

THE COGNITIVE NEUROSCIENCES

Fourth Edition

Michael S. Gazzaniga, *Editor-in-Chief*

Section Editors: Emilio Bizzi
Alfonso Caramazza
Leo M. Chalupa
Scott T. Grafton
Todd F. Heatherton
Christof Koch
Joseph E. LeDoux
Steven J. Luck
George R. Mangun
J. Anthony Movshon
Helen Neville
Elizabeth A. Phelps
Pasko Rakic
Daniel L. Schacter
Mriganka Sur
Brian A. Wandell

A BRADFORD BOOK
THE MIT PRESS
CAMBRIDGE, MASSACHUSETTS
LONDON, ENGLAND

2009

57 Early Language Acquisition: Neural Substrates and Theoretical Models

PATRICIA K. KUHL

ABSTRACT Infants learn language(s) with apparent ease, and the tools of modern neuroscience are providing valuable information about the mechanisms that underlie this capacity. Noninvasive, safe brain technologies have now been proven feasible for use with children starting at birth, and studies in the past decade at the phonetic, word, and sentence levels have produced an explosion in neuroscience research examining young children's language processing. At all levels of language, the neural signatures of learning can be documented at remarkably early points in development. Importantly both for theory and for the eventual application of this work to the diagnosis and treatment of developmental disabilities, early brain measures of infants' responses to phonetic differences are reflected in infants' language abilities in the second and third year of life. Developmental neuroscience studies using language are beginning to answer questions about the origins and development of human's language faculty.

Infants begin life with the capacity to detect phonetic distinctions across all languages, and they develop a language-specific phonetic capacity and acquire early words before the end of the first year (Jusczyk, 1997; Kuhl, Conboy, Padden, Rivera-Gaxiola, & Nelson, 2008; Werker & Curtin, 2005). A major question remains, however: Do infants' initial capacities and their ability to learn effortlessly from exposure to language reflect domain-specific mechanisms that operate exclusively on linguistic data or mechanisms that operate on more general learning mechanisms? In a classic debate, a nativist and a learning theorist took very different positions regarding the innate state and the nature of learning regarding language. Noam Chomsky (1959) argued that infants' innate capacities and the manner in which language was acquired were unique to language and to humans, while B. F. Skinner (1957) asserted that neither the initial state nor the manner in which language was learned was unique.

The tools of modern developmental neuroscience are bringing us closer to addressing these issues and may one

day help resolve the classic debate about the interaction between biology and culture that produces the human capacity for language. Neuroscientific studies will also provide valuable information that may allow us to diagnose developmental disabilities at a stage in development when interventions are more likely to improve children's lives.

Remarkable progress has been made in the last decade in scientists' abilities to examine the young infant brain while its owner processes language, reacts to social stimuli such as faces, listens to music, or hears the voice of the child's mother. This review focuses on the new techniques and what they are teaching us about the earliest phases of language acquisition.

Neuroscientific studies on infants and young children now extend from phonemes to words to sentences. These studies fuel the hope that an understanding of development in typically developing children and in children with developmental disabilities will be achieved. Studies show that exposure to language in the first year of life begins to set the neural architecture in a way that vaults the infant forward in the acquisition of language. The goal in this chapter is to explore what we have learned about the neural mechanisms that underlie language in typically developing children, and how they differ in children with developmental disabilities that involve language such as autism.

Neuroscience techniques measure language processing in the young brain

Rapid advances have been made in the development of noninvasive techniques to examine language processing in infants and young children (figure 57.1). These methods include electroencephalography (EEG)/event-related potentials (ERPs), magnetoencephalography (MEG), functional magnetic resonance imaging (fMRI), and near-infrared spectroscopy (NIRS). ERPs have been widely used to study speech and language processing in infants and young children (for reviews see Conboy, Rivera-Gaxiola, Silva-Pereyra, & Kuhl, 2008; Friederici, 2005; Kuhl, 2004; Kuhl

PATRICIA K. KUHL, Institute for Learning and Brain Sciences, University of Washington, Seattle, Washington

Neuroscience techniques used with infants

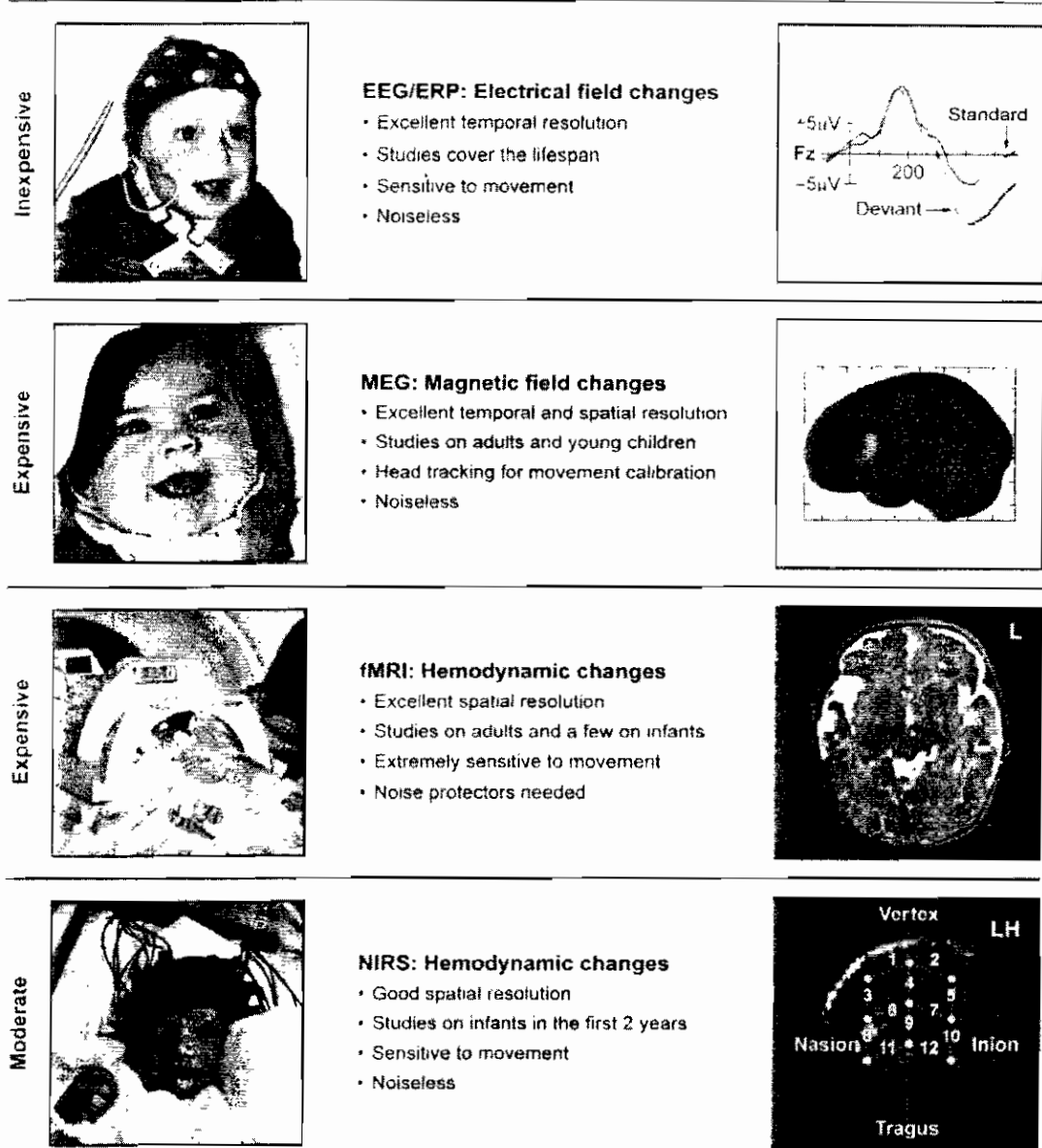


FIGURE 57.1 Four neuroscience techniques now used with infants and young children to examine the brain's responses to linguistic signals. (From Kuhl & Rivera-Gaxiola, 2008.)

& Rivera-Gaxiola, 2008). Event-related potentials (ERPs), a part of the EEG, reflect electrical activity that is time-locked to the presentation of a specific sensory stimulus (e.g., syllables, words) or a cognitive process (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, because of age or cognitive impairment, cannot provide overt responses. 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. MEG (as well as EEG) techniques are safe and noiseless, allowing data collection while infants listen to language in a quiet environment. 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. MEG allows precise localization of the neural currents responsible for the sources of the magnetic fields, and it has been used to test phonetic discrimination in adults (Kujala, Alho, Service, Ilmoniemi, & Connolly, 2004).

Recently a genuine advance was documented by the first MEG studies testing awake infants in the first year of life (Bosseler et al., 2008; Cheour et al., 2004; Imada et al., 2006, 2008). In these studies, the use of sophisticated head-tracking software and hardware allows correction for infants' head movements, so infants are free to move comfortably during the tests. MEG studies allow whole-brain imaging during speech discrimination, which is now providing data on the location and timing of brain activation in critical regions (Broca's and Wernicke's) involved in language acquisition (see Bosseler et al.; Imada et al., 2006, 2008).

MEG and/or EEG can be combined with magnetic resonance imaging (MRI), a technique that provides static structural/anatomical pictures of the brain. Using mathematical modeling methods, the specific brain regions that produce the magnetic or electrical signals can be identified in the human brain with high spatial resolution (millimeter). Structural MRIs allow measurement of anatomical changes in white and gray matter in specific brain regions across the life span. MRIs can be superimposed on the physiological activity detected by MEG or EEG to refine the spatial localization of brain activities for individual participants.

Functional magnetic resonance imaging (fMRI) is now considered a standard method of neuroimaging in adults because it provides high-spatial-resolution maps of neural activity across the entire brain (e.g., Gernsbacher & Kachak, 2003). However, 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/firing. Neural events happen in milliseconds, while the blood-oxygenation changes that they induce are spread out over several seconds, thereby severely limiting fMRI's temporal resolution. Adult studies are employing new fMRI data-analysis methods for speech stimuli and correlating the fMRI data to behavioral data. For example, Raizada, Tsao, Liu, and Kuhl (2009), using a multivariate pattern classifier, showed that English—but not Japanese—speakers exhibited distinct neural activity patterns for /ra/ and /la/ in primary auditory cortex. Subjects who behaviorally distinguished the sounds most accurately also had the most distinct neural activity patterns.

Functional MRI techniques would be very valuable with infants, but few studies have attempted fMRI with infants (Dehaene-Lambertz, Dehaene, & Hertz-Pannier, 2002; Dehaene-Lambertz, Hertz-Pannier, Dubois, Meriaux, & Roche, 2006). The technique requires subjects to be perfectly still, and the MRI device produces loud sounds making it necessary to shield infants' ears while delivering language stimuli.

Near-infrared spectroscopy (NIRS) also measures cerebral hemodynamic responses in relation to neural activity, but employs the absorption of light, which is sensitive to the concentration of hemoglobin, to measure activation (Aslin & Mehler, 2005). NIRS utilizes near-infrared light to measure changes in blood oxy- and deoxyhemoglobin concentrations in the brain as well as total blood volume changes in various regions of the cerebral cortex. The NIRS system can determine where and how active the specific regions of the brain are by continuously monitoring blood hemoglobin levels, and reports have begun to appear on infants in the first two years of life (Bortfeld, Wruck, & Boas, 2007; Hornac, Watanabe, Nakano, Asakawa, & Taga, 2006; Pena et al., 2003; Taga & Asakawa, 2007). Hornac and colleagues, for example, provided data using NIRS that suggest that sleeping 3-month-old infants process the prosodic information in sentences in the right temporoparietal region. As with other techniques relying on hemodynamic changes such as fMRI, NIRS does not provide good temporal resolution. One of the most important uses of this technique is that coregistration with other testing techniques such as EEG and MEG may be possible.

