

BRAIN MECHANISMS UNDERLYING THE CRITICAL PERIOD FOR LANGUAGE: LINKING THEORY AND PRACTICE

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Introduction

Half a century ago, humans' capacity for speech and language provoked classic debates on what it means to be human by strong proponents of nativism (Chomsky, 1959) and learning (Skinner, 1957). The debate centered on learning and development, and the remarkable transition that all children make as they acquire a language. While we are now far beyond these debates and informed by a great deal of data about infants, their innate predispositions and incredible abilities to learn once exposed to natural language (Kuhl, 2009; Saffran, Werker, and Werner, 2006), we are still just breaking ground with regard to the neural mechanisms that underlie language development and its 'critical period' (see Friederici and Wartenburger, 2010; Kuhl and Rivera-Gaxiola, 2008; Kuhl *et al.*, 2008). Developmental neuroscience is beginning to deepen our understanding of the nature of language and its 'window of opportunity' for learning.

To explore the topic of the critical period for language, and its practical implications, I will focus on the youngest learners – infants in the first year of life – and compare them to adult learners. The linguistic data will focus on the most elementary units of language – the consonants and vowels that make up words. Infants' responses to the basic building blocks of speech provide an experimentally accessible window on the roles of nature and nurture in language acquisition. Comparative studies at the phonetic level have allowed us to examine humans' unique language processing abilities at birth and as they respond to language experience. We are beginning to discover how exposure to two languages early in infancy produces a bilingual brain, and bilingualism is allowing us to test theories of the critical period. Neuroimaging of infants is advancing our understanding of the uniquely human capacity for language.

Windows to the young brain

Rapid advances have been made in noninvasive techniques that examine language processing in young children (Figure 1, see p. 239). They include

Electroencephalography (EEG)/Event-Related Potentials (ERPs), Magnetoencephalography (MEG), functional Magnetic Resonance Imaging (fMRI), and Near-Infrared Spectroscopy (NIRS).

Event-Related Potentials (ERPs) have been widely used to study speech and language processing in infants and young children (for reviews, see Conboy, Rivera-Gaxiola, Silva-Pereyra, and Kuhl, 2008; Friederici, 2005; Kuhl, 2004). ERPs, a part of the EEG, reflect electrical activity that is time-locked to the presentation of a specific sensory stimulus (for example, syllables or words) or a cognitive process (for example, recognition of a semantic violation within a sentence or phrase). By placing sensors on a child's scalp, the activity of neural networks firing in a coordinated and synchronous fashion in open field configurations can be measured, and voltage changes occurring as a function of cortical neural activity can be detected. ERPs provide precise time resolution (milliseconds), making them well suited for studying the high-speed and temporally ordered structure of human speech. ERP experiments can also be carried out in populations who cannot provide overt responses because of age or cognitive impairment. Spatial resolution of the source of brain activation is, however, limited.

Magnetoencephalography (MEG) is another brain imaging technique that tracks activity in the brain with exquisite temporal resolution. The SQUID (superconducting quantum interference device) sensors located within the MEG helmet measure the minute magnetic fields associated with electrical currents that are produced by the brain when it is performing sensory, motor, or cognitive tasks. Going beyond EEG, MEG allows precise localization of the neural currents responsible for the sources of the magnetic fields. Cheour *et al.* (2004) and Imada *et al.* (2006) used new head-tracking methods and MEG to show phonetic discrimination in newborns and in infants in the first year of life. Sophisticated head-tracking software and hardware enables investigators to correct for infants' head movements, and allows the examination of multiple brain areas as infants listen to speech (Imada *et al.*, 2006). MEG (as well as EEG) techniques are completely safe and noiseless.

Magnetic resonance imaging (MRI) can be combined with MEG and/or EEG, providing static structural/anatomical pictures of the brain. Structural MRIs show anatomical differences in brain regions across the lifespan, and have recently been used to predict second-language phonetic learning in adults (Golestani, Molko, Dehaene, LeBihan, and Pallier, 2007). Structural MRI measures in young infants identify the size of various brain structures and these measures correlate with later language abilities (Ortiz-Mantilla, Choe, Flax, Grant, and Benasich, 2010). When structural MRI images are superimposed on the physiological activity detected by MEG or

EEG, the spatial localization of brain activities recorded by these methods can be improved.

Functional magnetic resonance imaging (fMRI) is a popular method of neuroimaging in adults because it provides high spatial-resolution maps of neural activity across the entire brain (e.g., Gernsbacher and Kaschak, 2003). Unlike EEG and MEG, fMRI does not directly detect neural activity, but rather the changes in blood-oxygenation that occur in response to neural activation. Neural events happen in milliseconds; however, the blood-oxygenation changes that they induce are spread out over several seconds, thereby severely limiting fMRI's temporal resolution. Few studies have attempted fMRI with infants because the technique requires infants to be perfectly still, and because the MRI device produces loud sounds making it necessary to shield infants' ears. fMRI studies allow precise localization of brain activity and a few pioneering studies show remarkable similarity in the structures responsive to language in infants and adults (Dehaene-Lambertz, Dehaene, and Hertz-Pannier, 2002; Dehaene-Lambertz *et al.*, 2006).

Near-Infrared Spectroscopy (NIRS) also measures cerebral hemodynamic responses in relation to neural activity, but utilizes the absorption of light, which is sensitive to the concentration of hemoglobin, to measure activation (Aslin and Mehler, 2005). NIRS measures changes in blood oxygen and deoxy-hemoglobin concentrations in the brain as well as total blood volume changes in various regions of the cerebral cortex using near infrared light. The NIRS system can determine the activity in specific regions of the brain by continuously monitoring blood hemoglobin level. Reports have begun to appear on infants in the first two years of life, testing infant responses to phonemes as well as longer stretches of speech such as 'motherese' and forward versus reversed sentences (Bortfeld, Wruck, and Boas, 2007; Homae, Watanabe, Nakano, Asakawa, and Taga, 2006; Peña, Bonatti, Nespor, and Mehler, 2002; Taga and Asakawa, 2007). As with other hemodynamic techniques such as fMRI, NIRS typically does not provide good temporal resolution. However, event-related NIRS paradigms are being developed (Gratton and Fabiani, 2001a,b). One of the most important potential uses of the NIRS technique is possible co-registration with other testing techniques such as EEG and MEG.

