to create vowels in which systematic changes were made in the first (F_1) and second (F_2) components of the vowels (B). Infants' discrimination performance demonstrated that both American and Swedish infants ignored variations around the native-language prototype—indicating categorization of native-language vowels by 6 months. Redrawn from Kuhl [79].

with stimuli on the entire continuum, but experienced different distributional frequencies. A "bimodal" group heard more frequent presentations of stimuli at the ends of the continuum; a "unimodal" group heard more frequent presentations of stimuli from the middle of the continuum. After familiarization, infants were tested using a listening preference technique. The results showed that infants in the bimodal group discriminated the two sounds, whereas those in the unimodal group did not. These findings indicate that infants show a kind of *statistical learning* early in development, and that their ability to pick up the patterns of natural variation in language assists early phonetic learning.

1.3. Discovering Words Using Transitional Probabilities

Reading written words that lack spaces between them gives some sense of the task infants face in identifying spoken words. Without the spaces, printed words merge and reading becomes very difficult. Similarly, conversational speech does not provide acoustic breaks between words that reliably signal word boundaries. When we listen to another language, we perceive the words as run together and spoken too quickly. Without any obvious boundaries, how can an infant discover where one word ends and another begins?

Word segmentation is also advanced by infants' computational skills. Infants are sensitive to the sequential probabilities between adjacent syllables, which differ within and across word boundaries. Consider the phrase *pretty baby*; among English words, the probability that *ty* will follow *pre* is higher than the probability that *bay* will follow *ty*. If infants are sensitive to adjacent transitional probabilities in continuous speech, they might be able to parse speech and discover that *pretty* is a potential word, even before they understand its meaning.

Studies show that 8-month-old infants can learn word-like units on the basis of transitional probabilities. Saffran, Aslin and Newport [26] played two-minute strings of computer synthesized speech (e.g., tibudopabikugolatudaropi) to infants that contained no breaks, pauses, stress differences, or intonation contours. The transitional probabilities were 1.0 among the syllables contained in four pseudo-words that made up the string, *tibudo, pabiku, golatu, and daropi*, and 0.30 between other adjacent syllables. After exposure, infants were tested for listening preference with two of the original words, and two part-words formed by combining syllables that crossed word boundaries (for example, *tudaro*—the last syllable of *golatu* and the first two of *daropi*). The results show that infants learned the original pseudo-words. Two minutes of exposure to continuous syllable strings is sufficient for infants to detect word candidates, suggesting a potential mechanism for word learning.

2. SOCIAL INFLUENCES ON PHONETIC LEARNING: CONSTRAINTS ON COMPUTATION

Statistical learning suggests that infants learn merely by being exposed to the right kind of auditory information—brief auditory exposure to syllables in the laboratory is sufficient [25,26]. But is learning completely automatic?

Learning a natural language might require more than passive learning based on the statistical cues in speech.

A speech perception study that compared live social interaction with televised foreign-language material has shown the impact of social interaction on language learning in infants [27]. The study was designed to test whether infants can learn from short-term exposure to a natural foreign language for the first time at 9 months of age.

In the study, nine-month-old American infants listened to four native speakers of Mandarin during 12 sessions in which they read books and played with toys (Fig. 5A). After the sessions, infants were tested with a Mandarin phonetic contrast that does not occur in English to see whether exposure to the foreign language had reversed the typical decline in infants' foreign-language speech perception (Fig. 5B). The results showed that infants learned during these live sessions, compared with a control group that heard only English (Fig. 5C) [27].

To test whether such learning depends on live human interaction, a new group of infants saw the same Mandarin speakers on a television screen or heard them over loudspeakers (Fig. 5A). The auditory statistical cues available to the infants were identical in the televised and live settings, as was the use of 'motherese' (see below). If simple auditory exposure to language prompts learning, the presence of a live human being would not be essential. However, infants' Mandarin discrimination scores after exposure to televised or audiotaped speakers were no greater than those of the control infants; both groups differed significantly from the live-exposure group (Fig. 5C). Apparently, infants are not computational automatons—rather, they may need a social tutor when learning natural language. Speech learning may be 'gated' by the social brain [28].