The use of these techniques with infants and young children has produced an explosion of neuroscience studies using stimuli that tap all levels of language—phoneme, word, and sentence. In the next sections, examples of recent findings will be described to give a sense of the promise of neuroscience for the study of language acquisition in children.

Neural signatures of phonetic learning in typically developing children

Perception of the basic units of speech—the vowels and consonants that make up words—is one of the most widely studied behaviors in infancy and adulthood, and studies using ERPs have advanced our knowledge of development and learning.

Behavioral studies demonstrated that at birth young infants exhibit a universal capacity to detect differences between phonetic contrasts used in the world's languages (Eimas, Siqueland, Jusczyk, & Vigorito, 1971). We have referred to this as Phase 1 in development (Kuhl et al., 2008). This universal capacity is dramatically altered by language experience starting as early as 6 months for vowels and by 10 months for consonants: over time, native language

phonetic abilities significantly increase (Cheour et al., 1998; Kuhl et al., 2006; Kuhl, Williams, Lacerda, Stevens, & Lindblom, 1992; Rivera-Gaxiola, Silva-Pereyra, & Kuhl, 2005; Sundara, Polka, & Genesee, 2006) while the ability to discriminate phonetic contrasts that are not relevant to the language of the culture declines (Best & McRoberts, 2003; Cheour et al., 1998; Kuhl et al., 2006; Rivera-Gaxiola, Silva-Pereyra, et al., 2005; Werker & Tees, 1984).

By the end of the first year, the infant brain is no longer universally prepared for all languages, but primed to acquire the specific one(s) to which they have been exposed. We refer to this as Phase 2 in infant phonetic development (Kuhl et al., 2008). The explanation of this transition from Phase 1 to Phase 2 has become the focus of intense study because it illustrates the interaction between biology and culture—between infants' initial state and infants' abilities to learn. Speech offers the opportunity to study the brain's ability to be shaped implicitly by experience.

Kuhl and colleagues (2008) examined whether the transition in phonetic perception from a language-general ability to a language-specific one—from Phase 1 to Phase 2—can be linked to the growth of language. The work provided a critical test stemming from the native language neural commitment (NLNC) hypothesis (Kuhl, 2004). According to NLNC, initial native language learning involves *neural commitment* to the patterned regularities contained in ambient speech, with bidirectional effects: neural coding facilitates the detection of more complex language units (words) that build on initial learning, while simultaneously reducing attention to alternate patterns, such as those of a foreign language.

This formulation suggests that infants with excellent phonetic learning skills should advance more quickly toward language. In contrast, foreign-language phonetic perception reflects the degree to which the infant brain remains uncommitted to native-language patterns—still in Phase 1 as it were—at a more universal and immature phase of development. Infants in Phase 1 remain “open” to nonnative-speech patterns. As an open system reflects uncommitted circuitry, infants who remain highly skilled at discriminating foreign-language phonetic units would be expected to show a slower progression toward language.

New ERP studies of infants support the NLNC assertion. Kuhl and colleagues (2008) measured infants' ERPs at 7.5 months of age in response to changes in native (/p-t/) and nonnative (Mandarin /q-tʰ/ and Spanish /t-d/) phonemes. The mismatch negativity (MMN), which has been shown in adults to be a neural correlate of phonetic discrimination (Näätänen et al., 1997), was calculated for both the native and nonnative phonemes for each infant. Individual variation was observed for both native and nonnative discrimination, representing either “noise” or meaningful differences among infants.

The results supported the idea that the differences among infants were meaningful. MMN measurements taken at 7.5 months—for both the native and the nonnative phonetic contrasts—predicted later language. However, and in accord with the NLNC hypothesis, the native and nonnative contrasts predicted language growth in opposing directions (Kuhl et al., 2008).

The MMN component was elicited in individual infants (figure 57.2A). Native and nonnative contrasts were measured in counterbalanced order, and the MMN was observed between 250 and 400 ms (figure 57.2B). For the infant shown in figure 57.2A, greater negativity of the MMN, indicating better neural discrimination, was shown for the native when compared to the nonnative phonetic contrast; other infants showed equal discrimination for the two contrasts or better discrimination of the nonnative contrast. Infants' language abilities were measured at four later points in time: 14, 18, 24, and 30 months of age using the MacArthur-Bates Communicative Development Inventories (CDI), a reliable and valid measure assessing language and communication development from 8 to 30 months of age (Fenson et al., 1993).

The MMN measures taken at 7.5 months of age were related to the language measures taken between 14 and 30 months of age. For the native contrast, the strength of the MMN (better discrimination) predicted accelerated word production at 24 months, greater sentence complexity at 24 months, and longer mean length of utterance at 30 months of age. In contrast, for the nonnative stimulus pair, the strength of the MMN at the same age in the same infants predicted slower language development at the same future points in time. Behavioral (Kuhl, Conboy, Padden, Nelson, & Pruitt, 2005) and brain measures (Kuhl et al., 2008), collected on the same infants, were significantly correlated.

This pattern, showing differential effects of good discrimination for the native and nonnative contrasts, can be readily seen in the growth of vocabulary from 14 to 30 months (figure 57.2C). Hierarchical Linear Growth Curve modeling (Raudenbush, Bryk, Cheong, & Congdon, 2005) shows that both native and nonnative discrimination at 7.5 months significantly predicts vocabulary growth, but the effects of good phonetic discrimination are reversed for the native and nonnative predictors. Better native phonetic discrimination predicts accelerated vocabulary growth, whereas better nonnative phonetic discrimination predicts slower vocabulary growth (Kuhl et al., 2008). These results support the NLNC hypothesis.

Rivera-Gaxiola and colleagues (Rivera-Gaxiola, Klarman, García-Sierra, & Kuhl, 2005; Rivera-Gaxiola, Silva-Pereyra, et al., 2005) demonstrated a similar pattern of prediction using a different nonnative contrast. They recorded auditory ERP complexes in 7- and 11-month-old American infants in response to both Spanish and English voicing contrasts.

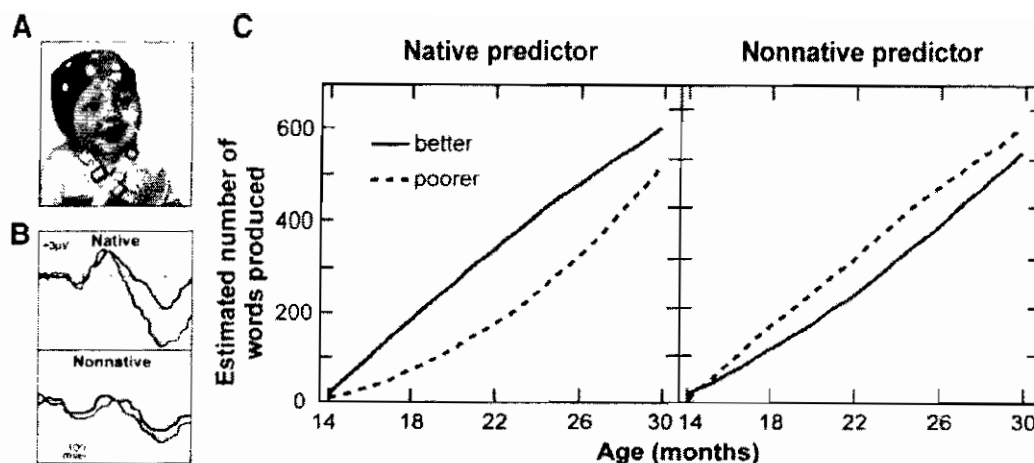


FIGURE 57.2 (A) A 7.5-month-old infant wearing an ERP electrocap (B) Infant ERP waveforms at one sensor location (CZ) for one infant in response to native (English) and nonnative (Mandarin) phonetic contrast at 7.5 months. The mismatch negativity (MMN) is obtained by subtracting the standard waveform (black) from the deviant waveform (gray). This infant's response suggests that native-language learning has begun because the MMN negativity in response to the native English contrast is considerably stronger (more negative) than that to the nonnative contrast (C) Hierarchical linear growth modeling of vocabulary growth between 14 and 30 months is shown for two groups of

Two patterns of ERP response were observed— an early positive-going wave (P150–250) and a later negative-going wave (N250–550) (Rivera-Gaxiola, Silva-Pereyra, et al., 2005). Further work examined the patterns of the same auditory ERP positive-negative complexes in a larger sample of 11-month-old monolingual American infants using the same contrasts used in the developmental study, and found that infants' response to the nonnative contrast predicted the number of words produced at 18, 22, 25, 27, and 30 months of age (Rivera-Gaxiola, Klarman, et al., 2005). Infants showing an N250–550 to the foreign contrast at 11 months of age (indexing better neural discrimination) produced significantly fewer words at all ages when compared to infants showing a less negative response. Scalp distribution analyses on 7-, 11-, 15-, and 20-month-old infants revealed that the P150–250 and the N250–550 components differ in distribution (Rivera-Gaxiola et al., 2007). Thus in both Kuhl and colleagues (2008) and Rivera-Gaxiola, Klarman, and colleagues (2005), an enhanced negativity in response to the nonnative contrast is associated with slower language development.

The continuity in language development documented in these studies using infants' early phonetic skills to predict later language (Kuhl, Conboy, et al., 2005; Kuhl et al., 2008; Rivera-Gaxiola, Klarman, et al., 2005; Tsao, Liu, & Kuhl, 2004) is also seen in studies that use infants' early pattern detection skills for speech to predict later language

children, those whose MMN values at 7.5 months indicated better discrimination (-1 SD) and those MMN values indicated poorer discrimination ($+1$ SD). Vocabulary growth was significantly faster for infants with better MMN phonetic discrimination for the native contrast at 7.5 months of age (C, left). In contrast, infants with better discrimination for the nonnative contrasts (-1 SD) as indicated by MMN at 7.5 months showed slower vocabulary growth (C, right). Both contrasts predict vocabulary growth, but the effects of better discrimination are reversed for the native and nonnative contrasts. (From Kuhl & Rivera-Gaxiola, 2008.)

(Newman, Ratner, Jusczyk, Jusczyk, & Dow, 2006), as well as in studies that use infants' early processing efficiency for words to predict later language (Fernald, Perfors, & Marchman, 2006). Taken as a whole, these studies form bridges between the early precursors to language in infancy and measures of language competencies in early childhood, bridges that are important to theory building as well as to clinical populations with developmental disabilities that involve language.

ERP studies at the phonetic level suggest that the young brain's response to the elementary building blocks of language matters and that initial native language phonetic learning is a pathway to language (Kuhl, 2008). The data also suggest that discriminating nonnative phonetic contrasts for a longer period of time in early development—reflecting infants' initial, more immature state—can be linked to slower language development. In infants exposed to a single language, the ability to attend to changes in the phonetic contrasts that are relevant to the culture's language, while at the same time reducing attention to phonetic contrasts from other languages that are discriminable but irrelevant to the language of their culture, appears to be an important first step toward the acquisition of language. What neuroscience tools may allow us to do in the future is to understand this process and its relation to the "critical period" for language development (see Kuhl, Conboy, et al., 2005, for discussion).