Phonetic learning

Perception of the phonetic units of speech – the vowels and consonants that make up words – is one of the most widely studied linguistic skills in infancy and adulthood. Phonetic perception and the role of experience in learning is studied in newborns, during development as infants are exposed to a

particular language, in adults from different cultures, in children with developmental disabilities, and in nonhuman animals. Phonetic perception studies provide critical tests of theories of language development and its evolution. An extensive literature on developmental speech perception exists and brain measures are adding substantially to our knowledge of phonetic development and learning (see Kuhl, 2004; Kuhl *et al.*, 2008; Werker and Curtin, 2005).

In the last decade, brain and behavioral studies indicate a very complex set of interacting brain systems in the initial acquisition of language early in infancy, many of which appear to reflect adult language processing (Dehaene-Lambertz *et al.*, 2006). In adulthood, language is highly modularized, which accounts for the very specific patterns of language deficits and brain damage in adult patients following stroke (Kuhl and Damasio, *in press*). Infants, however, must begin life with brain systems that allow them to acquire any and all languages to which they are exposed, and allow acquisition of language as either an auditory-vocal or a visual-manual code on roughly the same timetable (Petitto and Marentette, 1991). We are in a nascent stage of understanding the brain mechanisms underlying infants' early flexibility with regard to the acquisition of language – their ability to acquire language by eye or by ear, and their ability to acquire one or multiple languages – and also the reduction in this initial flexibility that occurs with age, dramatically decreasing our capacity to acquire a new language as adults (Newport, 1990). The infant brain is exquisitely poised to 'crack the speech code' in a way that the adult brain cannot. Uncovering why this is so is a very interesting puzzle.

In this review I will also explore a current working hypothesis and its implications for the critical period in language – that the critical period is not driven solely by *time* (maturation), but by *experience*. In exploring the critical period for phonetic learning we will examine the role of experience, particularly in *closing* the optimal period for learning. I will also develop the idea that systems-level top-down mechanisms, such as those controlling social cognition, play an essential role in infants' abilities to 'crack the speech code'. On this view, infants combine a powerful set of domain-general computational skills with their equally extraordinary social skills to enable learning. Thus, the underlying brain systems for social cognition and language processing mutually influence one another in controlling the opening and closing of the critical period during development. Nature's language experiments – the case of simultaneous bilinguals who learn more than one language – are revealing a great deal about how experience alters the brain, and these data are affecting arguments about the critical period as well. The data suggest revisions of theory. Of equal importance, the data how one might facilitate language learning and literacy in young children.

Regarding the social effects, I have suggested that the social brain – in ways we have yet to understand – ‘gates’ the computational mechanisms underlying learning in the domain of language (Kuhl, 2007; *in press*). The assertion that social factors gate language learning may help explain not only how typically developing children acquire language, but also why children with autism exhibit twin deficits in social cognition and language, and why nonhuman animals with impressive computational abilities do not acquire language. Moreover, this gating hypothesis may explain why social factors play a far more significant role than previously realized in human learning across domains throughout our lifetimes (Meltzoff, Kuhl, Movellan, and Sejnowski, 2009). Theories of social learning have traditionally emphasized the role of social factors in language acquisition (Bruner, 1983; Tomasello, 2003a, b; Vygotsky, 1962). However, these models emphasized the development of lexical understanding and the use of others’ communicative intentions to help understand the mapping between words and objects. The new data indicate that social interaction gates an even more basic aspect of language – learning of the elementary phonetic units – suggesting a more fundamental connection between the brain mechanisms underlying human social understanding and the origins of language than has previously been hypothesized.

Research on infants’ phonetic perception in the first year of life shows how computational, cognitive, and social skills combine to form a very powerful learning mechanism. Interestingly, this mechanism does not resemble Skinner’s operant conditioning and reinforcement model of learning, nor Chomsky’s detailed view of parameter setting. The processes that infants employ when learning from exposure to language are complex and multi-modal, but also child’s play in that they grow out of infants’ heightened attention to items and events in the natural world: the faces, actions, and voices of other people.

Language exhibits a ‘critical period’ for learning

A stage-setting concept for human language learning is the graph shown in Figure 2, redrawn from a study by Johnson and Newport on English grammar in native speakers of Korean learning English as a second language (1989). The graph as rendered shows a simplified schematic of second language competence as a function of the age of second language acquisition.

Figure 2 is surprising from the standpoint of more general human learning. In the domain of language, infants and young children are superior learners when compared to adults, in spite of adults’ cognitive superiority. Language is one of the classic examples of a ‘critical’ or ‘sensitive’ period in neurobiology (Bruer, 2008; Johnson and Newport, 1989; Knudsen, 2004; Kuhl, 2004; Newport, Bavelier, and Neville, 2001).