The impact of social interaction on human language learning has been dramatically illustrated by the (thankfully few) instances in which children have been raised in social isolation; these cases have shown that social deprivation has a severe negative impact on language development, to the extent that normal language skill is never acquired [29]. In children with autism, language and social deficits are tightly coupled — aberrant neural responses to speech are strongly correlated with an interest in listening to non-speech signals as opposed to speech signals [30]. Recent data and theory posit that language learning is grounded in children's appreciation of others' communicative intentions, their sensitivity to joint visual attention, and their desire to imitate [31]. Only recently has the notion that social learning mediates language been extended to the earliest phases of language learning and the phonetic level [28].

In other species, such as songbirds, communicative learning is also enhanced by social contact. Young zebra finches need visual interaction with a tutor bird to learn song in the laboratory [32], and their innate preference for conspecific song can be overridden by a Bengalese finch foster father who feeds them, even when adult zebra finch males can be heard nearby [33]. White crown sparrows, who reject the audiotaped songs of alien species, learn the same alien songs when they are sung by a live tutor [34]. In barn owls [35] and white-crowned sparrows [34], a richer social environment extends the duration of the sensitive period for learning. Social contexts also advance song production in birds; male cowbirds respond to the social gestures and displays of females, which affect the rate, quality, and retention of song elements in their repertoires [36], and white-crowned sparrow tutors provide acoustic feedback that affects the repertoires of young birds [37].

2.1. What Accounts for the Impact of Social Interaction?

Why does social interaction affect early speech learning? We raised two possibilities in our original report [27]. The first was a global mechanism involving infants' *motivation*—and the attention and arousal it induces, which can strongly affect learning. The second was a more specific mechanism involving the *information* content of natural settings—the relations between auditory labels, objects, and speakers' intentions that are available during natural linguistic interaction [27].

Attention and Arousal As a Mechanism

Attention and arousal affect learning in a wide variety of domains [38]. Could they impact learning during exposure to a new language? Infant attention, measured in our studies, was significantly higher in response to the live person than to either inanimate source [27]. Attention has been shown to play a role in the distributional learning studies as well. 'High-attender' 10-month-olds learned from bimodal stimulus distributions when 'low-attenders' did not [39]. And arousal, while not measured in our first tests, appeared to be enhanced. Infants in the live exposure sessions were visibly aroused before the sessions—they watched the door expectantly, and were excited by the tutor's arrival, whereas infants in the non-social conditions did not. Heightened attention and arousal could produce an overall increase in the quantity or quality of the speech information that infants code and remember. Our current studies are testing the hypothesis that individual infants' attention and arousal predict the degree of phoneme and word learning in individual infants in our natural foreign-language learning situation [40].

Information as a Mechanism

We raised a second hypothesis to explain the effectiveness of social interaction—live situations provide specific information that fosters learning [27]. During live exposure, tutors focus their visual gaze on pictures in the books or on the toys they talk about, and infants' gaze tends to follow the speaker's gaze [41,42]. Referential information is present in both the live and televised conditions, but it is more difficult to pick up via television, and is totally absent during audio-only presentations. Gaze following is a significant predictor of receptive vocabulary [41,43,44], and may help infants segment foreign speech. When 9-month-old infants follow a tutors' line of regard in our foreign-language learning situation, the tutor's specific meaningful social cues, such as eye gaze and pointing to an object of reference, might help infants segment words from ongoing speech, thus facilitating phonetic learning of the sounds contained in those words.

Several key developments coincide with the ability to understand reference. By 9 months infants begin to engage in triadic "person-person-object games'—they systematically combine attention to objects with looks that promote interest from another human, reflecting a "secondary intersubjectivity" [45]. Shared perception of communicative intentions, which emerges at around 9 months of age, has been argued to be crucial for the acquisition of language [31,46,47]. Attending to objects of another person's reference is linked to the infant's growing ability to understand others as intentional agents [31,48]. The timing of these social abilities coincides with the beginnings of word comprehension. The suggestion here is that attunement to the communicative intentions of other humans enhances attention to linguistic units at several levels. Attention to the meaning of a communicative act enhances the uptake of units of language present in that act. In our current studies, which involve exposure to Spanish, we are measuring specific interactions between the tutor and the infant to examine whether specific kinds of interactive episodes can be related to learning of either phonemes or words [40].