Brain measures of learning from exposure to a second language

Recent studies have shown that young infants are capable of phonetic learning at 9 months of age from exposure to a new language but only when exposure occurs during live human presentation; television or audio-only exposure did not produce learning (Kuhl, Tsao, & Liu, 2003). Social interaction appears to be a critical component for language learning, a finding that ties early communicative learning in speech to examples of communicative learning in neurobiology more generally, as shown by the importance of social factors in song learning in birds (e.g., Brainard & Knudsen, 1998). I have used these second-language exposure studies to argue that the social brain may “gate” the computational mechanisms underlying language learning during the earliest stages of human language acquisition (Kuhl, 2007).

The social “gating” hypothesis was tested in studies using ERP measures of second-language learning (Conboy, Brooks, Taylor, Meltzoff, & Kuhl, 2008; Conboy & Kuhl, 2007). In the study, American monolingual infants were exposed to Spanish at 9 months of age by native Spanish speakers, and their ability to learn both phonemes and words from this foreign-language exposure was tested. The study tested the social hypothesis by examining whether the infants’ tendency to interact in socially sophisticated ways during the exposure sessions would predict the degree to which individual infants learned both phonemes and words from the new language.

Infants’ ERPs in response to English and Spanish phonemes, as well as their ERP responses to Spanish words, were measured before and after exposure to Spanish. As in the Mandarin study, exposure consisted of live interaction with foreign-language “tutors” during 12 sessions, each of which lasted 25 minutes. All sessions were videotaped using a four-camera system, and detailed measures of shared visual attention between the infants and their tutors were taken by an independent observer.

The ERP results demonstrated that the MMN response to the Spanish contrast was not present before exposure, but that following exposure to Spanish, the MMN was robust (Conboy & Kuhl, 2007), replicating the behavioral findings in the Mandarin study (Kuhl et al., 2003). This result confirms infants’ ability to learn phonetically from exposure to a foreign language at 9 months of age. Extending these previous findings beyond phoneme learning, Conboy and Kuhl also showed that infants learned Spanish words that were presented during the exposure sessions. When compared to Spanish words that had not been presented, infants’ ERPs to the Spanish words revealed the classic components related to known words (Conboy & Kuhl, 2007).

The social gating hypothesis was also strongly supported. Infants’ degree of social engagement—for example, the

degree to which infants alternated their visual attention between a newly presented toy and the tutor’s eyes, as opposed to simply focusing on the toy or on the tutor—predicted the degree of learning both for phonemes and for words (Conboy, Brooks, et al., 2008). In other words, the degree to which an individual infant interacted socially during the 12 language sessions predicted the degree of learning measured well after the four-week exposure was complete (Conboy, Brooks, et al., 2008). Gaze following has previously been shown to predict word learning in infants (Brooks & Meltzoff, 2008). These results show that the relationship between social interaction and language learning can be demonstrated experimentally for new learning of language material at 9 months of age. Finally, the results of the study suggest the possibility that exposure to a new language provides a cognitive enhancement. Pre- and post-exposure measures of “cognitive control”—the ability to attend selectively and inhibit prepotent responses, which has previously been shown to be enhanced in bilingual adults (Bialystok, 1999) and children (Carlson & Meltzoff, 2008)—were also obtained from the children involved in the language exposure experiments. These measures indicated that cognitive control skills are enhanced after, but not prior to, Spanish exposure, linking bilingual learning to the enhancement of particular cognitive skills (Conboy, Sommerville, & Kuhl, 2008).

In sum, ERPs provide a highly sensitive measure of learning for both phonemes and words. ERP responses to speech not only predict the growth of language over the first 30 months (Kuhl et al., 2008; Rivera-Gaxiola, Klarman, et al., 2005), but are also sufficiently sensitive to reflect the subtle abilities that contribute to infant learning, such as infants’ social eye-gaze following (Conboy, Brooks, et al., 2008). Complex natural language learning may demand social interaction, because language evolved in a social setting. The neurobiological mechanisms underlying language likely utilized interactional cues made available only in a social setting. In the future, whole-brain measures, such as those provided by MEG, will allow us to observe brain activation during live presentations of language versus those that are merely televised to explore hypotheses about why human interaction is essential to language learning (Kuhl et al., 2003). Moreover, using “social” robots, we are now conducting studies that will define what constitutes a social agent for a young child (Virnes, Cardillo, Kuhl, & Movellan, 2008).

Neural signatures of word learning

A sudden increase in vocabulary typically occurs between 18 and 24 months of age—a “vocabulary explosion” (Fernald et al., 2006; Ganger & Brent, 2004)—but word learning starts much earlier. Infants show recognition of their own

name at 4.5 months (Mandel, Jusczyk, & Pisoni, 1995). At 6 months, infants use their own names or the word *Mommy* in an utterance to identify word boundaries (Bortfeld, Morgan, Góhnikoff, & Rathbun, 2005) and look appropriately to pictures of their mother or father when hearing *Mommy* or *Daddy* (Fincoff & Jusczyk, 1999). By 7 months, infants listen longer to passages containing words they previously heard rather than passages containing words they have not heard (Jusczyk & Hohne, 1997), and by 11 months infants prefer to listen to words that are highly frequent in language input over infrequent words (Halle & de Boysson-Bardies, 1994).

Behavioral studies indicate that infants learn words using both “statistical learning” strategies in which the transitional probabilities between syllables are exploited to identify likely words (Newport & Aslin, 2004; Saffran, 2003; Saffran, Aslin, & Newport, 1996) and pattern detection strategies in which infants use the typical pattern of metric stress that characterizes ambient language to segment running speech into likely words (Cutler & Norris, 1988; Höhle, Bijeljac-Babic, Herold, Weissenborn, & Nazzi, 2009; Johnson & Jusczyk, 2001; Nazzi, Iakimova, Bertoncini, Frédonic, & Alcantara, 2006).

How is word recognition evidenced in the brain? ERPs in response to words index word familiarity as early as 9 months of age and word meaning by 13–17 months of age. ERP studies have shown differences in amplitude and scalp distributions for components that are related to words that are known versus unknown to the child (Mills, Coffey-Corina, & Neville, 1993, 1997; Mills, Plunkett, Prat, & Schafer, 2005; Molfese, 1990; Molfese, Morse, & Peters, 1990; Molfese, Wetzell, & Gill, 1993; Thierry, Vihman, & Roberts, 2003).

As early as 9 months of age, ERPs indicate word familiarity, and by 13–17 months of age, studies show ERP components that reliably signal the brain’s coding of words that are known versus unknown by the child (Mills et al., 1993, 1997, 2005; Molfese et al., 1990, 1993; Thierry et al., 2003). Toddlers with larger vocabularies tend to have a more focalized and larger N200 for known words—they show an enhanced negativity to known versus unknown words only at left temporal and parietal electrode sites—whereas children with smaller vocabularies show more broadly distributed effects (Mills et al., 1993), features that also distinguish typically developing preschool children from preschool children with autism (Coffey-Corina, Padden, Kuhl, & Dawson, 2007).

Processing efficiency for phonemes and words can be seen as well in the relative focalization and duration of brain activation in adult MEG studies (Zhang, Kuhl, Imada, Kotani, & Tohkura, 2005), indicating that these features index language experience and proficiency not only in children (Comboy, Riverra-Gaxiola, et al., 2008; Friederici,

2005), but also over the life span. Individual differences in the response latency to a familiar word at the age of 2 are related to both lexical and grammatical measures collected between 15 and 25 months, providing more evidence that processing speed is associated with greater language facility (Fernald et al., 2006).

Mills and colleagues (2005) used ERPs in 20-month-old toddlers to examine new word learning. The children listened to known and unknown words, and to nonwords that were phonotactically legal in English. ERPs were recorded as the children were presented with novel objects paired with the nonwords. After the learning period, ERPs to the nonwords that had been paired with novel objects were shown to be similar to those of previously known words, suggesting that new words may be encoded in the same neural regions as previously learned words.

ERP studies on German infants reveal the development of word-segmentation strategies based on the typical stress patterns of German words. When presented with bisyllabic strings with either a trochaic (typical in German) or iambic pattern, infants who heard a trochaic pattern embedded in an iambic string showed the N200 ERP component, similar to that elicited in response to a known word, whereas infants presented with the iambic bisyllable embedded in the trochaic pattern showed no response (Weber, Hahne, Friedrich, & Friederici, 2004). The data suggest that German infants at this age are applying a metric segmentation strategy, consistent with the behavioral data of Höhle and colleagues (2009).

Infants’ early lexicons

There is evidence suggesting that young children’s word representations are phonetically underspecified. Children’s growing lexicons must code words in a way that distinguishes words from one another, and, given that by the end of the first year infants’ phonetic skills are language specific (Best & McRoberts, 2003; Kuhl et al., 2006; Werker & Tees, 1984), it was assumed that children’s early word representations were phonetically detailed. However, studies suggest that learning new words taxes young children’s capacities, and that as a result, new word representations are not phonetically complete.

Reactions to mispronunciations—the age at which children no longer accept *tip* for *cup* or *bog* for *dog*—provides information about phonological specificity. Studies across languages suggest that by one year of age mispronunciations of common words (Fennel & Werker, 2003; Jusczyk & Aslin, 1995), words in stressed syllables (Vihman, Nakai, DePaolis, & Halle, 2004), or monosyllabic words (Swingley, 2005) are not accepted as target words, indicating well-specified representations. Other studies using visual fixation of two targets (e.g., apple and ball) while one is named (*Where’s the ball?*)

show that between 14 and 25 months children's tendencies to fixate the target item when it is mispronounced diminish over time (Bailey & Plunkett, 2002; Ballem & Plunkett 2005; Swingley & Aslin, 2000, 2002).

However, behavioral and neural evidence suggests that learning new words can tax children's phonological skills. Stager and Werker (1997) demonstrated that 14-month-old infants fail to learn new words when similar-sounding phonetic units are used to distinguish those words ("bih" and "dih"), but do learn if the two new words are distinct phonologically ("leef" and "neem"). By 17 months of age, infants can learn to associate similar-sounding nonsense words to novel objects (Bailey & Plunkett, 2002; Werker, Fennell, Corroran, & Stager, 2002). Infants with larger vocabularies succeeded on this task even at the younger age, suggesting the possibility that infants with greater phonetic learning skills acquire new words more rapidly, consistent with studies showing that better native phonetic learning skills are associated with advanced word-learning skills (Kuhl, Conboy, et al., 2005; Kuhl et al., 2008; Rivera-Gaxiola, Klarman et al., 2005; Tsao et al., 2004).

Mills and colleagues (2004) used ERPs to corroborate these results. They compared ERP responses to familiar words that were either correctly pronounced or mispronounced, as well as nonwords. At the earliest age tested, 14 months, a negative ERP component (N200-400) distinguished known versus dissimilar nonsense words (*bear* versus *kobe*) but not known versus phonetically similar nonsense words (*bear* versus *gare*). By 20 months, this same ERP component distinguished correct pronunciations, mispronunciations, and nonwords, supporting the idea that between 14 and 20 months children's phonological representations of early words become increasingly detailed. Other evidence of early processing limitations stems from infants' failure to learn a novel word when its auditory label closely resembles a word they already know (*gall* which closely resembles *ball*), suggesting lexical competition effects (Swingley & Aslin, 2007).