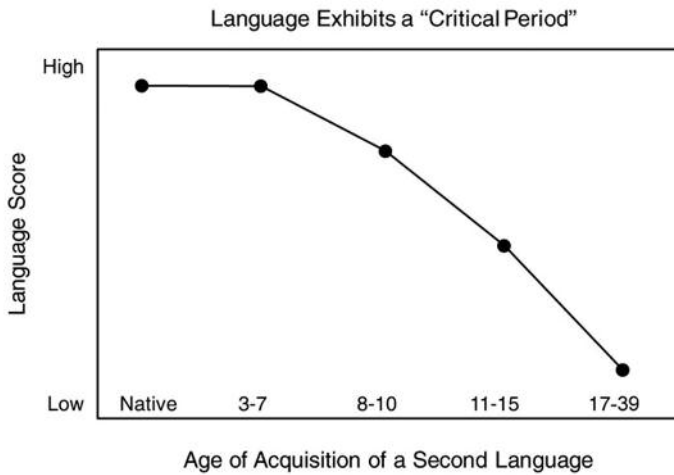


Figure 2. The relationship between age of acquisition of a second language and language skill (adapted from Johnson and Newport, 1989).

Scientists are generally in agreement that this learning curve is representative of data across a wide variety of second-language learning studies (Bialystok and Hakuta, 1994; Birdsong and Molis, 2001; Flege, Yeni-Komshian, and Liu, 1999; Johnson and Newport, 1989; Kuhl, Conboy, Padden, Nelson, and Pruitt, 2005a; Kuhl *et al.*, 2008; Mayberry and Lock, 2003; Neville *et al.*, 1997; Weber-Fox and Neville, 1999; Yeni-Komshian, Flege, and Liu, 2000; though see Birdsong, 1992; White and Genesee, 1996). However, not all aspects of language exhibit the same temporally defined critical window. The developmental timing of critical periods for learning phonetic, lexical, and syntactic levels of language vary, though studies cannot yet document the precise timing at each individual level. Studies indicate, for example, that the critical period for phonetic learning occurs prior to the end of the first year, whereas syntactic learning flourishes between 18 and 36 months of age. Vocabulary development explodes at 18 months of age, but does not appear to be as restricted by age as other aspects of language learning – one can learn new vocabulary items at any age. One goal of future research will be to document the ‘opening’ and ‘closing’ of critical periods for all levels of language and understand how they overlap and why they differ.

Given widespread agreement on the fact that we do not learn equally well over the lifespan, theory is currently focused on attempts to understand how and why learning is restricted to certain periods. What accounts for adults’ inability to learn a new language with the facility of an infant?

Recent data on critical periods in the visual domain – particularly in the case of ocular dominance – are exploring from a physiological perspective the pharmacological triggers at the cellular level that open the critical period and those that close the period of optimum learning. For example, we have known since the pioneering work of Hubel and Wiesel (Hubel and Wiesel, 1963; Wiesel and Hubel, 1963; Hensch, 2005) that ocular dominance in the brain's visual cortex is determined by experience at a particular point in development – input from the two eyes determines the relative dominance of one eye over another. Closing one eye during the critical period for binocular fusion results in a permanent reduction in visual acuity. Recent research indicates that in the case of binocular vision, the brain's inhibitory circuits are responsible for both the onset and offset of plasticity (Hensch and Stryker, 1996; Hensch, 2005). This finding represents an exciting new step in understanding the underlying mechanisms of the critical period for vision.

Work on the molecular components (inhibitory GABAergic systems, etc.) that control the opening and narrowing of learning periods pose an important question from a theoretical perspective: Something has to trigger these inhibitory circuits – is it maturation that triggers the cellular mechanisms causing them to initiate learning, and eventually to slow learning, or does the trigger stem from the environment? Vision research has provided a clue: Rearing animals completely in the dark (by eye-suturing for example), and then opening the animal's eye after the typical learning period is over, extends the critical period (Cho and Bear, 2010). At least for binocular vision, the critical period is not strictly maturational. Knowing whether this is the case more generally – beyond vision – will advance theory.

Phonetic level contributions to 'critical period' theory

Work in my laboratory has focused on the idea that *experience*, not simply *time or maturation*, opens and closes the critical period in the case of language (Kuhl, 2000). Our published work focuses on closing mechanisms, ones that may cause phonetic learning to decline with language experience. Work on the opening of the critical period has recently begun.

Language acquisition is often cited as an example of a critical learning period that is constrained by time, or factors such as hormones, that are outside the learning process itself. The studies on speech (as well as those on birds acquiring bird song, see Doupe and Kuhl, 1999) suggest an alternative (Kuhl, 2000). The work on speech suggests that early learning itself may constrain later learning. In earlier writings, I advanced the concept of *neural commitment*, the idea that neural circuitry and overall architecture forms early in infancy to detect the phonetic and prosodic patterns of

speech (Kuhl, 2004; Zhang, Kuhl, Imada, Kotani, and Tohkura, 2005; Zhang *et al.*, 2009). The neural architecture formed with experience is designed to maximize the efficiency of processing for the language(s) experienced by the infant. Once fully established, the neural architecture arising from exposure to French or Tagalog, for example, impedes learning of a new language that does not conform.

Infant phonetic learning: computation ‘gated’ by the social brain

The world’s languages contain approximately 600 consonants and 200 vowels (Ladefoged, 2001). Each language uses a unique set of distinct elements, *phonemes*, which change the meaning of a word (e.g. from *bat* to *pat* in English). But phonemes are actually groups of non-identical sounds, *phonetic units*, which are functionally equivalent in the language. Japanese-learning infants have to group the phonetic units *r* and *l* into a single phonemic category (Japanese *r*), whereas English-learning infants must uphold the distinction to separate *rake* from *lake*. Spanish learning infants must distinguish phonetic units critical to Spanish words (*baño* and *pañó*), whereas English learning infants must combine them into a single category (English *b*).

If infants were exposed only to the subset of phonetic units that will eventually be used phonemically to differentiate words in their language, the problem would be trivial. But infants are exposed to many more phonetic variants than will be used phonemically. The baby’s task in the first year of life, therefore, is to make some progress in figuring out the composition of the 40-odd phonemic categories in their language before trying to acquire words that depend on these elementary units. An important discovery in the 1970s was that infants initially hear all phonetic differences; they have a universal phonetic capacity at birth (Eimas, 1975; Eimas, Siqueland, Jusczyk, and Vigorito, 1971; Lasky, Syrдал-Lasky, and Klein, 1975; Werker and Lalonde, 1988).