2.2. What Constitutes a Social Agent?

Our findings raise a more fundamental question: What defines a 'social agent' for infants? Must a social agent involve a human being (with sight, smell, and all other indicators of humanness), or would an inanimate entity, imbued with certain interactive features, induce infant perception of a social being? And if so, could infants learn language from such a socially augmented entity?

Social interaction might be effective *because* it involves other humans, or because features inherent in social settings, such as interactivity and contingency, are critical for learning. Contingency plays a role in human vocalization learning [49–51], and in infant cognition [52,53]. Interactivity, the reciprocity that is integral in social exchange, could therefore be a key component of speech learning. Infants have a great deal of experience with people whose vocalizations are contingent on their own: Reciprocity in adult-infant language is common as infants alternate their vocalizations with those of an adult [54], and the pervasive use of motherese by adults tends to encourage infant reciprocity [55,56].

Whether contingency and interactivity in the absence of a live human would produce learning is an open question. Would infants learn from an interactive TV presentation, one in which the adult tutor was shown on a television but actually performing live from another room so that contingent looking, smiling, and other reciprocal reactions could occur? Could infants learn a new language from a socially interactive robot? Defining what constitutes a social agent for infants is itself of interest, and investigating how the perception of social agency affects learning in young children has both theoretical and practical implications. Further studies will be needed to understand how the social brain supports language learning.

2.3. Motherese as a Social Signal that Assists Infant Learning

When we talk to infants and children, we use a special speech "register" that has a unique acoustic signature, called "motherese" [57,58]. Caretakers in most cultures use it when addressing infants and children. When compared to adult-directed speech, infant-directed speech is slower, has a higher average pitch, and contains exaggerated pitch contours, as shown in the comparison between the pitch contours contained in adult-directed (AD) versus infant-directed (ID) speech (Fig. 6A).

Infant-directed speech may assist infants in learning speech sounds. Women speaking English, Russian, or Swedish were recorded while they spoke to another adult versus their young infants [59]. Acoustic analyses showed that the vowel sounds (the /i/ in 'see,' the /a/ in 'saw,' and the /u/ in 'sue') in infant-directed speech were more clearly articulated. Women from all three countries exaggerated the acoustic components of vowels (see the "stretching" of the formant frequencies, creating a larger triangle for infant-directed, as opposed to adult-directed, speech) (Fig. 6B). This acoustic stretching makes the vowels contained in motherese more distinct.

Infants may benefit from the exaggeration of the sounds in motherese. When the size of a mother's vowel triangles are measured, reflecting how clearly she speaks, and compared to her infant's skill in distinguishing the phonetic units of speech, a relationship is observed [60,61] (Fig. 6C). Mothers who stretch the vowels to a greater degree have infants who are better able to hear the subtle distinctions in speech. A social interest in listening to speech appears to be fundamental in typical infants and, when absent, as in children with autism, may provide a diagnostic early marker of the disorder [30].