How phonetic and word learning interact—and whether the progression is from phonemes to words, words to phonemes, or bidirectional—is a topic of strong interest that will be aided by the use of neuroscientific methods. Recent theoretical models of early language acquisition such as NLM-c (Kuhl et al., 2008) and PRIMER (Werker & Curtin, 2005), suggest that phonological and word learning may bidirectionally influence one another. On the one hand, infants with better phonetic learning skills advance more quickly toward language because phonetic skills assist the detection of phonotactic patterns, the detection of transitional probabilities in adjacent syllables, and the ability to phonologically distinguish minimally contrastive words (Kuhl, Conboy, et al., 2005). On the other hand, the more words children

learn, the more crowded lexical space becomes, putting pressure on children to attend to the phonetic units that distinguish them (see Swingley & Aslin, 2007, for discussion). Further studies examining both phoneme and word learning in the same children, as in the studies using exposure to a foreign language and ERP measures as assessments of learning, will help address this issue (Conboy & Kuhl, 2007).

ERP research shows that the young brain has difficulty representing phonetic detail when focused on the task of assigning a new auditory label to a novel object. ERP results also show that brain signatures distinguish words that are known from ones that are unfamiliar to toddlers. ERPs recorded to words in the first two years suggest that experience with words results in the formation of neural representations of those words that are increasingly well specified toward the end of the second year of life.

Neural signatures of early sentence processing

To understand sentences, the child must have exquisite phonological abilities that allow segmentation of the speech signal into words, and the ability to extract word meaning. In addition, the relationship among words composing the sentence—between a subject, its verb, and its accompanying object—must be deciphered to arrive at a full understanding of the sentence. Human language is based on the ability to process hierarchically structured sequences (Friederici, Fiebach, Schleewsky, Bornkessel, & von Cramon, 2006).

Electrophysiological components have been recorded in children and contribute to our knowledge of when and how the young brain decodes syntactic and semantic information in sentences. In adults, specific neural systems process semantic versus syntactic information within sentences, and the ERP components elicited in response to syntactic and semantic anomalies are well established (figure 57.3). For example, a negative ERP wave occurring between 250 and 500 ms that peaks around 400 ms, referred to as the N400, is elicited to semantically anomalous words in sentences (Kutas, 1997). A late positive wave peaking at about 600 ms and largest at parietal sites, known as the P600, is elicited in response to syntactically anomalous words in sentences (Friederici, 2002). And a negative wave over frontal sites between 300 and 500 ms, known as the "late anterior negativity" (LAN), is elicited in response to syntactic and morphological violations (Friederici, 2002).

Beginning in the second year of life, ERP data on sentence processing in children suggest that adultlike components in response to semantic and syntactic violations can be elicited, but also that there are differences in the latencies and scalp distributions of these components in children and adults (Harris, 2001; Friederich & Friederici, 2005, 2006; Oberecker & Friederici, 2006; Oberecker, Friedrich,

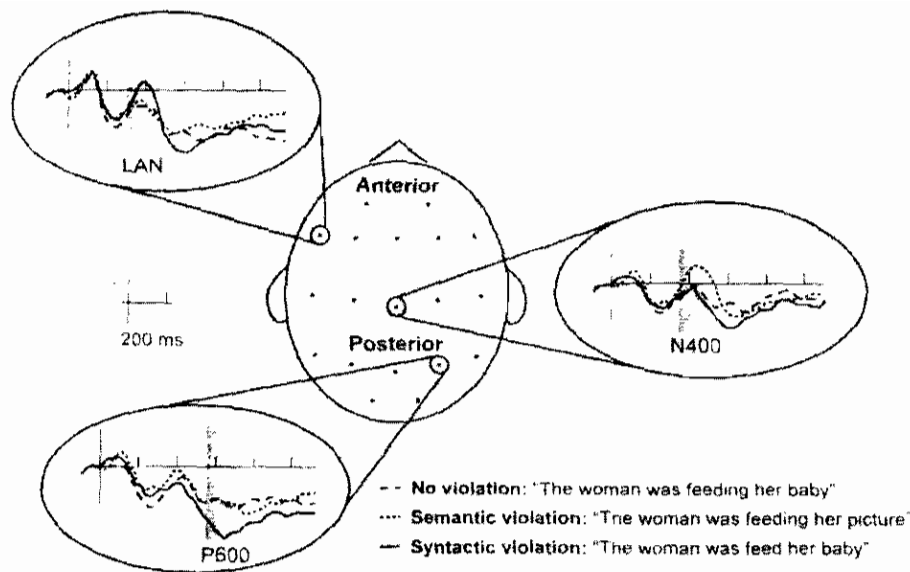


FIGURE 57.3 ERP responses to normal sentences and sentences with either semantic or syntactic anomalies show distinct distribution and polarity differences in adults. (From Kuhl & Rivera-Gaxiola, 2008.)

& Friederici, 2005; Silva-Pereyra, Conboy, Klarman, & Kuhl, 2007; Silva-Pereyra, Klarman, Lin, & Kuhl, 2005; Silva-Pereyra, Rivera-Gaxiola, & Kuhl, 2005). Holcomb, Coffey, and Neville (1992) reported the N400 in response to semantic anomaly in children from 5 years of age to adolescence; the latency of the effect was shown to decline systematically with age (see also Hahne, Eckstein, & Friederici, 2004; Neville, Coffey, Holcomb, & Tallal, 1993). Studies also show that syntactically anomalous sentences elicit the P600 in children between 7 and 13 years of age (Hahne et al.).

Recent studies have examined these ERP components in preschool children. Harris (2001) reported an N400-like effect in 36-38-month-old children, which was largest over posterior regions of both hemispheres, unlike the adult scalp distribution. Friederich and Friederici (2005) observed an N400-like wave to semantic anomalies in 19- and 24-month-old German-speaking children.

Silva-Pereyra, Rivera-Gaxiola, and Kuhl (2005) recorded ERPs in children between 36 and 48 months of age in response to semantic and syntactic anomalies. In both cases the ERP effects in children were more broadly distributed and elicited at later latencies than in adults. In work with even younger infants (30 month olds), Silva-Pereyra, Klarman, and colleagues (2005) used the same stimuli and observed late positivities distributed broadly posteriorly in response to syntactic anomalies and anterior negativities in response to semantically anomalous sentences, though in each case with longer latencies than seen in the older children and in adults (figure 57.4), a pattern seen repeatedly

and attributed to the immaturities and inefficiencies of the developing processing mechanisms.

Syntactic processing of sentences with semantic content information removed – “jabberwocky sentences” – has also been tested using ERP measures with children. Silva-Pereyra and colleagues (2007) recorded ERPs to phrase structure violations in 36-month-old children using sentences in which the content words were replaced with pseudowords while leaving grammatical function words intact. The ERP components elicited to the jabberwocky phrase-structure violations differed from the same violations in real sentences. Two negative components, one from 750 to 900 ms and the other from 950 to 1050 ms, rather than the positivities seen in response to phrase structure violations in real sentences in the same children, were observed. Jabberwocky studies with adults (Canseco-Gonzalez, 2000; Hahne & Jeschenick, 2001; Munte, Matzke, & Johannes, 1997) have also reported negative-going waves for jabberwocky sentences, though at much shorter latencies.

ERP measures of early language processing in children with autism spectrum disorder (ASD)

Scientific discoveries on the progression toward language by typically developing children are now providing new insights into the language deficit shown by children with autism spectrum disorder (ASD). Neural measures of language processing in children with autism, involving both phonemes and words, when coupled with measures of ASD children’s social interest in speech, are revealing a tight coupling

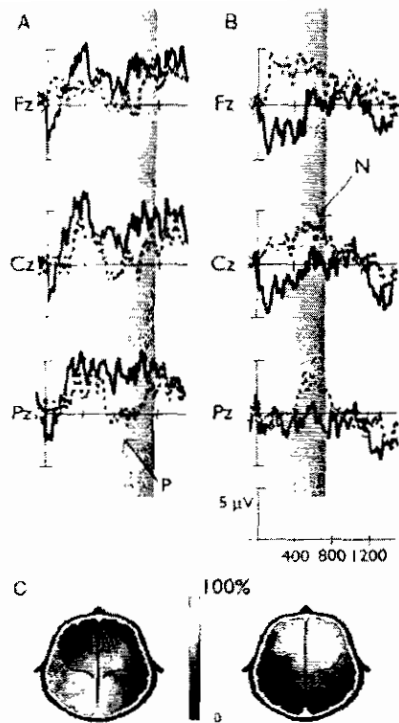


FIGURE 57.4 ERP waveforms elicited from 30-month-old children in response to sentences with (A) syntactic or (B) semantic violations. (C) Children's ERP responses resemble those of adults (see figure 57.3) but have longer latencies and are more broadly distributed. (From Silva-Pereira, Klarman, Lin, & Kuhl, 2005.)

between social interaction skills and language acquisition. These measures hold promise as potential diagnostic markers of risk for autism in very young children, and therefore there is a great deal of excitement surrounding the application of these basic measures of speech processing in very young children with autism.

In typically developing children, ERP responses to simple speech syllables such as "pa" and "ta" predict the growth of language to the age of 30 months (Kuhl et al., 2008). It is therefore interesting to test whether ERP measures of autism at the phonetic level are sensitive to the degree of severity of autism, and also the degree to which the brain's responses to syllables can be predicted by other factors, such as a social interest in speech.

The first study of preschool-aged children with ASD using ERP methods examined phonetic perception (Kuhl, Coffey-Corina, Padden, & Dawson, 2005). ERPs to a simple change in two speech syllables, as well as a measure of social interest in speech, were taken. In these experiments, a listening choice test allowed young toddlers with autism to select between listening to motherese or nonspeech signals in which the formant frequencies of speech were matched by pure tones—the resulting signal was a computer warble

that exactly followed the frequencies and amplitudes of the 5-s speech samples over time. Slight head turns in one direction or the other allowed the toddlers to choose their preferred signal on each trial. The goal was to compare performance at the group level between typically developing children and children with ASD, as well as to examine the relationship between brain measures of speech perception and measures of social processing of speech in children with ASD.

Considering first the ERP measures of phonetic perception, the results showed that, as a group, children with ASD exhibited no MMN to the simple change in syllables. However, when children with ASD were subgrouped on the basis of their preference for infant-directed (ID) speech (often called motherese), very different results were obtained.

The results showed that while typically developing children listen to both signals, children with autism strongly preferred the nonspeech-analogue signals. Moreover, the degree to which they did so was significantly correlated with both the severity of autism symptoms, and individual children's MMN responses to speech syllables. Toddlers with ASD who preferred motherese produced MMN responses that resembled those of typically developing children, whereas those who preferred the nonspeech analogue did not show an MMN response to the change in a speech syllable.

These results underscore the importance of a social interest in speech early in development, especially an interest in motherese. Research has shown that the phonetic units in motherese are acoustically exaggerated, making them more distinct from one another (Burnham, Kitamura, & Vollmer-Conna, 2002; Englund, 2005; Kuhl et al., 1997; Liu, Kuhl, & Tsao, 2003; Liu, Tsao, & Kuhl, 2007). Infants whose mothers use the exaggerated phonetic patterns to a greater extent when talking to them show significantly better performance in phonetic discrimination tasks (Liu et al., 2003). In the absence of a listening preference for motherese, children with autism would miss the benefit these exaggerated phonetic cues provide.

Infant-directed speech also produces unique brain responses in typically developing infants. Brain measures of typical infants' response to infant-directed speech, used by Pena and colleagues (2003) in the first study using NIRS, showed more activation in left temporal areas when infants were presented with infant-directed speech as opposed to backward speech or silence. Bortfeld and colleagues (2007) obtained analogous results using NIRS in a sample of 6–9-month-old infants presented with infant-directed speech and visual stimulation. It will be of interest to examine brain activation while children with autism listen to motherese as opposed to acoustically matched nonspeech signals. In children with ASD, brain activation to carefully controlled

speech versus nonspeech signals may provide clues to their aversion to the highly intonated speech signals typical of motherese.