Between 6 and 12 months of age nonnative discrimination declines (Best and McRoberts, 2003; Rivera-Gaxiola, Silvia-Pereyra, and Kuhl, 2005a; Tsao, Liu, and Kuhl, 2006; Werker and Tees, 1984), and native language speech perception shows a significant increase (Kuhl *et al.*, 2006; Tsao *et al.*, 2006) (see Figure 3, 240).

What happens during this 2-month window to prompt the transition? Available data now allows us to create a model of the transition in phonetic perception, and our current working model of the process (Kuhl *et al.*, 2008) shows that two factors are key to phonetic learning during the sensitive period – computational learning and social cognition.

The computational component

An implicit form of learning, referred to as ‘statistical learning’ (Saffran, Aslin, and Newport, 1996), plays an important role in infants’ phonetic learning. Figure 4 (p. 240) provides a cartoon version of the process. Research shows that adult speakers of English and Japanese produce the English *r*, the English /*l*/, and the Japanese *r* sounds, so it is not the mere presence of the sound in language spoken to infants that accounts for learning (Werker *et al.*, 2007). Instead, it is the patterns of distributional frequency of the sounds across the two languages that provide the information that English-learning and Japanese-learning infants use to learn phonetically.

When infants listen to English and Japanese, they attend to the distributional properties of the phonetic units contained in the two languages, and the distributional data affect their perception (Kuhl, Williams, Lacerda, Stevens, and Lindblom, 1992; Maye, Weiss, and Aslin, 2008; Maye, Werker, and Gerken, 2002; Teinonen, Fellman, Naatanen, Alku, and Huotilainen, 2009). These distributional differences are exaggerated in ‘motherese’, the prosodically and phonetically stretched utterances that are near universal in languages spoken to children around the world, (Kuhl *et al.*, 1997; Vallabha, McClelland, Pons, Weker, and Amano, 2007; Werker *et al.*, 2007).

As illustrated in the idealized case (see Figure 4, p. 240), the distributions of English and Japanese sounds differ: English motherese contains many English *r* and *l* sounds and very few of the Japanese retroflex *r* sounds, while the reverse is true for Japanese motherese. A variety of studies show that infants pick up the distributional frequency patterns in ambient speech, whether they experience them during short-term laboratory experiments or over months in natural environments, and that this alters phonetic perception (Maye *et al.*, 2002; Maye *et al.*, 2008). Statistical learning from the distributional properties in speech thus supports infants’ transition in early development from universal perception exhibited at birth to native-language perception that is exhibited by the end of the first year of life.

The foregoing data and arguments led us to suggest that statistical learning processes could govern brain plasticity (Kuhl, 2002; Kuhl *et al.*, 2008). If infants build up statistical distributions of the sounds contained in the language they hear, at some point these distributions would become stable. At the point of stability, additional language input would not cause the overall statistical distribution of sounds to change substantially, and, according to our model, this stability would cause a decline in sensitivity to language input. In other words, the decline in plasticity is hypothesized to be driven by a statistical process in which stability reduces plasticity. Hypothetically, for instance, the infants’ representation of the vowel /*a*/ might have stabilized by the time the child hears

her one-millionth token of the vowel /a/, and this could instigate the beginning of the closure of the critical period. On this account, plasticity is independent of time, and instead dependent on the amount and the variability of input provided by experience. This reasoning lends itself to testable hypotheses. Studies of bilingual infants, reviewed later in this chapter, provide one example of an empirical test of the model.

Brain rhythms index statistical learning for speech

Statistical learning is an implicit strategy that induces phonetic learning in infancy but not in adulthood – spending months in a foreign country does not change speech perception in spite of the new statistical distributions we experience. Work in my laboratory has recently shown that brain oscillations (‘rhythms’), associated with higher cognitive functions such as attention and cognitive effort, index the shift in statistical learning in speech (Bosseler, Taulu, Imada, and Kuhl, 2011).

A brain rhythm, theta (~4–8Hz), has been shown in previous studies to index attention and cognitive effort in adults (Jensen and Tesche, 2002) as well as infants (Kahana, Sekuler, Caplan, Kirschen, and Madsen, 1999). Using native and nonnative speech sounds, presented frequently or infrequently in the classic oddball paradigm, we tested three age groups: 6–8 month-old infants, 10–12 month-old infants, and adults. Data was collected using magnetoencephalography (MEG), a whole-brain imaging technology that is completely safe and noiseless.

Bosseler *et al.* (2011) predicted that early in development, when infants are maximally sensitive to language experience, attention and cognitive effort are driven by infants’ sensitivity to the distributional frequency of events, as portrayed in Figure 4. Once learning occurs (after neural commitment is complete), attention and cognitive effort are dominated by learned categories; stimuli that fit learned phonetic categories are processed easily, and increased attention and mental effort are required for novel stimuli that do not fit learned categories. We expected 6–8 month-old infants to show theta increases for any frequent stimulus, regardless of language, and adults to show theta increases for novel stimuli, regardless of frequency. 10–12 month-old infants were expected to show an intermediate pattern resembling that of adults.

Our results confirmed these predictions (Bosseler *et al.*, 2011). 6–8-month-old infants demonstrated increased theta for frequently presented speech sounds, regardless of whether they were native or nonnative. Adults showed the opposite pattern of response, with increased theta shown to nonnative sounds regardless of frequency. The 10–12-month-old infants showed an intermediate pattern of results, approximating the adult theta pattern.