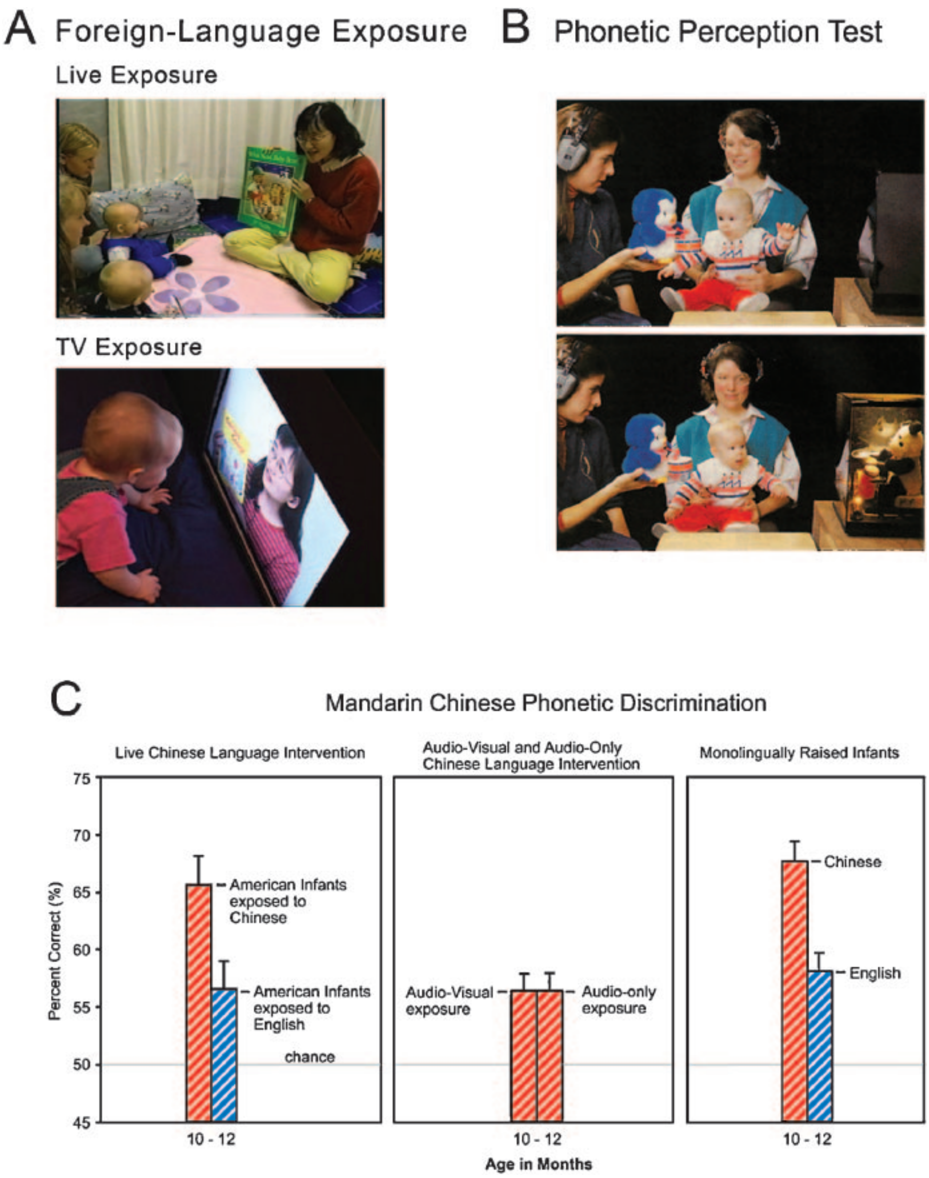

Fig. 5 American infants exposed to Mandarin Chinese for the first time at 9 months via live speakers as opposed to a standard television for 12 sessions (A). A control group had 12 sessions of English. After exposure to the new language, infants were tested with Mandarin Chinese phonetic units using a head-turn conditioning technique. Infants heard one phonetic unit as the background that played while they watched toys (B, top); when the phonetic unit changed, they were rewarded for turning toward the loudspeaker (B, bottom). No-change control trials assess the rate of false positives. The results show that infants learn from live presentation of Mandarin, performing significantly above the control group (C, left), that TV or audio-only presentation does not result in learning (C, center), and that performance of the live-exposure group was equivalent to the performance of monolingual Mandarin-learning infants raised in Taiwan (C, right). From Kuhl and Damasio [78].

3. LANGUAGE AND THE INFANT BRAIN

3.1. Brain Measures in Infants

Brain measures are providing more detail about the spatial and temporal unfolding of language processing in the infant brain. Electoencephalography (EEG) and Magnetoencephalography (MEG) techniques have been used to examine phonetic-level processing both in adults and infants.