Recent studies extend the findings on children with autism to word processing using ERP measures (Coffey-Corina, Padden, Kuhl, & Dawson, 2008). In this study, 24 toddlers with autism spectrum disorders between 18 and 31 months of age were separated into high-functioning and low-functioning subgroups defined by the severity of their social symptoms. ERP measures were recorded in response to known words, unknown words, and words played backward. They were compared to ERPs elicited from a group of 20 typically developing toddlers between the ages of 20 and 31 months of age.

The results for typically developing toddlers showed a highly localized response to the difference between known and unknown words at a left temporal electrode site (T3) in the 200–500-ms and 500–700-ms windows (figure 57.5A). These data replicate previous data on typically developing children published by Mills and colleagues (1993) and indicate that highly localized responses are a marker of increasing developmental sophistication in the processing of words in typically developing children. It was therefore of interest to observe that toddlers with ASD showed a very diffuse response to known and unknown words. Known words showed a greater negativity than unknown words across all electrode sites, and at a later latency than age-matched typically developing children (figure 57.5B). Both the more diffuse pattern of brain activation and responses with longer latencies are patterns observed in younger typically developing children (Mills et al., 1997).

Replicating the pattern seen in the studies of phonetic perception in children with autism, the word-processing results for children with ASD differed markedly depending on the children's social skills. High-functioning toddlers with ASD produced ERP responses that were similar to those of typically developing children—they exhibited a localized left-hemisphere response to known and unknown words. Significant word-type effects were observed only at the left parietal electrode site (P3) in the 200–500-ms time window (figure 57.5C). In contrast, ERP waveforms of low-functioning toddlers with ASD exhibited a diffuse response to words. Known words were significantly more negative than unknown words at multiple electrode sites and in all measurement windows (figure 57.5D).

The idea that ERP measures in response to syllables and words may allow us to predict future language outcomes in young children with ASD is exciting. Toward that end, we note that children with ASD exhibited highly significant correlations between their ERP components at the initial test time and their verbal IQ scores measured one year after ERP data collection (figure 57.6).

In new studies with the siblings of children with autism spectrum disorder, we are now exploring whether these early brain and behavioral responses to syllables, and listening preferences for speech, are diagnostic markers for autism. The interest in these measures is that they can be used reliably in infants as early as 6 months of age, an age at which intervention measures might be more effective in changing the course of development for children at risk for autism.

Mirror neurons and shared brain systems

Neuroscience studies that focus on shared neural systems for perception and action have a long tradition in speech research (Fowler, 2006; Liberman & Mattingly, 1985). The discovery of *mirror neurons* for social cognition (Gallese 2003; Meltzoff & Decety, 2003; Pulvermüller, 2005; Rizzolatti, 2005; Rizzolatti & Craighero, 2004) has reinvigorated this tradition. Neuroscience studies using speech and whole-brain imaging techniques have the capacity to examine the origins of shared brain systems in infants from birth (Bosseler et al., 2008; Imada et al., 2006).

In speech, the theoretical linkage between perception and action came in the form of the original *motor theory* (Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967) and in a different formulation of the direct perception of gestures, named *direct realism* (Fowler, 1986). Both posited close interaction between speech perception and speech production. The perception-action link for speech was viewed as innate by the original motor theorists (Liberman & Mattingly, 1985). Alternatively, it was viewed as forged early in development through experience with speech motor movements and their auditory consequences (Kuhl & Meltzoff, 1982, 1996). Two new infant studies have shed some light on the developmental issue.

Imada and colleagues (2006) used magnetoencephalography (MEG), studying newborns, 6-month-old infants, and 12-month-old infants while they listened to nonspeech signals, harmonics, and syllables (figure 57.7). Dehaene-Lambertz and colleagues (2006) used fMRI to scan 3-month-old infants while they listened to sentences. Both studies show activation in brain areas responsible for speech production (the inferior frontal, Broca's area) in response to auditorially presented speech. Imada and colleagues reported synchronized activation in response to speech in auditory and motor areas at 6 and 12 months, and Dehaene-Lambertz and colleagues reported activation in motor speech areas in response to sentences in 3-month-olds.

Is activation of Broca's area to the pure perception of speech present at birth? Newborns tested by Imada and colleagues showed no activation in motor speech areas for any signals, whereas auditory areas responded robustly to all signals, suggesting the possibility that perception-action

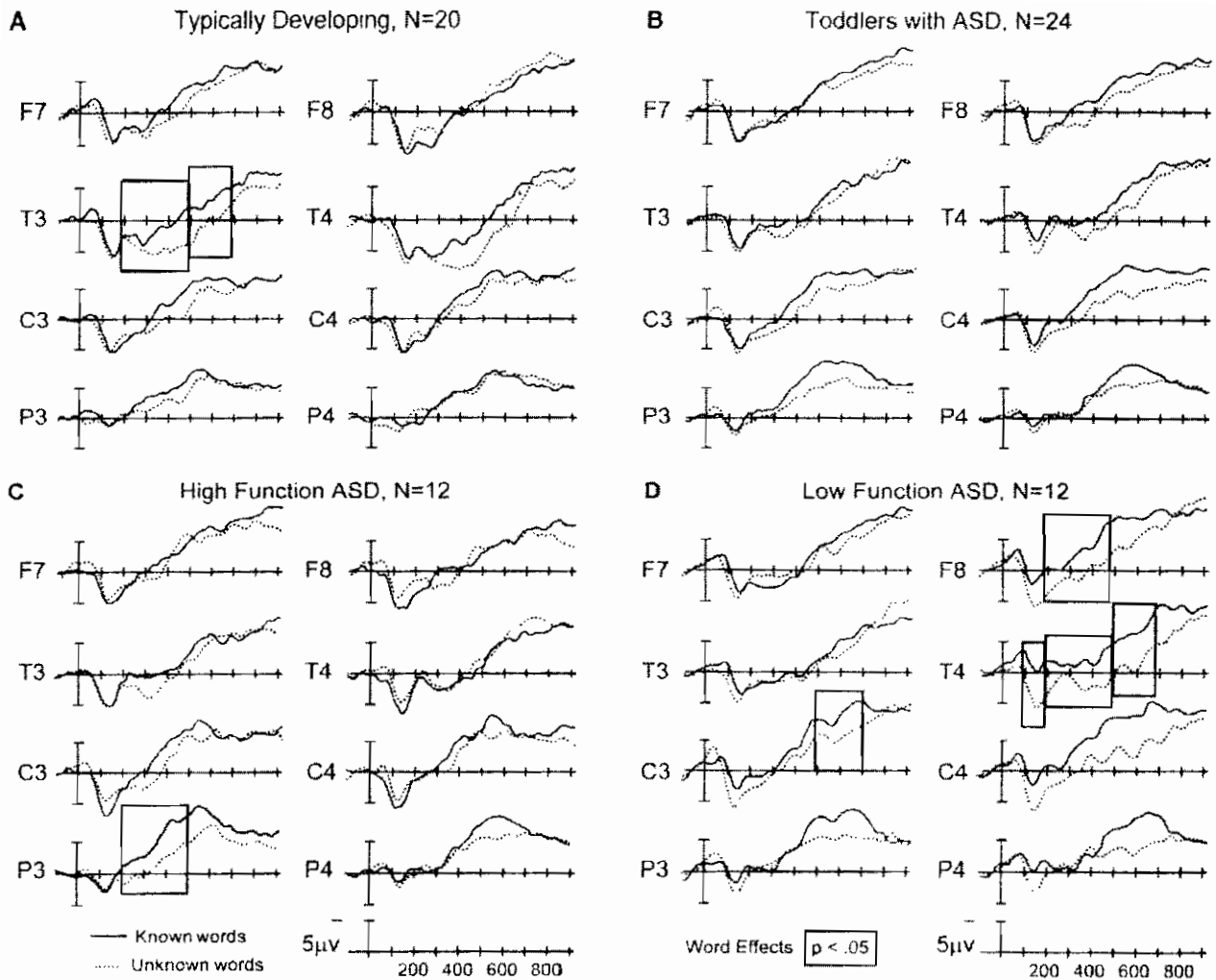


FIGURE 57.5 Group data showing ERP waveforms for (A) typically developing toddlers and (B) toddlers with autism spectrum disorder. TD toddlers exhibit a localized response with significant differences between known and unknown words at the left temporal electrode site (T3). Toddlers with ASD exhibit a diffuse response to known and unknown words, but the differences are significant across all electrode sites in the 500–700-ms measurement window. (C) Subgroup analysis shows that ERP waveforms for high-functioning toddlers with ASD exhibit a localized response

with significant differences between known and unknown words at a parietal electrode site in the left hemisphere (P3), similar to typically developing children. (D) Low-functioning toddlers with ASD exhibit a diffuse response to known and unknown words with significant differences in multiple time windows and electrode sites, and a significant effect when collapsed across all electrode sites in the 500–700-ms measurement window. (From Coffey-Corina, Padden, Kuhl, & Dawson, 2008.)

linkages for speech develop by 3 months of age as infants produce vowel-like sounds. But further work must be done to answer the question. How the binding of perception and action takes place, and whether it requires experience, is one of the exciting questions that can now be addressed with infants from birth using the tools of modern neuroscience.

We now know a great deal about the linkages and the circuitry underlying language processing in adults (Kuhl & Damasio, in press). What is unknown, but waiting to be discovered, is the state of this circuitry at birth and how refined

connections are forged in early infancy as perception and action are jointly experienced.

Bilingual infants: two languages, one brain

One of the most interesting questions is how infants map two distinct languages in the brain. From phonemes to words, and then to sentences, how do infants simultaneously bathed in two languages develop the neural networks necessary to respond in a nativelike manner to two different codes?

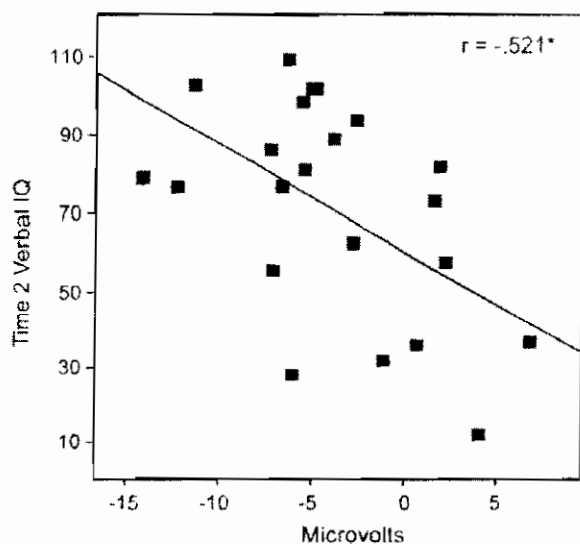


Figure 57.6 Predictive correlations for children with ASD between the mean amplitude of ERPs to known words at the left parietal electrode site (P3) and verbal IQ measured one year later. A more negative response predicted significantly higher verbal IQ ($r = -.521$, $p = .013$). (From Coffey-Corina, Padden, Kuhl, & Dawson, 2006.)

Bilingual language experience could potentially have an impact on development because the learning process requires the development of two codes and because it could take a longer period of time for sufficient data from both languages to be experienced than in the monolingual case. Infants learning two first languages simultaneously might reach the developmental change in perception at a later point in development than infants learning either language monolingually. This difference could depend on such factors as the number of people in the infants' environment producing the two languages in speech directed toward the child and the amount of input they provide. These factors could change the rate of development in bilingual infants.