These results show that theta indexes the well-established change in speech perception that is brought about by exposure to a specific language – as infants experience a particular language, the brain’s neural circuitry focuses on registering high frequency speech events that represent the phonetic categories used in the ambient language. This implicit strategy provides infants with an ability to learn through experience with language to attend to the sounds that are critical to the ambient language used in their cultural community. Adults no longer implicitly absorb the statistical properties of phonetic units in a new language. Attention and cognitive effort is driven by learned category structure.

The question that remains is whether the implicit strategy indexed by theta brain rhythms is unique to speech. A range of studies show that the perceptual narrowing first observed for speech perception (Werker and Teas, 1984) occurs in other domains. Infants show perceptual narrowing between 8 and 12 months of age for visual discrimination of faces (Pascalis, de Haan, and Nelson, 2002) or languages (Weikum, *et al.*, 2007), for recognition of the conceptual distinctions that underpin word meanings (Hespos and Spelke, 2004), and when detecting inter-sensory correspondences (Lewkowicz and Ghazanfar, 2006). In all cases, young infants’ abilities are initially better than those shown in adults and decline during the second half of the first year. Infants begin life with the capacity to differentiate many forms, and this initial capacity narrows as a function of experience.

The perceptual narrowing phenomenon may therefore reflect a domain-general developmental shift in perceptual strategy brought about by the brain’s response to experience rather than a specific critical learning window for speech. Stimuli that reflect cultural categories that are learned socially (speech, faces, conceptual categories, musical intervals) are candidate domains for which this pattern might hold. Further empirical research will be needed to test this broader hypothesis with a variety of stimuli.

The social component

Whether or not the perceptual narrowing indexed by theta and observed in speech turns out to be a domain-general phenomenon, studies on phonetic learning have gone one step further than studies in other domains in understanding the complex conditions that must be met in order for infants to learn during the period from 6–12 months. In the domain of speech, data now show that infants’ computational skills cannot solely account for the transition in phonetic perception that occurs in the second half of the first year of life. Our studies demonstrate that infant language learning in complex natural environments requires something more than raw compu-

tation. Laboratory studies testing infant phonetic and word learning from exposure to complex natural language demonstrated limits on statistical learning, and provided new information suggesting that social brain systems are integrally involved and, in fact, may be necessary to instigate natural phonetic learning (Kuhl, Tsao, and Liu, 2003; Conboy and Kuhl, 2011).

The new experiments tested infants in the following way: At 9 months of age, the age at which the initial universal pattern of infant perception has changed to one that is more language-specific, infants were exposed to a foreign language for the first time (Kuhl *et al.*, 2003). Nine-month-old American infants listened to 4 different native speakers of Mandarin during 12 sessions scheduled over 4–5 weeks. The foreign language ‘tutors’ read books and played with toys in sessions that were unscripted. A control group was also exposed for 12 sessions but heard only English from native speakers. After infants in the experimental Mandarin exposure group and the English control group completed their sessions, all were tested with a Mandarin phonetic contrast that does not occur in English. Both behavioral and ERP methods were used. The results indicated that infants showed a remarkable ability to learn from the ‘live-person’ sessions – after exposure, they performed significantly better on the Mandarin contrast when compared to the control group that heard only English. In fact, they performed equivalently to infants of the same age tested in Taiwan who had been listening to Mandarin for 10 months (Kuhl *et al.*, 2003).

The study revealed that infants can learn from first-time natural exposure to a foreign language at 9 months, and answered what was initially the experimental question: can infants learn the statistical structure of phonemes in a new language given first-time exposure at 9 months of age? If infants required a long-term history of listening to that language – as would be the case if infants needed to build up statistical distributions over the initial 9 months of life – the answer to our question would have been no. However, the data clearly showed that infants are capable of learning at 9 months when exposed to a new language. Moreover, learning was durable. Infants returned to the laboratory for their behavioral discrimination tests between 2 and 12 days after the final language exposure session, and between 8 and 33 days for their ERP measurements. No ‘forgetting’ of the Mandarin contrast occurred during the 2 to 33 day delay.

Infants exposed to Mandarin were socially very engaged in the language sessions. Would infants learn if they were exposed to the same information in the absence of a human being, say, via television or an audiotape? If statistical learning is sufficient, the television and audio-only conditions should produce learning. Infants who were exposed to the same foreign-language material at the same time and at the same rate, but via standard television

or audiotape only, showed no learning – their performance equaled that of infants in the control group who had not been exposed to Mandarin at all (see Figure 5, p. 241).

Thus, the presence of a human being interacting with the infant during language exposure, while not required for simpler statistical-learning tasks (Maye *et al.*, 2002; Saffran *et al.*, 1996), is critical for learning in complex natural language-learning situations (Kuhl *et al.*, 2003). Using the same experimental design, this work has been extended to Spanish and advanced beyond the Kuhl *et al.* (2003) study. Conboy showed that infants not only learn Spanish phonemes (Conboy and Kuhl, 2011) but also the Spanish words they were exposed to during the language-exposure sessions (Conboy and Kuhl, 2010). Moreover, Conboy and colleagues demonstrated that individual differences in infants' social behaviors during the Spanish exposure sessions is significantly correlated to the degree to which infants learn both phonemes and words, as indicated by the relationship between social behaviors during the sessions and brain measures documenting learning post-exposure (Conboy, Brooks, Meltzoff, and Kuhl, 2008).

These studies suggest that infants' computational abilities are enabled by social interaction, a situation mirrored in neurobiological studies on vocal communication learning in other species, such as birds (Doupe and Kuhl, 2008). The notion that social interaction acts as a 'gate' for infants initial language learning has important implications for children with autism that we are beginning to explore (see Kuhl, Coffey-Corina, Padden, and Dawson, 2005b; Kuhl, 2010a). The broader role of socio-cultural context on language learning is also illustrated in studies focusing on language and brain with children from families with low socio-economic status. Our work in this arena links the degree of left-hemisphere specialization for language and literacy at the age of 5 years to the extent to which a child's environment provides opportunities for learning (See Raizada, Richards, Meltzoff, and Kuhl, 2008; Neville, this volume). The growing body of work suggests that the early language environment of the child has a significant effect on the trajectory of language learning.