An event-related potential (ERP) component of the EEG, the mismatch negativity (MMN), reflects phonetic discrimination and has been recorded in both infants and adults [19,62]. During the EEG recording, participants listen to syllables while they are engaged in another activity which helps the infants remain still; adults read a book, or watch silent television, whereas babies are tested while watching 'toy waving' by an assistant (Fig. 7). Babies wear a soft cap with the electrodes embedded in it (Fig. 7A). In adults, the MMN is elicited by a change in a speech syllable about 250 ms after the onset of the new

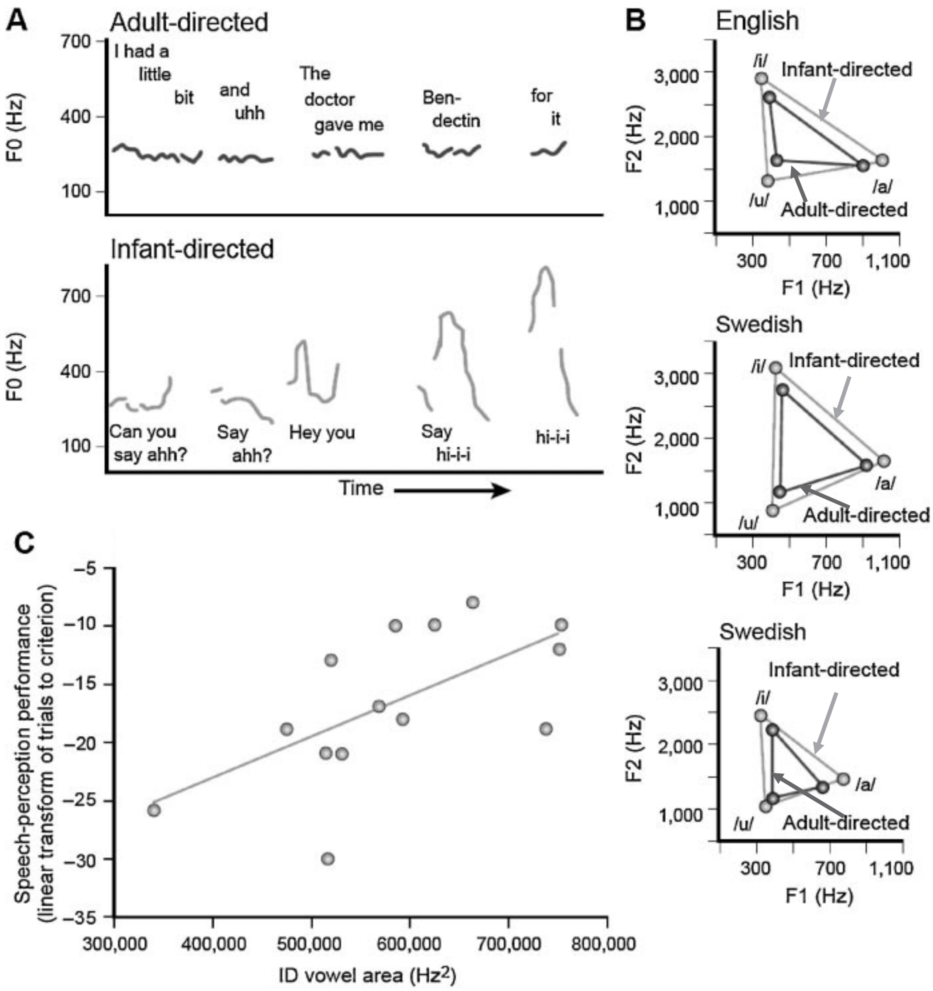

Fig. 6 Infant versus adult-directed speech has a higher pitch, a slower tempo, and exaggerated intonation contours (A), across languages mothers producing infant-directed speech exaggerate the acoustic features of speech sounds, acoustically stretching the differences between the formant frequencies of the vowels (B), the degree to which mothers exaggerate the acoustic cues is associated with the degree to which the infants perform well in tests of infant speech sound discrimination; (C) the more mothers exaggerate the sounds in infant-directed speech, the better infants perform in the tests. From Kuhl [79].