There are very few studies that address this question thus far, and the data that do exist provide somewhat mixed results. Some studies suggest that infants exposed to two languages show later acquisition of phonetic skills in the two languages when compared to monolingual infants (Bosch & Sebastian-Galles, 2003a, 2003b). This is especially the case when infants are tested on contrasts that are phonemic in only one of the two languages; this has been shown both for vowels (Bosch & Sebastian-Galles, 2003b) and consonants (Bosch & Sebastian-Galles, 2003a). However, other studies report no change in the timing of the developmental transition in phonetic skills in the two languages of bilingual infants (Burns, Yoshida, Hill, & Werker, 2007; Sundara, Polka, & Molnar, 2008). For example, Sundara and colleagues, testing monolingual English and monolingual French as well as

bilingual French-English infants, examined discrimination of dental (French) and alveolar (English) consonants. They demonstrated that at 6–8 months, infants in all three language groups succeeded; at 10–12 months, monolingual English infants and French-English bilingual infants, but not monolingual French infants, distinguished the English contrast. Thus bilingual infants performed on par with their English monolingual peers and better than their French monolingual peers. Moreover, data from an ERP study of Spanish-English bilingual infants show that, at both 6–9 and 9–12 months of age, bilingual infants show MMN responses to both Spanish and English phonetic contrasts (Rivera-Gaxiola & Romo, 2006), distinguishing them from English-learning monolingual infants who fail to respond to the Spanish contrast at the later age (Rivera-Gaxiola, Silva-Pereyra, et al., 2005).

ERP studies on word development in bilingual children have just begun to appear. Conboy and Mills (2006) recorded ERPs to known and unknown English and Spanish words in bilingual children at 19–22 months. Expressive vocabulary sizes were obtained in both English and Spanish, and were used to determine language dominance for each child. A conceptual vocabulary score was calculated by summing the total number of words in both languages and then subtracting the number of times a pair of conceptually equivalent words (e.g., “water” and “agua”) occurred in the two languages.

ERP differences to known and unknown words in the dominant language occurred as early as 200–400 and 400–600 ms in these 19–22-month-old infants, and were broadly distributed over the left and right hemispheres, resembling patterns observed in younger (13–17-month-old) monolingual children (Mills et al., 1997). In the nondominant language of the same children, these differences were not apparent until late in the waveform, from 600 to 900 ms. Moreover, children with high versus low conceptual vocabulary scores produced greater responses to known words in the left hemisphere, particularly for the dominant language (Conboy & Mills, 2006).

Research has just begun to explore the nature of the bilingual brain, and it is one of the areas in which neuroscience techniques will be of strong interest. Using whole-brain imaging, we may be able to understand whether learning a second language at different ages—in infancy as opposed to adulthood—recruits different brain structures. These kinds of data may play a role in our eventual understanding of the “critical period” for language learning.

Conclusions

Knowledge of infant language acquisition is now beginning to reap benefits from information obtained by experiments that directly examine the human brain's response to

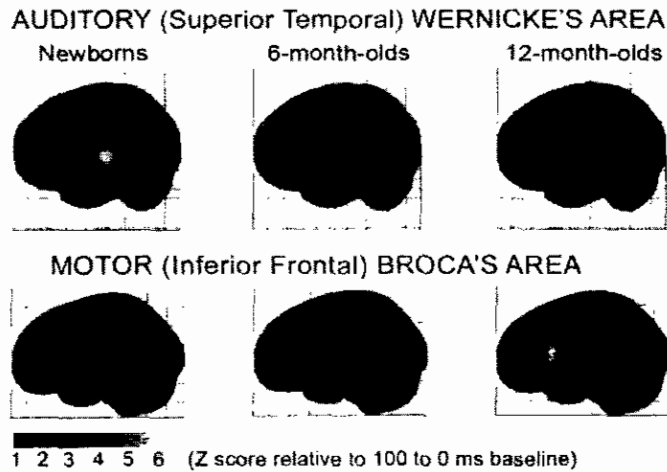


FIGURE 37.7 Neuromagnetic signals were recorded using MEG in newborns, 6-month-old infants, and 12-month-old infants while listening to speech (shown) and nonspeech auditory signals. Brain activation recorded in auditory (*top row*) and motor (*bottom row*) brain regions revealed no activation in the motor speech areas in the

newborn in response to auditory syllables. However, activation increased in the motor areas in response to speech (but not nonspeech) in 6- and 12-month-old infants that was temporally synchronized between the auditory and motor brain regions. (From Inada et al., 2006.) (See color plate 74.)

linguistic material as a function of experience. EEG, MEG, fMRI, and NIRS technologies—all safe, noninvasive, and proven feasible—are now being used in studies with very young infants, including newborns, as they listen to the phonetic units, words, and sentences of a specific language. Brain measures now document the neural signatures of learning as early as 7 months for native-language phonemes, 9 months for familiar words, and 30 months for semantic and syntactic anomalies in sentences. Studies show continuity from the earliest phases of language learning in infancy to the complex processing evidenced at the age of three when all typically developing children show the ability to carry on a sophisticated conversation. Individual variation in language-specific processing at the phonetic level—at the cusp of the transition from Phase 1, in which all phonetic contrasts are discriminated, to Phase 2, in which infants focus on the distinctions relevant to their native language—is strongly linked to infants' abilities to process words and sentences two years later. This finding is important theoretically but is also vital to the eventual use of these early speech

precursors to diagnose children with developmental disabilities that involve language. In fact, new studies suggest the possibility that early measures of the brain's responses to speech may provide a diagnostic marker for autism spectrum disorder. The fact that language experience affects brain processing of both the signals being learned (native patterns) and the signals to which the infant is not exposed (nonnative patterns) may play a role in our understanding of the brain mechanisms underlying the critical period. At the phonetic level, the data suggest that learning itself, not merely time, may contribute to the critical-period phenomenon. Whole-brain imaging now allows us to examine multiple brain areas during speech processing, including both auditory and motor brain regions, revealing the possible existence of a shared brain system (a "mirror" system) for speech. Research has also begun to use these measures to understand how the bilingual brain maps two distinct languages. Answers to the classic questions about the unique human capacity to acquire language will be enriched by studies that utilize the tools of modern neuroscience to peer into the infant brain.

ACKNOWLEDGMENTS The author is supported by the National Science Foundation's Science of Learning Center grant to the University of Washington LIFE Center (SBE 0354453), by grants from the National Institutes of Health (HD 37954; MH066399; HD34565; HD55782), by core grants (P30 HD02274; P30 DC04661), and by a grant from the Cure Autism Now Foundation. This chapter updates the information in Kuhl, Conboy, Padden, Rivera-Gaxiola, and Nelson, *Philosophical Transactions of the Royal Society of London [Biology]* (2006) and Kuhl and Rivera-Gaxiola, *Annual Review of Neuroscience* (2008).

REFERENCES

- ASLIN, R. N., & MEHLER, J. (2005). Near-infrared spectroscopy for functional studies of brain activity in human infants: Promise, prospects, and challenges. *J. Biomed. Opt.*, *10*, 011009.
- BAILEY, T. M., & PLUNKETT, K. (2002). Phonological specificity in early words. *Cogn. Dev.*, *17*, 1265-1282.
- BALIEM, K. D., & PLUNKETT, K. (2005). Phonological specificity in children at 1;2. *J. Child Lang.*, *32*, 159-173.
- BEST, C. C., & McROBERTS, G. W. (2003). Infant perception of non-native consonant contrasts that adults assimilate in different ways. *Lang. Speech*, *46*, 183-216.
- BIALYSTOK, E. (1999). Cognitive complexity and attentional control in the bilingual mind. *Child Dev.*, *70*, 636-644.
- BORTHELD, H., MORGAN, J. L., GOLINKOFF, R. M., & RATIBUN, K. (2005). Mommy and me: Familiar names help launch babies into speech-stream segmentation. *Psychol. Sci.*, *16*, 298-304.
- BORTHELD, H., WRUCK, E., & BOAN, D. A. (2007). Assessing infants' cortical response to speech using near-infrared spectroscopy. *NeuroImage*, *34*, 407-415.
- BOSCH, L., & SEBASTIAN-GALLES, N. (2003a). *Language experience and the perception of a voicing contrast in fricatives: Infant and adult data*. Paper presented at the Proceedings of the International Congress of Phonological Sciences, Barcelona.
- BOSCH, L., & SEBASTIAN-GALLES, N. (2003b). Simultaneous bilingualism and the perception of a language-specific vowel contrast in the first year of life. *Lang. Speech*, *46*, 217-243.
- BOSSELER, A. N., IMADA, T., PIHKO, E., MAKELA, J., TAULU, S., AHONEN, A., et al. (2008). Neural correlates of speech and non-speech processing: Role of language experience in brain activation. *J. Acoust. Soc. Am.*, *123*, 3333.
- BRAINARD, M. S., & KNUDSEN, E. I. (1998). Sensitive periods for visual calibration of the auditory space map in the barn owl optic tectum. *J. Neurosci.*, *18*, 3929-3942.
- BROOKS, R., & MELTZOFF, A. N. (2008). Gaze following and pointing predicts accelerated vocabulary growth through two years of age: A longitudinal growth curve modeling study. *J. Child Lang.*, *35*, 207-220.
- BURNHAM, D., KITAMURA, C., & VOLLMER-CORINA, U. (2002). What's new, pussycat? On talking to babies and animals. *Science*, *296*, 1435.
- BURNS, T. C., YOSHIDA, K. A., HILL, K., & WERKER, J. F. (2007). The development of phonetic representation in bilingual and monolingual infants. *Appl. Psycholinguist.*, *28*, 455-474.
- CANSECO-GONZALEZ, E. (2000). Using the recording of event-related brain potentials in the study of sentence processing. In *Language and the brain: Representation and processing* (pp. 229-266). San Diego: Academic Press.
- CARLSON, S. M., & MELTZOFF, A. N. (2008). Bilingual experience and executive functioning in young children. *Dev. Sci.*, *11*, 282-298.
- CHEOUR, M., CEPONIENE, R., LEHTOKOSKI, A., LUUK, A., ALLIK, J., ALHO, K., et al. (1998). Development of language-specific phoneme representations in the infant brain. *Nat. Neurosci.*, *1*, 351-353.
- CHEOUR, M., IMADA, T., TAULU, S., AHONEN, A., SALONEN, J., & KUHL, P. (2004). Magnetoencephalography is feasible for infant assessment of auditory discrimination. *Exp. Neurol.*, *190*, 44-51.
- CHOMSKY, N. (1959). Review of *Verbal behavior* by B. F. Skinner. *Language*, *35*, 26-58.
- COFFEY-CORINA, S., PADDEN, D., KUHL, P. K., & DAWSON, G. (2007). *Electrophysiological processing of single words in toddlers and school-age children with autism spectrum disorder*. Paper presented at the Annual Meeting of the Cognitive Neuroscience Society, New York.
- COFFEY-CORINA, S., PADDEN, D., KUHL, P. K., & DAWSON, G. (2008). ERPs to words correlate with behavioral measures in children with autism spectrum disorder. *J. Acoust. Soc. Am.*, *123*, 3742.
- CONBOY, B. T., BROOKS, R., TAYLOR, M., MELTZOFF, A. N., & KUHL, P. K. (2008). *Joint engagement with language tutors predicts brain and behavioral responses to second language phonetic stimuli*. Paper presented at the XVIIth Biennial International Conference on Infant Studies, Vancouver, BC.
- CONBOY, B. T., & KUHL, P. K. (2007). *ERP mismatch negativity effects in 11-month-old infants after exposure to Spanish*. Paper presented at the Society for Research in Child Development, Boston.
- CONBOY, B. T., & MILLS, D. L. (2006). Two languages, one developing brain: Event-related potentials to words in bilingual toddlers. *Dev. Sci.*, *9*, F1-F12.
- CONBOY, B. T., RIVERA-GAXIOLA, M., SILVA-PEREYRA, J., & KUHL, P. K. (2008). Event-related potential studies of early language processing at the phoneme, word, and sentence levels. In A. D. Friederici & G. Thierry (Eds.), *Early language development*, Vol. 5: *Bridging brain and behavior: Trends in language acquisition research* (pp. 23-64). Amsterdam: John Benjamins.
- CONBOY, B. T., SOMMERVILLE, J., & KUHL, P. K. (2008). Cognitive control skills and speech perception after short-term second language experience during infancy. *J. Acoust. Soc. Am.*, *123*, 3581.
- CUTLER, A., & NORRIS, D. (1988). The role of strong syllables in segmentation for lexical access. *J. Exp. Psychol. Hum. Percept. Perform.*, *14*, 113-121.
- DEHAENE-LAMBERTZ, G., DEHAENE, S., & HERTZ-PANNIER, L. (2002). Functional neuroimaging of speech perception in infants. *Science*, *298*, 2013-2015.
- DEHAENE-LAMBERTZ, G., HERTZ-PANNIER, L., DUBOIS, J., MERIAUX, S., & ROCHE, A. (2006). Functional organization of perisylvian activation during presentation of sentences in preverbal infants. *Proc. Natl. Acad. Sci. USA*, *103*, 14240-14245.
- EIMAS, P. D., SIQUELAND, E. R., JUSCZYK, P., & VIGORITO, J. (1971). Speech perception in infants. *Science*, *171*, 303-306.
- ENGLUND, K. T. (2005). Voice onset time in infant directed speech over the first six months. *First Lang.*, *25*, 219-234.
- FENNELL, C. T., & WERKER, J. F. (2003). Early word learners' ability to access phonetic detail in well-known words. *Lang. Speech*, *46*, 245-264.
- FENSON, L., DALE, P., REZNIK, J. S., THAL, D., BATES, E., HARTUNG, J., et al. (1993). *MacArthur communicative development inventories: User's guide and technical manual*. San Diego: Singular Publishing Group.
- FERNALD, A., PERFORIS, A., & MARCHMAN, V. A. (2006). Picking up speed in understanding: Speech processing efficiency and vocabulary growth across the 2nd year. *Dev. Psychol.*, *42*, 98-116.

