

# The Perception of Speech: From sound to meaning

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## Early language acquisition: phonetic and word learning, neural substrates, and a theoretical model

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Infants learn language(s) with apparent ease, and behavioral and brain studies 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. The past decade has produced an explosion in neuroscience research examining young children's processing of language at the phonetic, word, and sentence levels, and studies have begun to explore how children develop bilingual language skills. At all levels of language, the neural signatures of learning can be documented at remarkably early points in development. Individual continuity in linguistic development is seen in data showing that infants' responses to phonemes in the first year of life predicts those same children's language abilities in the second and third year of life, a finding with theoretical and clinical implications. Developmental neuroscience studies using language are beginning to answer questions about the origins of humans' language faculty.

### 5.1 Introduction

Infants begin life with the capacity to detect phonetic distinctions across all languages, and develop a language-specific phonetic capacity and acquire early words before the end of the first year (Jusczyk 1997; Werker & Curtin 2005; Kuhl *et al.* 2008). The tools of modern developmental neuroscience are bringing us closer to understanding how the interaction between biology and culture 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 their mother's voice. This review focusses 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 of 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.

## 5.2 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 5.1). 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 Kuhl 2004; Friederici 2005; Conboy *et al.* 2008b; and Kuhl & Rivera-Gaxiola 2008). ERPs, a part of the EEG, reflect electrical activity that is time-locked to the presentation of a specific sensory stimulus (e.g. syllables or words) or

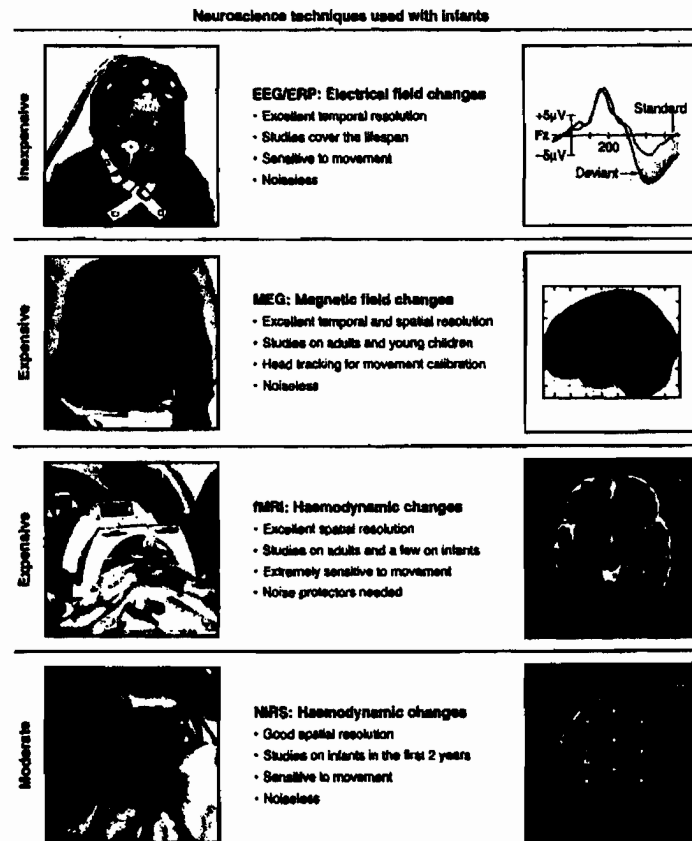


Figure 5.1 Four neuroscience techniques now used with infants and young children to examine the brain's responses to linguistic signals. From Kuhl & Rivera-Gaxiola (2008).

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.

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 has been used to test phonetic discrimination in adults (Kujala *et al.* 2004).

Recently, a genuine advance has been documented by the first MEG studies testing awake infants in the first year of life (Cheour *et al.* 2004; Imada *et al.* 2006; Bosseler *et al.* 2008; Imada *et al.* 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, providing data on the location and timing of brain activation in critical regions (Broca's and Wernicke's) involved in language acquisition (see Imada *et al.* 2006; Bosseler *et al.* 2008; Imada *et al.* 2008).

MEG and/or EEG can be combined with MRI, a technique that provides static structural/anatomical pictures of the brain. Using mathematical modelling 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 grey matter in specific brain regions across the lifespan. MRIs can be superimposed on the physiological activity detected by MEG or EEG to refine the spatial localization of brain activities for individual participants.