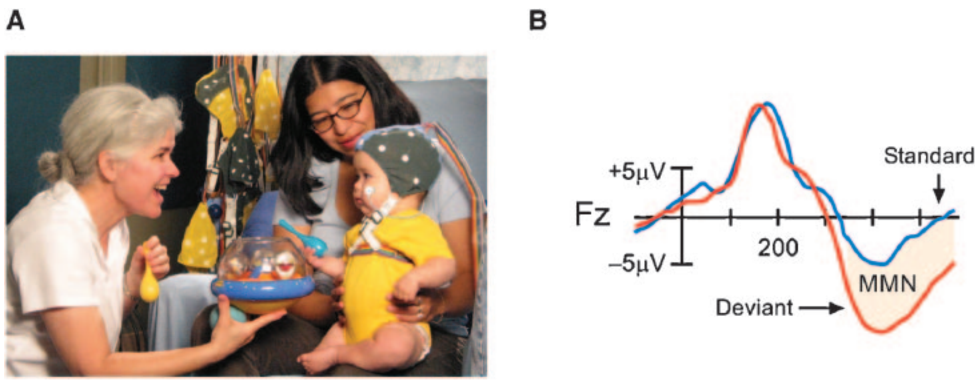

Fig. 7 6-month-old infant wearing a nylon cap that record event-related potentials (ERPs) in response to speech sounds. ERPs show the Mismatch Negativity (MMN), a brainwave with negative polarity, about 350 ms after a change in syllables. From Kuhl and Damasio [78].

syllable. Infants as young as 6 months of age show an MMN occurring slightly later, at about 350 ms after the presentation of a new stimulus (Fig. 7B).

The MMN is a sensitive indicator of linguistic experience. Infant studies confirm that the developmental change in phonetic perception observed in behavioral experiments between 6 and 12 months is mirrored in infant MMN measures. In 6-month-old infants both native and nonnative phonetic contrasts produce an MMN; by 12 months of age, the MMN to the nonnative contrast is greatly reduced [19]. Moreover, infant studies show that the strength of the MMN at 7 months of age in response to a change in a native-language sound predicts the rate of language growth between 11 and 30 months of age [68].

Megnetoencephalography (MEG) produces the magnetic equivalent of the MMN, the Mismatch Magnetic Field (MMNf). Studies conducted in English- and Japanese-speaking adults show that the MMNf is more prominent in individuals for native as opposed to nonnative phonetic contrasts [63]. Zhang *et al.* confirm the fact that speech perception involves bilateral activation of the two hemispheres, though greater left hemisphere activity occurs when processing native-language phonetic signals. Moreover, the MEG study revealed both the spatial localization of brain activity and the time course of processing. The results show that native-language sounds activate the brain more focally and for a significantly shorter period of time when compared to nonnative sounds, suggesting greater neural efficiency when processing native as opposed to nonnative speech [63].

Young infants can now be tested using MEG [64]. Special hardware and software has been developed to track infants' head movements during the MEG recordings. Imada *et al.* compared the brain's response to auditory speech and non-speech sounds in newborns, 6-month-old and 12-month-old infants. We used MEG to examine how the brain's auditory (superior temporal, Werniecke's area) versus motor areas (inferior frontal, Broca's area) responded to the pure perception of speech. As expected, the results show that at all ages and for all signals, the brain's auditory areas are activated to sound. In contrast, Broca's area was not activated in newborns for any signal. However, by 6 months of age, speech signals not only activated Broca's area, brain activity was precisely synchronized in the auditory and motor areas of the infant brain [64]. This work suggests that the connection between action and perception may be forged by experience as infants practice vocalizing. Broca's area is involved in social cognition—homologous areas in the nonhuman primate brain contain 'mirror neurons' [65]. Future studies using MEG will be of great interest in linking perception and action for speech and its relationship to the brain's social networks.

3.2. Early Phonetic Learning Predicts Later Language

One of the most interesting recent findings is the demonstration that measures of speech discrimination abilities in infancy predict children's later language skills [66]. Several studies in our laboratory now show that infants' native-language speech discrimination abilities, measured at 6–7 months of age either behaviorally or using ERPs, predict language skills between 11 and 30 months of age. Infants whose speech discrimination skills are *better* show *faster* language growth. Interestingly, the better infants are at *non*-native phonetic discrimination, phonetic units they have never been exposed to, the *slower* their language growth. This dissociation between native- and nonnative-speech discrimination and its relation to future language is important: It suggests that it is infants' abilities to sort out and focus on native-language sounds, rather than their more general auditory or cognitive skills, that encourages language development [67].