The model we have developed indicates that the interaction between computational skills and social cognition potentially opens the critical period for phonetic learning. Infants have computational skills from birth (Teinonen *et al.*, 2009). The fact that the effects of linguistic experience on phonetic perception are not observed until 8 months of age suggests that computation itself is not the trigger for learning. As discussed, we initially reasoned that infants might require 8 months of listening to build up reliable statistical distributions of the sounds contained in the language they expe-

rienced, but our results verified that 9-month-old infants did not require 8 months of listening to learn from experiencing a new language – they learned after less than 5 hours of exposure to a new language, as long as exposure occurred in a social context.

These data raise the possibility that infants' social skills – the ability to track eye movements, achieve joint visual attention, and begin to understand others' communicative intentions and develop at this time – serve as a trigger to instigate plasticity. Social understanding might be the 'gate' that initiates phonetic learning in human infants (Kuhl, in press). There is a neurobiological precedent for social interaction acting as a trigger for learning in songbirds. It is well established that a more natural social setting extends the learning period and that manipulating other social features can either shorten or extend the optimum period for learning (Knudsen, 2004; Wooley and Doupe, 2008). The possibility of a social interaction plasticity trigger in humans raises many new questions, and also has implications for developmental disabilities (see Kuhl, 2010a for discussion).

Bilingual language learning

In our model of early language development (Kuhl *et al.*, 2008), bilingual language learners are expected to follow the same principles as monolingual learners – both computational and social factors influence the period of plasticity. Nonetheless, we argue that this process might result in bilingual infants reaching the developmental transition in perception at a later point in time than infants learning either language monolingually. We have argued that infants learning two first languages simultaneously would remain open to experience for a longer period of time because they are mapping language input in two forms, each with distinct statistical distributions. Social input often links the statistical distribution for a particular language to individual social partners, and thus perhaps assists infants in separating the statistics of one language from another. If this reasoning is correct, it should take a longer period of time to begin to close the critical period in bilinguals because it takes longer for sufficient data from both languages to reach distributional stability – depending on factors such as the number of people in the infant's environment producing the two languages in speech directed toward the child, and the amount of input each speaker in the infant's environment provides. It would be highly adaptive for bilingual infants to remain perceptually open for a longer period of time.

Only a few studies have addressed the timing issue and results have been mixed, perhaps due to differences in methodology, differences in the amount of language exposure to the two languages in individual bilingual participants,

and the specific characteristics of the languages and speech contrasts studied. Bosch and Sebastián-Gallés (2003a) compared 4-, 8- and 12-month-old infants from Spanish monolingual households, Catalan monolingual households, and Spanish-Catalan bilingual households on a vowel contrast that is phonemic in Catalan but not in Spanish. Their results showed that at 4 months infants discriminated the vowel contrast but that at 8 months of age only infants exposed to Catalan succeeded. Interestingly, the same group of bilinguals regained their ability to discriminate the speech contrast at 12 months of age. The authors reported the same developmental pattern in bilingual infants in a study of consonants (Bosch and Sebastián-Gallés, 2003b) and in a later study of vowels (Sebastián-Gallés and Bosch, 2009). The authors interpreted their results as evidence that different processes may underlie bilingual and monolingual phoneme category formation.

In contrast, other investigations have found that bilingual infants discriminate phonetic contrasts in their native languages on the same timetable as monolingual infants. For example, Burns, Yoshida, Hill, and Werker (2007) tested consonant discrimination using English-relevant as well as French-relevant values at 6-8, 10-12, and 14-20 months in English monolingual and English-French bilingual infants. 6-8 month old English monolingual infants discriminated both contrasts while 10-12 and 14-20 month old English monolingual infants discriminated only the English contrast. In bilingual infants, all age groups were able to discriminate both contrasts. Similarly, Sundara, Polka, and Molnar (2008) found that 10-12-month-old French-English bilingual infants were able to discriminate a French /d/ from an English /d/ while age-matched French monolingual infants were unable to do so. These studies support the view that monolingual and bilingual infants develop phonetic representations at the same pace (see also Sundara and Scutellaro, in press).

We conducted a longitudinal study of English-Spanish bilingual infants using a brain measure of discrimination for phonetic contrasts in both languages (Event Related Potentials, or ERPs) and assessments of language input in the home at two early points in development, followed by examination of word production in both languages months later (Garcia-Sierra *et al.*, in press). It is the first ERP study of speech perception in bilingual infants that combined concurrent and longitudinal methods to assess early phonetic perception, early language exposure, and later word production. The study addressed three questions: Do bilingual infants show the ERP components indicative of neural discrimination for the phonetic units of both languages on the same timetable as monolingual infants? Is there a relationship between brain measures of phonetic discrimination and the amount of exposure to the two lan-

guages? Is later word production in the infants' two languages predicted by early ERP responses to speech sounds in both languages and/or the amount of early language exposure to each language?

As predicted by our model of speech perception development, bilingual infants displayed a pattern of neural commitment that is different from that of monolingual infants previously tested using the same stimuli and methods (Rivera-Gaxiola *et al.*, 2005a; Rivera-Gaxiola, Klarman, Garcia-Sierra, and Kuhl, 2005b). Rivera-Gaxiola *et al.* (2005a, b) collected data from English monolingual infants at 7 and 11 months of age. Monolingual infants at 7 months showed neural discrimination (in the form of a Mismatch negativity, or MMN) of both the native phonetic contrast (English) and the non-native contrast (Spanish); at 11 months monolingual infants showed an MMN for the native phonetic contrast (English) only, indicating that they had learned native sounds and were no longer in the initial universal stage of perception. Bilingual infants did not show an MMN for Spanish and English contrasts at 6–8 months, but showed a non-significant positivity, a more immature response. By 10–12 months of age, the MMN was observed for both contrasts. In studies of 11- and 14-month-old monolingual and bilingual infants, this pattern is replicated; bilingual infants show the MMN to sounds from their (two) native languages at a later point in time when compared to monolingual infants. We believe this represents an extended period of openness to experience in bilingual children (see Figure 6, p. 242).