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 & Kaschak 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 behavioural data. For example, Raizada and colleagues (2009), using a multivariate pattern classifier, showed that English – but not Japanese – speakers exhibited distinct neural activity patterns for /ra/ and /la/ in the primary auditory cortex. Subjects who behaviourally distinguished the sounds most accurately also had the most distinct neural activity patterns.

fMRI techniques would be very valuable with infants, but few studies have attempted fMRI with infants (Dehaene-Lambertz *et al.* 2002; 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.

NIRS also measures cerebral haemodynamic responses in relation to neural activity, but employs the absorption of light, which is sensitive to the concentration of haemoglobin, to measure activation (Aslin & Mehler 2005). NIRS utilizes near-infrared light to measure changes in blood oxy- and deoxy-haemoglobin 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 haemoglobin levels, and reports have begun to appear on infants in the first 2 years of life (Peña *et al.* 2003; Homae *et al.* 2006; Bortfeld *et al.* 2007; Taga & Asakawa 2007). Homae *et al.*, e.g. 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 haemodynamic changes such as fMRI, NIRS does not provide good temporal resolution. One of the most important aspects of this technique is that co-registration 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.

### 5.3 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 behaviours in infancy and adulthood, and studies using ERPs have advanced our knowledge of development and learning.

Behavioural studies demonstrated that, at birth, young infants exhibit a universal capacity to detect differences between phonetic contrasts used in the world's languages (Eimas *et al.* 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 (Kuhl *et al.* 1992; Cheour *et al.* 1998; Rivera-Gaxiola *et al.* 2005b; Kuhl *et al.* 2006; Sundara *et al.* 2006), while the ability to discriminate phonetic contrasts that are not relevant to the language of the culture declines (Werker & Tees 1984; Cheour *et al.* 1998; Best & McRoberts 2003; Rivera-Gaxiola *et al.* 2005b; Kuhl *et al.* 2006).

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 *et al.* (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 alternative patterns, such as those of a foreign language.

This formulation suggests that infants with excellent phonetic learning skills should advance more quickly towards 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 non-native 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 towards language.

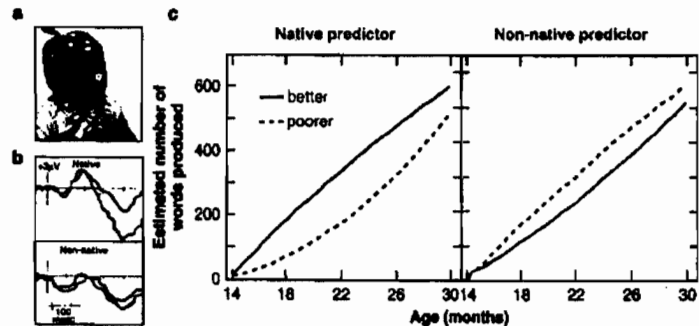
New ERP studies of infants support the NLNC assertion. Kuhl *et al.* (2008) measured infants' ERPs at 7.5 months of age in response to changes in native (*p-t*), non-native (Mandarin *ʈ-tʂ*, and Spanish *t-d*) phonemes. The Mismatch Negativity (MMN), which has been shown in adults to be a neural correlate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

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

The MMN component was elicited in individual infants (Figure 5.2a). Native and non-native contrasts were measured in counterbalanced order, and the MMN was observed between 250 and 400 ms (Figure 5.2b). For the infant shown in Figure 5.2a, greater negativity of the MMN – indicating better neural discrimination – was shown for the native than for the non-native phonetic contrast; other infants showed equal discrimination for the two contrasts, or better discrimination of the non-native 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 non-native 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. Behavioural (Kuhl *et al.* 2005b) 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 non-native contrasts, can be readily seen in the growth of vocabulary from 14 to 30 months (Figure 5.2c). Hierarchical linear growth curve modelling (Raudenbush *et al.* 2005) shows that both native and non-native discrimination at 7.5 months significantly predict vocabulary growth, but the effects of good phonetic discrimination are reversed for the native



**Figure 5.2** (a) A 7.5-month-old infant wearing an ERP electrocap. (b) Infant ERP waveforms at one sensor location (CZ) for one infant are shown in response to a native (English) and non-native (Mandarin) phonetic contrast at 7.5 months. The mismatch negativity (MMN) is obtained by subtracting the standard waveform (black) from the deviant waveform (colour). 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 non-native contrast. (c) Hierarchical linear growth modelling of vocabulary growth between 14 and 30 months is shown for two groups of children, those whose MMN values at 7.5 months indicated better discrimination ( $-1$  SD) and those whose 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, for the non-native contrasts, infants with better discrimination ( $-1$  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 non-native contrasts.