Kuhl *et al.* [68] used ERP measures of infants' speech discrimination to test the hypothesis that native- and nonnative sounds both predict future language, but differentially. ERPs were recorded in thirty monolingual full term infants (14 female) at 7.5 months of age. Infants were tested on both a native phonetic contrast, /pa–ta/, and one of two nonnative contrasts, either a Mandarin affricate-fricative distinction or a Spanish voicing contrast [27,69], in counter-balanced order. EEG was collected continuously at 16 electrode sites using Electro-caps with standard international 10/20 placements.

The children's developing language abilities were assessed at 14-, 18-, 24-, and 30-months of age using the MacArthur-Bates Communicative Development Inventory (CDI), a reliable and valid parent survey for assessing language and communication development from 8 to 30 months [70]. The Infant form (CDI: Words and Gestures) assesses vocabulary comprehension, vocabulary production, and gesture production in children from 8 to 16 months. The Toddler form (CDI: Words and Sentences) is designed to measure language production in children from 16 to 30 months of age. Three sections were used: vocabulary production, sentence complexity and mean length of the longest three utterances (M3L).

The results supported the prediction that both native- and nonnative phonetic perception at 7.5 months predicts later language, but in opposite directions. Significant findings were obtained with all CDI measures, including word production, sentence complexity and mean length of utterance between 14 and 30 months [68]. To illustrate the findings I will use the word production measure. The number of words produced can be measured at each of the four ages we tested, 14, 18, 24 and 30 months of age.

We used the Hierarchical Linear Models analyses [71] to examine whether brain responses to speech sounds at 7.5 months predicted rates of expressive vocabulary development from 14 to 30 months. Separate analyses were conducted for the native and nonnative ERP data. We estimated individual growth curves for each child using a quadratic equation with the intercept centered at 18

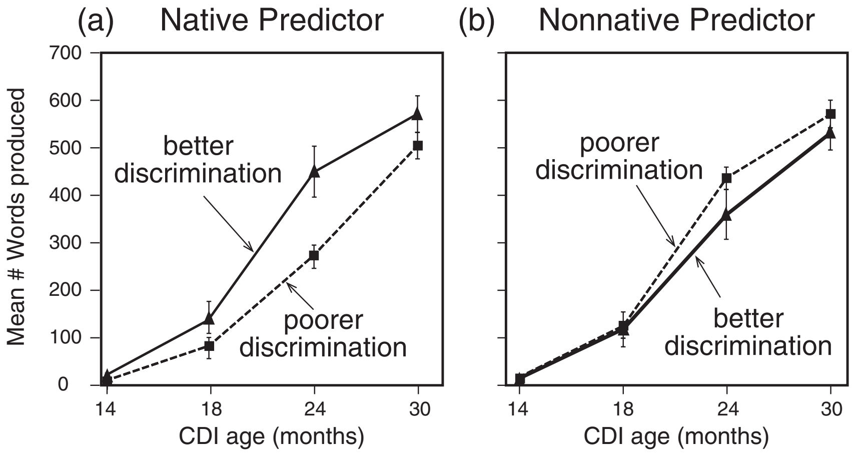

Fig. 8 A median split of infants whose MMNs indicate better versus poorer discrimination of native (a) and nonnative (b) phonetic contrasts is shown along with their corresponding Longitudinal Growth Curve Functions for the number of words produced between 14 and 30 months of age. From Kuhl *et al.* [68].

months. Several reports on expressive vocabulary development in this age range have indicated that quadratic models capture typical growth patterns, both a steady increase and acceleration [72–74]. Centering at 18 months allowed us to evaluate individual differences in vocabulary size at an age during which the 'vocabulary spurt' occurs.

Figure 8 shows the growth of words as predicted by the native contrast tested at 7.5 months (Fig. 8, left) and by the nonnative contrast tested at the same time in the same infants (Fig. 8, right). For both the native and nonnative predictors, we show the growth patterns for children whose 7.5-month discrimination skills (as measured by their MMNs) were below and above the median. Better discrimination is indicated by a more negative MMN value. As shown, for the native contrasts, children with better discrimination (more negative MMN values, solid curve) show faster initial vocabulary growth with a later leveling off function (likely due to a CDI ceiling effect). Children with poorer discrimination of the native contrast (less negative MMN, dashed curve) show less rapid growth in the number of words.