Thus, our brain measures of bilingual phonetic development provide some support for the idea that bilingual infants instigate phonetic learning at the same time as monolingual infants, but that they may remain open to experience for a longer period of time. This pattern represents bilingual infants' highly adaptive response to their more variable language environments.

We also hypothesized that bilingual infants' discrimination of the sounds of English and Spanish would be related to language exposure in the home, and that the pattern of the relationship would be influenced by age. The results showed an interesting relationship between the pattern of brain activity as a function of high vs. low exposure to the language. Specifically, only infants who had high exposure to English (or Spanish), and consequently lower exposure to the second language, showed an age effect in their brain responses to speech. Work is underway to further investigate this relationship, but the findings of Garcia-Sierra *et al.* (in press) suggest that bilingual infants exposed to high levels of one language have neural responses to that language that resemble those of monolingual infants. Given the variability in language experience in bilingual infants, more research is required to determine how much language input is sufficient to close the

critical period, and, whether there is greater plasticity for language throughout life as a function of early experience with two languages.

Finally, we hypothesized a relationship between early brain measures and later word production, as well as relationships between early language exposure and later word production. Both hypotheses were confirmed. Children who were English dominant in word production at 15 months showed relatively better neural discrimination of the English contrast, as well as stronger English exposure in the home. Similarly, children who were Spanish dominant in word production at 15 months showed relatively better neural discrimination of the Spanish contrast and stronger Spanish exposure in the home.

Taken as a whole, the results suggest that bilingual infants tested with phonetic units from both of their native languages stay perceptually open longer when compared to monolingual infants – indicating perceptual narrowing at a later point in time. We reasoned that this is highly adaptive for bilingual infants. We also show that individual differences in infants' neural responses to speech, as well as their later word production, are influenced by the amount of exposure infants have to each of their native languages at home.

Is adult second language learning enhanced by social experience?

Can understanding the role of computational and social mechanisms help design interventions that improve adults' acquisition of a second language? Our studies in Japan with native speakers of Japanese attempting to learn English suggest that it may be possible. The difficulty of the /r-l/ distinction for native speakers of Japanese is well documented, even after extensive training (Flege, Takagi, and Mann, 1996; Goto, 1971; Miyawaki *et al.*, 1975; Yamada and Tohkura, 1992). We hypothesize that processing English requires the development of new distributional frequency maps unique to English, because early exposure to Japanese caused neural commitment to the distributional patterns of Japanese which would subsume English /r/ and /l/ into the Japanese /r/ category (see Fig 4, p. 240). Computational neural modeling experiments have produced findings that are consistent with this view (Vallabha and McClelland, 2007).

New training studies conducted by our laboratory group in collaboration with the MEG researchers at Nippon Telephone and Telegraph in Tokyo suggest that training which capitalizes on a natural infant-learning strategies may provide the impetus to build new perceptual maps during second language learning. We examined perception of English /ra/ vs. /la/ in ten Japanese subjects and ten American subjects (Zhang *et al.*, 2005). Behavioral measures included identification and discrimination of the speech syllables. MEG recordings were made while subjects listened to the syllables.

Listening to native language sounds resulted in brain activation that was both significantly more focalized in the brain and occurred with shorter durations – we interpreted these patterns as greater neural efficiency when listening to native language speech. We reasoned that neural efficiency reflected the expertise resulting from early learning, and that neural efficiency developed at the expense of neural plasticity.

We tested this notion in a follow-up training study, in which we used highly social speech signals to train Japanese listeners to respond to the /r/ and /l/ stimuli (Zhang *et al.*, 2009). Taking our cue from the ‘motherese’ studies, Japanese participants heard and viewed American speakers producing acoustically modified /ra/ and /la/ syllables. Stimuli had greatly exaggerated formant frequencies, reduced bandwidths, and extended durations, like those produced by mothers when speaking to their infants. In the computer-training program, listeners were allowed to choose from many different talkers, and the syllables presented varied greatly. The listeners presented the stimuli to themselves via computer during 12 sessions, and no explicit feedback was provided. The behavioral data revealed a significant improvement in identification of these English (nonnative) speech stimuli, larger by a factor of 3 over that reported by previous studies. Correspondingly, the MEG results showed greater neural efficiency in the left hemisphere – more focal brain activation over a shorter duration – when listening to the English syllables.

These results suggest that the principles underlying motherese speech may help elicit adult second-language learning. Three parameters are of greatest interest: (a) exaggeration of the acoustic dimensions critical to the phonetic contrast, (b) an unsupervised ‘social’ learning situation, and (c) wide variability in speech, mimicking natural learning. Our studies show that feedback and reinforcement are not necessary in this process; listeners simply need the right kind of listening experience exaggerated acoustic cues, multiple instances by many talkers who can be seen and heard and selected by the participants, and mass listening experience without ‘testing’ – features that motherese provides infants – may represent a natural way to learn a language. These features, especially the more social nature of the experience – seeing talkers and choosing to listen to them – may allow listeners to create new perceptual maps rather than simply subsuming the English /r/ and /l/ stimuli into existing Japanese distributions, which would obscure the English distinction (see McClelland, Thomas, McCandliss, and Fiez, 1999). We are exploring this further in current studies.