From Kuhl & Rivera-Gaxiola (2008).

and non-native predictors. Better native phonetic discrimination predicts accelerated vocabulary growth, whereas better non-native phonetic discrimination predicts slower vocabulary growth (Kuhl *et al.* 2008). These results support the NLNC hypothesis.

Rivera-Gaxiola and colleagues (Rivera-Gaxiola *et al.* 2005a) demonstrated a similar pattern of prediction using a different non-native contrast. They recorded auditory ERP complexes in 7- and 11-month-old American infants in response to both Spanish and English voicing contrasts. Two patterns of ERP response were observed, an early positive-going wave (P150–250), and a later negative-going wave (N250–550) (Rivera-Gaxiola *et al.* 2005b). 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 as for the developmental study, and found that infants' response to the non-native contrast predicted the number of words produced at 18, 22, 25, 27, and 30 months of age (Rivera-Gaxiola *et al.* 2005a). 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 than 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 *et al.* (2008) and Rivera-Gaxiola *et al.* (2005a), an enhanced negativity in response to the non-native contrast is associated with slower language development.

The continuity in language development documented in these studies using infants' early phonetic skills to predict concurrent language (Conboy *et al.* 2005), and later language (Tsao *et al.* 2004; Kuhl *et al.* 2005b; Rivera-Gaxiola *et al.* 2005a; Kuhl *et al.* 2008), is also seen in studies that use infants' early pattern-detection skills for speech to predict later language (Newman *et al.* 2006), and in studies that use infants' early processing efficiency for words to predict later language (Fernald *et al.* 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 non-native 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 towards the acquisition of language. Behavioural studies by Conboy *et al.*, (2008c) indicate that non-native phonetic perception is significantly correlated with cognitive control abilities – especially those that tap inhibitory control – but that native phonetic abilities are not similarly linked. Moreover, Conboy *et al.* (2008c) show that native phonetic abilities are strongly linked to concurrent vocabulary skills, whereas non-native phonetic abilities are not. Taken together, these results suggest that infants' abilities to attend to and process native-language phonetic categories, while at the same time disregarding discriminable non-native categories, predict more rapid advancements in language. What the tools of modern neuroscience may allow us to do in the future is more fully understand this interaction between language learning and cognitive development, and its relation to the 'critical period' for language development (Kuhl *et al.* 2005b).

#### 5.4 Learning from exposure to a second language

Recent studies in my laboratory 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 *et al.* 2003). Social interaction appears to be a critical component for language learning. This finding 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). These second language exposure studies have been used 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 a set of studies using ERP as a measure of learning from foreign language exposure to Spanish (Conboy & Kuhl 2007; Conboy *et al.* 2008a). In the study, American monolingual infants were exposed to Spanish at 9 months of age

by native Spanish speakers. Infants were tested after exposure to see if they learned phonemes and words from this foreign language experience. 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 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 min. 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 phonetic learning results that were measured behaviourally in the Mandarin study (Kuhl *et al.* 2003). The new results provide convincing evidence of 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 – e.g. the degree to which infants alternated their visual attention between a newly presented toy and the tutor's eyes, as opposed to simply focussing on the toy or on the tutor – predicted the degree of learning both for phonemes and for words (Conboy *et al.* 2008a). The fact that an individual infant's social interest during the 12 language sessions predicted the degree of learning supports the argument that the social factors may 'gate' language learning (Kuhl 2007). Gaze following has previously been shown to predict word learning in infants (Brooks & Meltzoff 2008). The present 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 cognitive enhancement. Pre- and post-exposure measures of 'cognitive control,' the ability to attend selectively and inhibit pre-potent responses, and one previously 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 *et al.* 2008c).