The opposite pattern was obtained for the nonnative-language contrast (Fig. 8, right). Children with better discrimination of the nonnative contrast as measured by the MMN (more negative values, solid curve) showed significantly slower growth in the number of words produced, while those with poorer discrimination skill (less negative MMN values) showed faster vocabulary growth. In both the native and nonnative case, growth curve analysis shows that the results are significant.

A model that explains these effects, the Native Language Magnet Expanded (NLM-e), has been described [68]. The model relies on the concept of native language neural commitment (NLNC) to explain the results. According to NLNC, early language learning produces dedicated neural networks that code the patterns of native-language speech. The hypothesis focuses on the aspects of language learned early—the statistical and prosodic regularities in language input that lead to phonetic learning —and how they influence the brain's future abilities to learn language. According to the theory, neural commitment to the phonetic properties of one's native language promotes the future use of these learned patterns in higher-order native-language learning, such as word learning. At the same time, NLNC decreases the processing of foreign-language phonetic patterns that do not conform to the learned patterns.

The NLNC hypothesis predicts that an infant's early skill in native-language phonetic perception should predict that child's later success at language acquisition. This is because phonetic perception promotes the detection of phonotactic patterns and words. Infants who have better phonetic perception would be expected to advance faster. Advanced phonetic abilities in infancy should 'bootstrap' language learning, propelling infants to more sophisticated levels earlier in development.

While native-language perception should predict faster advancement toward language, nonnative phonetic discrimination in infants who have never experienced a foreign language should reflect the degree to which the brain remains 'open' or *un*committed to native-language speech patterns. The degree to which an infant remains open to foreign language speech reflects an earlier stage in development, one in which native and nonnative contrasts are discriminated equally. Therefore nonnative phonetic discrimination should correlate negatively with later language learning. An *open* system reflects *un*committed circuitry. Several studies from my laboratory, using both behavioral [66,75,76] and brain [68,77] measures, now support this conclusion.

As described in recent publications, these data and the theoretical arguments they support suggests a mechanism that could underlie a 'critical period' at the phonetic level of language [66,68]. According to the NLNC concept, phonetic learning causes a decline in neural flexibility, suggesting that *experience*, not simply *time*, is a critical factor driving phonetic learning and perception of a second language. As the brain's neural commitment increases, it is more difficult to acquire the patterns of a new language.

In bilingual children who hear two languages from birth, both with distinct statistical and prosodic properties, NLNC predicts that the learning process would take longer, and studies are underway to test this hypothesis. Bilingual children are mapping two distinct systems, and it is to their advantage to stay 'open' longer. We are now testing this hypothesis. The NLM-e model also shows how social interaction plays a critical role in the neural commitment process; both social cues during conversation [27] and 'motherese' [59,60] are argued to play a critical role in language learning at the phonetic level and may assist bilingual children by helping infants who hear two different languages from two different people 'sort out' the statistics of the two languages [67] (see Kuhl [67] for discussion).

4. CONCLUDING REMARKS

Phonetic perception is providing a great deal of information about how language is learned by infants. Innate abilities to differentiate the phonetic units of all languages and a powerful ability to learn specific phonetic patterns from exposure to natural language in natural contexts allows infants in the first year to develop skills that will propel them towards language. Exposure to a specific language results in neural commitment to the phonetic properties of that language—native-language phonetic learning then advances more complex language skills, such as word learning, while constraining the detection of alternative patterns such as those represented by nonnative languages. Learning is strongly influenced by social skills as seen by infants' inability to learn a new language from a television or from an audio-tape. The phenomenon of 'motherese' is also a social factor that is viewed as strongly supporting phonetic learning—it exaggerates and emphasizes the critical phonetic components of language that infants must learn to advance toward language. Infants who do not show an interest in 'motherese,' such as infants with autism, may be restricted in their ability to acquire language. Social factors in language, and their relation to new theorizing in social cognition especially with regard to 'mirror neurons,' will be fruitful areas for further research. A comprehensive view of language acquisition is now emerging—a new theoretical model of early language learning, NLM-E, shows how infants' computational, social, and cognitive skills each contribute to language acquisition in the child.

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