- FOWLER, C. A. (1986). An event approach to the study of speech perception from a direct-realist perspective. *J. Phonetics*, *14*, 3-28.
- FOWLER, C. A. (2006). Compensation for coarticulation reflects gesture perception, not spectral contrast. *Percept. Psychophys.*, *68*, 161-177.
- FRIEDERICI, A. D. (2002). Towards a neural basis of auditory sentence processing. *Trends Cogn. Sci.*, *6*, 78-84.
- FRIEDERICI, A. D. (2005). Neurophysiological markers of early language acquisition: From syllables to sentences. *Trends Cogn. Sci.*, *9*, 181-188.
- FRIEDERICI, A. D., FIEBACH, C. J., SCHLESEWSKY, M., BORNKESSEL, I. D., & VON CRAMON, D. Y. (2006). Processing linguistic complexity and grammaticality in the left frontal cortex. *Cereb. Cortex*, *16*, 1709-1717.
- FRIEDRICH, M., & FRIEDERICI, A. D. (2005). Lexical priming and semantic integration reflected in the event-related potential of 14-month-olds. *NeuroReport*, *16*, 653-656.
- FRIEDRICH, M., & FRIEDERICI, A. D. (2006). Early N400 development and later language acquisition. *Psychophysiology*, *43*, 1-12.
- GALLESE, V. (2003). The manifold nature of interpersonal relations: The quest for a common mechanism. *Philos. Trans. R. Soc. Lond. B Biol. Sci.*, *358*, 517-528.
- GANGER, J., & BRENT, M. R. (2004). Reexamining the vocabulary spurt. *Dev. Psychol.*, *40*, 621-632.
- GERNSBACHER, M. A., & KASCHAK, M. P. (2003). Neuroimaging studies of language production and comprehension. *Annu. Rev. Psychol.*, *54*, 91-114.
- HABINE, A., ECKSTEIN, K., & FRIEDERICI, A. D. (2004). Brain signatures of syntactic and semantic processes during children's language development. *J. Cogn. Neurosci.*, *16*, 1302-1318.
- HABINE, A., & JESCHENIAK, J. D. (2001). What's left if the Jabberwock gets the semantics? An ERP investigation into semantic and syntactic processes during auditory sentence comprehension. *Cogn. Brain Res.*, *11*, 199-212.
- HALLE, P. A., & DE BOYSSON-BARDIES, B. (1994). Emergence of an early receptive lexicon: Infants' recognition of words. *Infant Behav. Dev.*, *17*, 119-129.
- HARRIS, A. M. (2001). Processing semantic and grammatical information in auditory sentences: Electrophysiological evidence from children and adults. *Diss. Abstr. Int.*, *61*, 6729B.
- HEULE, B., BIJEJAC-BABIC, R., HEROLD, B., WEISENBORN, J., & NAZZI, T. (2009). Language specific prosodic preferences during the first half year of life: Evidence from German and French infants. *Infant Behav. Dev.* [Epub ahead of print. doi:10.1016/j.inbeh.2009.03.004.]
- HOLCOMB, P. J., COFFEY, S. A., & NEVILLE, H. J. (1992). Visual and auditory sentence processing: A developmental analysis using event-related brain potentials. *Dev. Neuropsychol.*, *8*, 203-241.
- HOMAE, F., WATANABE, H., NAKANO, T., ASAKAWA, K., & TAGA, G. (2006). The right hemisphere of sleeping infant perceives sentential prosody. *Neurosci. Res.*, *51*, 276-280.
- IMADA, T., BOSSELER, A. N., TAULU, S., PIHKO, E., MÄKELÄ, J., AHONEN, A., et al. (2008). Magnetoencephalography as a tool to study speech perception in awake infants. *J. Acoust. Soc. Am.*, *123*, 3742.
- IMADA, T., ZHANG, Y., CHEOUR, M., TAULU, S., AHONEN, A., & KUHL, P. K. (2006). Infant speech perception activates Broca's area: A developmental magnetoencephalography study. *NeuroReport*, *17*, 957-962.
- JOHNSON, E. K., & JUSCZYK, P. W. (2001). Word segmentation by 8-month-olds: When speech cues count more than statistics. *J. Mem. Lang.*, *44*, 548-567.
- JUSCZYK, P. W. (1997). Finding and remembering words: Some beginnings by English-learning infants. *Durr. Dir. Psychol. Sci.*, *6*, 170-174.
- JUSCZYK, P. W., & ASLIN, R. N. (1995). Infants' detection of the sound patterns of words in fluent speech. *Cogn. Psychol.*, *29*, 1-23.
- JUSCZYK, P. W., & HOBNE, E. A. (1997). Infants' memory for spoken words. *Science*, *277*, 1984-1986.
- KUHL, P. K. (2004). Early language acquisition: Cracking the speech code. *Nat. Rev. Neurosci.*, *5*, 831-841.
- KUHL, P. K. (2007). Is speech learning "gated" by the social brain? *Dev. Sci.*, *10*, 110-120.
- KUHL, P. K. (2008). Linking infant speech perception to language acquisition: Phonetic learning predicts language growth. In P. McCardle, J. Colombo, & L. Freund (Eds.), *Infant pathways to language: Methods, models, and research directions* (pp. 213-243). New York: Lawrence Erlbaum.
- KUHL, P. K., ANDRUSKI, J. E., CHISTOVICH, I. A., CHISTOVICH, L. A., KOZHEVNIKOVA, E. V., RYSKINA, V. L., et al. (1997). Cross-language analysis of phonetic units in language addressed to infants. *Science*, *277*, 684-686.
- KUHL, P. K., COFFEY-CORINA, S., PADDEN, D., & DAWSON, G. (2005). Links between social and linguistic processing of speech in preschool children with autism: Behavioral and electrophysiological measures. *Dev. Sci.*, *8*, F1-F12.
- KUHL, P. K., CONBOY, B. T., PADDEN, D., NELSON, T., & PRUITT, J. (2005). Early speech perception and later language development: Implications for the "critical period." *Lang. Learn. Dev.*, *1*, 237-264.
- KUHL, P. K., CONBOY, B. T., PADDEN, D., RIVERA-GAXIOLA, M., & NELSON, T. (2008). Phonetic learning as a pathway to language: New data and native language magnet theory expanded (NLM-e). *Philos. Trans. R. Soc. Lond. B Biol. Sci.*, *363*, 979-1000.
- KUHL, P. K., & DAMASIO, A. (in press). Language. In E. R. Kandel, J. H. Schwartz, T. M. Jessell, S. Siegelbaum, & J. Hudspeth (Eds.), *Principles of neural science* (5th ed.). New York: McGraw Hill.
- KUHL, P. K., & MELTZOFF, A. N. (1982). The bimodal perception of speech in infancy. *Science*, *218*, 1138-1141.
- KUHL, P. K., & MELTZOFF, A. N. (1996). Infant vocalizations in response to speech: Vocal imitation and developmental change. *J. Acoust. Soc. Am.*, *100*, 2425-2438.
- KUHL, P. K., & RIVERA-GAXIOLA, M. (2008). Neural substrates of language acquisition. *Annu. Rev. Neurosci.*, *31*, 511-534.
- KUHL, P. K., STEVENS, E., HAYASHI, A., DEGUCHI, T., KIRITANI, S., & IVERSON, P. (2006). Infants show a facilitation effect for native language phonetic perception between 6 and 12 months. *Dev. Sci.*, *9*, F13-F21.
- KUHL, P. K., TSAO, F.-M., & LIU, H.-M. (2003). Foreign-language experience in infancy: Effects of short-term exposure and social interaction on phonetic learning. *Proc. Natl. Acad. Sci. U.S.A.*, *100*, 9096-9101.
- KUHL, P. K., WILLIAMS, K. A., LAGERDA, F., STEVENS, K. N., & LINDBLOM, B. (1992). Linguistic experience alters phonetic perception in infants by 6 months of age. *Science*, *255*, 606-608.
- KUJALA, A., ALHO, K., SERVICE, F., ILMONEN, R. J., & CONNOLLY, J. F. (2004). Activation in the anterior left auditory cortex associated with phonological analysis of speech input: Localization of the phonological mismatch negativity response with MEG. *Cogn. Brain Res.*, *21*, 106-113.
- KUTAS, M. (1997). Views on how the electrical activity that the brain generates reflects the functions of different language structures. *Psychophysiology*, *34*, 383-398.