Phonetic learning predicts the rate of language growth

The forgoing review suggests that early phonetic learning is a complex process: Infants, computational skills are involved, as well as social cognition,

in opening a window of increased plasticity at about 8 months of life. Between 8 and 10 months monolingual infants show an increase in native language phonetic perception, a decrease in nonnative phonetic perception, and phonetic learning from a new language can be induced by social experience with a speaker of a new language in the laboratory (though not via a standard TV).

This early initial step in language learning is strongly correlated with the growth of future language skills, and with later pre-literacy skills. In our initial work demonstrating the link between early speech perception and later language, we conducted a longitudinal study examining whether a test of phonetic discrimination for vowels at 6 months of age predicted children's language skills measured up to 18 months later. The data demonstrated that infants' phonetic discrimination ability at 6 months of age was significantly correlated with their language skills at 13, 16, and 24 months of age (Tsao, Liu, and Kuhl, 2004). However, we recognized that in this initial study the association we observed might be due to infants' cognitive skills, such as the ability to perform in the behavioral task we used to assess discrimination, or to sensory abilities that affected auditory resolution of the differences in formant frequencies that underlie phonetic distinctions.

To address these issues, we assessed both native and nonnative phonetic discrimination in 7.5-month-old infants, and used both a behavioral (Kuhl *et al.*, 2005a) and an event-related potential measure, the mismatch negativity (MMN), to assess infants' performance (Kuhl *et al.*, 2008). Using a neural measure removed potential cognitive effects on performance; the use of both native and nonnative contrasts addressed the sensory issue, since better sensory abilities would be expected to improve both native and nonnative speech discrimination.

According to our developmental model, future language growth should be associated with early performance on both native and nonnative contrasts, but in opposite directions. We predicted that better *native* language perception should result in significantly advanced language abilities at 14, 18, 24, and 30 months of age, whereas better *nonnative* phonetic perception at the same age should show poorer language abilities at the same four future points in time. The results conformed to this prediction. When both native and nonnative phonetic discrimination was measured in the same infants at 7.5 months of age, (Kuhl *et al.*, 2005a; Kuhl *et al.*, 2008), better native speech discrimination was associated with better later language outcomes, whereas better nonnative performance was associated with poorer performance. Hierarchical linear growth modeling of vocabulary between 14 and 30 months for MMN values (see Figure 7, p. 242) showed that native and nonnative discrimination pre-

dicted future language, but in opposite directions. Better native discrimination predicted advanced future language development and better nonnative discrimination predicted less advanced future language development.

These results are explained by our model: better native phonetic discrimination enhances infants' skills in detecting words and this vaults infants towards language, whereas better nonnative abilities indicated that infants remained longer at an earlier phase of development – still sensitive to all phonetic differences. Infants' ability to *learn* which phonetic units are relevant in the language(s) in their environment, while decreasing or inhibiting their attention to the phonetic units that do not distinguish words in their language, is the necessary first step on the path toward language.

Importantly, recent data from our laboratory indicate *long*-term associations between early measures of infants' phonetic perception and future language and reading skills. Our studies show that the trajectory of change in the discrimination two simple vowels between 7 and 11 months of age predicts those children's language abilities and also their phonological awareness skills, which are critical to reading, at the age of 5 years (Cardillo, 2010; Cardillo Lebedeva and Kuhl, 2009).

Infants were tested at 7 and 11 months of age, and their patterns of speech perception development were categorized in one of three ways: (1) infants who show excellent native discrimination at 7 months and maintain that ability at 11 months – the 'high-high' group, (2) infants who show poor abilities at 7 months but increased performance at 11 months – the 'low-high' group, and (3) infants who show poor abilities to discriminate at both 7 and 11 months of age – the 'low-low' group. We followed these children until the age of 5: receptive and expressive language skills were assessed at 18 months, 24 months, and 5 years of age; phonological awareness skills, the most accurate measure of eventual reading skills, were assessed at age 5. Strong relationships were observed between infants' early speech perception performance and their later language skills at all ages, and between infants' early speech perception performance and phonological awareness skills at 5 years of age. In all cases, the infants who showed excellent skill in detecting phonetic differences in native language sounds by 11 months of age (the 'high-high' and the 'low-high' groups) had significantly higher expressive and receptive language skills at the ages of 18- and 24-months, as well as at the age of 5 years. Moreover, at the age of 5 years, these same two groups scored significantly higher in pre-literacy skills involving phonological awareness; importantly, these significance patterns held after measures of socio-economic status (SES) were partialled out in the regression analysis (Cardillo, 2010; Cardillo Lebedeva and Kuhl, 2009).

From theory to practice

While recommendations extending theory to practice should be done cautiously, it is not difficult to extend the results of early language and literacy studies reviewed here to practice. First, the data show that the initial steps that infants take toward language in the first year of life *matter* – they appear to be a pathway to children’s development of later language and literacy. Infants’ early language abilities, which can be tested with fairly simple measures in the first year of life, predict language skills and literacy skills up to 4.5 years later. While these data are correlational as opposed to causal in nature, our data allow us to begin to connect the dots and suggest that the richness of the early language environment of the child creates the kind of neural architecture that is necessary for robust language and literacy development. Our model and data suggest as well that environmental influences affect these early steps. The trajectory of phonetic learning between 6 and 12 months of life (which predict children’s future skills) are themselves strongly correlated with the complexity and frequency of the language young children experience at home (Raizada *et al.*, 2008; in preparation). Hearing the exaggerated speech known widely as ‘motherese’ early in development is strongly correlated with early speech discrimination measured in the laboratory (Liu, Kuhl and Tsao, 2003). Motherese exaggerates the critical acoustic cues in speech (Kuhl *et al.*, 1997; Werker *et al.*, 2007), and infants social interest in speech is, we believe, important to the social learning process. Thus, we assert that talking to children early in life, reading to children early in life, and doing both of these things while interacting socially with children around language and literacy activities, creates the milieu in which plasticity during the critical period can be maximized for all children.

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