- LIBERMAN, A. M., COOPER, F. S., SHANKWILER, D. P., & STUDDERT-KENNEDY, M. (1967). Perception of the speech code. *Psychol. Rev.*, *74*, 431-461.
- LIBERMAN, A. M., & MAFINGLY, I. G. (1985). The motor theory of speech perception revised. *Cognition*, *21*, 1-36.
- LIU, H.-M., KUHL, P. K., & TSAO, F.-M. (2003). An association between mothers' speech clarity and infants' speech discrimination skills. *Dev. Sci.*, *6*, F1-F10.
- LIU, H.-M., TSAO, F.-M., & KUHL, P. K. (2007). Acoustic analysis of lexical tone in Mandarin infant-directed speech. *Dev. Psychol.*, *43*, 912-917.
- MANDELL, D. R., JUSCZYK, P. W., & PISONI, D. (1995). Infants' recognition of the sound patterns of their own names. *Psychol. Sci.*, *6*, 314-317.
- MELTZOFF, A. N., & DEGUY, J. (2003). What imitation tells us about social cognition: A rapprochement between developmental psychology and cognitive neuroscience. *Philos. Trans. R. Soc. Lond. B Biol. Sci.*, *358*, 491-500.
- MILLS, D. L., COFFLY-CORINA, S. A., & NEVILLE, H. J. (1993). Language acquisition and cerebral specialization in 20-month-old infants. *J. Cogn. Neurosci.*, *5*, 317-334.
- MILLS, D. L., COFFLY-CORINA, S. A., & NEVILLE, H. J. (1997). Language comprehension and cerebral specialization from 13-20 months. *Dev. Neuropsychol.*, *13*, 233-237.
- MILLS, D. L., PLUNKETT, K., PRAT, C., & SCHAFER, G. (2005). Watching the infant brain learn words: Effects of vocabulary size and experience. *Cogn. Dev.*, *20*, 19-31.
- MILLS, D. L., PRAT, C., ZANGI, R., STAGER, C. L., NEVILLE, H. J., & WERKER, J. F. (2004). Language experience and the organization of brain activity to phonetically similar words: ERP evidence from 14- and 20-month-olds. *J. Cogn. Neurosci.*, *16*, 1452-1464.
- MOLFESI, D. L. (1990). Auditory evoked responses recorded from 16-month-old human infants to words they did and did not know. *Brain Lang.*, *38*, 345-363.
- MOLFESI, D. L., MORSE, P. A., & PETERS, C. J. (1990). Auditory evoked responses to names for different objects: Cross-modal processing as a basis for infant language acquisition. *Dev. Psychol.*, *26*, 780-797.
- MOLFESI, D. L., WETZEL, W., & GILL, L. A. (1993). Known versus unknown word discriminations in 12-month-old human infants: Electrophysiological correlates. *Dev. Neuropsychol.*, *9*, 241-258.
- MUNTE, T. F., MAZSKI, M., & JOHANNES, S. (1997). Brain activity associated with syntactic incongruities in words and pseudo-words. *J. Cogn. Neurosci.*, *9*, 318-329.
- NAATANEN, R., LEHTOKOSKI, A., LENNES, M., CHEOUR, M., HUOTILAINEN, M., IVONEN, A., et al. (1997). Language-specific phoneme representations revealed by electric and magnetic brain responses. *Nature*, *385*, 432-434.
- NAZZI, T., IAKIMOVA, G., BERTONCINI, J., FRÉDONIE, S., & ALCANTARA, C. (2006). Early segmentation of fluent speech by infants acquiring French: Emerging evidence for crosslinguistic differences. *J. Mem. Lang.*, *54*, 283-299.
- NEVILLE, H. J., COFFLY, S. A., HOLCOMB, P. J., & TALLAL, P. (1993). The neurobiology of sensory and language processing in language-impaired children. *J. Cogn. Neurosci.*, *5*, 235-253.
- NEWMAN, R. N., RATNER, B., JUSCZYK, A. M., JUSCZYK, P. W., & DOW, K. A. (2006). Infants' early ability to segment the conversational speech signal predicts later language development: A retrospective analysis. *Dev. Psychol.*, *42*, 643-655.
- NEWPORT, E. L., & ASLIN, R. N. (2004). Learning at a distance. I. Statistical learning of non-adjacent dependencies. *Cogn. Psychol.*, *48*, 127-162.
- OBRECKEKER, R., & FRIEDRICH, A. D. (2006). Syntactic event-related potential components in 24-month-olds' sentence comprehension. *NeuroReport*, *17*, 1017-1021.
- OBRECKEKER, R., FRIEDRICH, M., & FRIEDRICH, A. D. (2005). Neural correlates of syntactic processing in two-year-olds. *J. Cogn. Neurosci.*, *17*, 1667-1678.
- PENA, M., MAKI, A., KOVACIC, D., DEHAENE-LAMBERTZ, G., KOIZUMI, H., BOUQUET, F., et al. (2003). Sounds and silence: An optical topography study of language recognition at birth. *Proc. Natl. Acad. Sci. USA*, *100*, 11702-11705.
- PUTZ-VERMULLER, F. (2005). *The neuroscience of language: On brain circuits of words and serial order*. Cambridge, UK: Medical Research Council, Cambridge University Press.
- RAIZADA, R. D. S., TSAO, F.-M., LIU, H.-M., & KUHL, P. K. (2009). Quantifying the adequacy of neural representations for a cross-language phonetic discrimination task: Prediction of individual differences. *Cereb. Cortex*. [Epub ahead of print. doi:10.1093/cercor/bhp076.]
- RAUDENBUSH, S. W., BRAY, A. S., CHENG, Y. F., & CONGDON, R. (2005). *HLM 6: Hierarchical Linear and Nonlinear Modeling*. Lincolnwood, IL: Scientific Software International.
- RIVERA-GAXIOLA, M., KLARMAN, L., GARCIA-SIERRA, A., & KUHL, P. K. (2005). Neural patterns to speech and vocabulary growth in American infants. *NeuroReport*, *16*, 495-498.
- RIVERA-GAXIOLA, M., & ROMO, H. (2006). *Infant head-start learners: Brain and behavioral measures and family assessments*. Paper presented at the From Synapse to Schoolroom: The Science of Learning, NSF Science of Learning Centers Satellite Symposium, Society for Neuroscience Annual Meeting, Atlanta.
- RIVERA-GAXIOLA, M., SILVA-PEREYRA, J., KLARMAN, L., GARCIA-SIERRA, A., LARA-AVALA, L., CADENA-SALAZAR, C., et al. (2007). Principal component analyses and scalp distribution of the auditory P150-250 and N250-550 to speech contrasts in Mexican and American infants. *Dev. Neuropsychol.*, *31*, 363-378.
- RIVERA-GAXIOLA, M., SILVA-PEREYRA, J., & KUHL, P. K. (2005). Brain potentials to native and non-native speech contrasts in 7- and 11-month-old American infants. *Dev. Sci.*, *8*, 162-172.
- RIZZOLATTI, G. (2005). The mirror neuron system and its function in humans. *Anat. Embryol.*, *210*, 419-421.
- RIZZOLATTI, G., & CRAIGHERO, L. (2004). The mirror-neuron system. *Annu. Rev. Neurosci.*, *27*, 169-192.
- SATYAN, J. R. (2003). Statistical language learning: Mechanisms and constraints. *Curr. Dir. Psychol. Sci.*, *12*, 110-114.
- SAFFRAN, J. R., ASLIN, R. N., & NEWPORT, E. L. (1996). Statistical learning by 8-month-old infants. *Science*, *274*, 1926-1928.
- SILVA-PEREYRA, J., CONBOW, B. T., KLARMAN, L., & KUHL, P. K. (2007). Grammatical processing without semantics? An event-related brain potential study of preschoolers using Jaberwocky sentences. *J. Cogn. Neurosci.*, *19*, 1050-1065.
- SILVA-PEREYRA, J., KLARMAN, L., LIN, L. J.-F., & KUHL, P. K. (2005). Sentence processing in 30-month-old children: An ERP study. *NeuroReport*, *16*, 645-648.
- SILVA-PEREYRA, J., RIVERA-GAXIOLA, M., & KUHL, P. K. (2005). An event-related brain potential study of sentence comprehension in preschoolers: Semantic and morphosyntactic processing. *Cogn. Brain Res.*, *23*, 247-258.
- SKINNER, B. F. (1957). *Verbal behavior*. New York: Appleton-Century-Crofts.
- STAGER, C. L., & WERKER, J. F. (1997). Infants listen for more phonetic detail in speech perception than in word-learning tasks. *Nature*, *388*, 381-382.

- SUNDARA, M., POLKA, L., & GENESSEE, F. (2006). Language-experience facilitates discrimination of /d-/ in monolingual and bilingual acquisition of English. *Cognition*, *100*, 369-388.
- SUNDARA, M., POLKA, L., & MOLSAR, M. (2008). Development of coronal stop perception: Bilingual infants keep pace with their monolingual peers. *Cognition*, *108*, 232-242.
- SWINGLEY, D. (2005). 11-month-olds' knowledge of how familiar words sound. *Dev. Sci.*, *8*, 432-443.
- SWINGLEY, D., & ASLIN, R. N. (2000). Spoken word recognition and lexical representation in very young children. *Cognition*, *76*, 117-166.
- SWINGLEY, D., & ASLIN, R. N. (2002). Lexical neighborhoods and the word-form representations of 11-month-olds. *Psychol. Sci.*, *13*, 480-484.
- SWINGLEY, D., & ASLIN, R. N. (2007). Lexical competition in young children's word learning. *Cogn. Psychol.*, *54*, 99-132.
- TAGA, G., & ASAKAWA, K. (2007). Selectivity and localization of cortical response to auditory and visual stimulation in awake infants aged 2 to 4 months. *NeuroImage*, *36*, 1246-1252.
- THERRY, G. C. A., VIHMAN, M., & ROBERTS, M. (2003). Familiar words capture the attention of 11-month-olds in less than 250 ms. *NeuroReport*, *14*, 2307-2310.
- TINCQUEL, R., & JUSZYK, P. W. (1999). Some beginnings of word comprehension in 6-month-olds. *Psychol. Sci.*, *10*, 172-175.
- TSAO, F.-M., LIU, H.-M., & KUHL, P. K. (2004). Speech perception in infancy predicts language development in the second year of life: A longitudinal study. *Child Dev.*, *75*, 1067-1084.
- VIHMAN, M. M., NAKAI, S., DEPAOLIS, R. A., & HALLE, P. (2004). The role of accentual pattern in early lexical representation. *J. Mem. Lang.*, *50*, 336-353.
- VIRNES, M., CARDILLO, G., KUHL, P. K., & MOVELLAN, J. R. (2008). *LIFFE TDLIC Collaboration: Social robots for learning language*. Poster presented at the Learning in Formal and Informal Environments Collaboration, NSF Science of Learning Center, University of Washington, Seattle.
- WEBER, C., HAINE, A., FRIEDRICH, M., & FRIEDRICH, A. D. (2004). Discrimination of word stress in early infant perception: Electrophysiological evidence. *Cogn. Brain Res.*, *18*, 149-161.
- WERKER, J. F., & CURTIN, S. (2005). PRIMIR: A developmental framework of infant speech processing. *Lang. Learn. Dev.*, *1*, 197-234.
- WERKER, J. F., FENNEL, C. T., CORCORAN, K. M., & STAGER, C. L. (2002). Infants' ability to learn phonetically similar words: Effects of age and vocabulary size. *Infancy*, *3*, 1-30.
- WERKER, J. F., & TIES, R. C. (1984). Cross-language speech perception: Evidence for perceptual reorganization during the first year of life. *Infant Behav. Dev.*, *7*, 49-63.
- ZHANG, Y., KUHL, P. K., IMADA, I., KOFANI, M., & TOHKURA, Y. (2005). Effects of language experience: Neural commitment to language-specific auditory patterns. *NeuroImage*, *26*, 703-720.