In sum, ERPs provide a highly sensitive measure of learning for both phonemes and words in a variety of experiments. ERP responses to speech not only predict the growth of language over the first 30 months (Rivera-Gaxiola *et al.* 2005a; Kuhl *et al.* 2008), but are also sufficiently sensitive to reflect the effects of differences in subtle abilities that contribute to infant learning, such as infants' social eye gaze following (Conboy *et al.* 2008a). 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 *et al.* 2008).

## 5.5 Neural signatures of word learning

A sudden increase in vocabulary typically occurs between 18 and 24 months of age – a 'vocabulary explosion' (Ganger & Brent 2004; Fernald *et al.* 2006), but word learning starts much earlier. Infants show recognition of their own name at 4.5 months (Mandel *et al.* 1995). At 6 months, infants use their own names or the word 'Mommy' in an utterance to identify word boundaries (Bortfeld *et al.* 2005), and look appropriately to pictures of their mother or father when hearing 'Mommy' or 'Daddy' (Tincoff & Jusczyk 1999). By 7 months, infants listen longer to passages containing words they have previously heard than to 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).

Behavioural studies indicate that infants learn words using both 'statistical learning' strategies in which the transitional probabilities between syllables are exploited to identify likely words (Saffran 2003; Saffran *et al.* 1996; Newport & Aslin 2004), 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; Johnson & Jusczyk 2001; Nazzi *et al.* 2006; Hohle *et al.* 2009).

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 (Molfese 1990; Molfese *et al.* 1990, 1993; Mills *et al.* 1993, 1997, 2005; Thierry *et al.* 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; 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 *et al.* 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 *et al.* 2005), indicating that these features index language experience and proficiency not only in children (Friederici 2005; Conboy *et al.* 2008b), but over the lifespan. 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 *et al.* (2005) used ERPs in 20-month-old toddlers to examine new word learning. The children listened to known and unknown words, and to non-words that were phonotactically legal in English. ERPs were recorded as the children were presented with novel objects paired with the non-words. After the learning period, ERPs to the non-words 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 bi-syllabic 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 bi-syllable embedded in the trochaic pattern showed no response (Weber *et al.* 2004). The data suggest that German infants at this age are applying a metric segmentation strategy, consistent with the behavioural data of Hohle *et al.* (2009).

### 5.6 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. Given that by the end of the first year infants' phonetic skills are language specific (Werker & Tees 1984; Best & McRoberts 2003; Kuhl *et al.* 2006), 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 *tup* for *cup* or *bog* for *dog* – provide information about phonological specificity. Studies across languages suggest that by 1 year of age mispronunciations of common words (Jusczyk & Aslin 1995; Fennel & Werker 2003), words in stressed syllables (Vihman *et al.* 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 (Swingley & Aslin 2000, 2002; Bailey & Plunkett 2002; Ballem & Plunkett 2005).

However, behavioural and neural evidence suggest 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 *et al.* 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 (Tsao *et al.* 2004; Kuhl *et al.* 2005b; Rivera-Gaxiola *et al.* 2005a; Kuhl *et al.* 2008).

Mills *et al.* (2004) used ERPs to corroborate these results. They compared ERP responses to familiar words that were either correctly pronounced or mispronounced, as

well as non-words. At the earliest age tested, 14 months, a negative ERP component (N200–400) distinguished known versus dissimilar nonsense words (*bear* vs. *kobe*) but not known versus phonetically similar nonsense words (*bear* vs. *gare*). By 20 months, this same ERP component distinguished correct pronunciations, mispronunciations, and non-words, 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-e (Kuhl *et al.* 2008) and PRIMER (Werker & Curtin 2005) suggest that phonological and word learning may bidirectionally influence one another. Infants with better phonetic learning skills advance more quickly towards 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 *et al.* 2005b). 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 (Swingley & Aslin 2007). 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 focussed on the task of assigning a new auditory label to a novel object. ERP results with toddlers also show that brain signatures distinguish words that are known from ones that are unfamiliar. ERPs recorded to words in the first 2 years suggest that experience with words results in the formation of neural representations of those words that are increasingly well specified towards the end of the second year of life.

### 5.7 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 *et al.* 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 5.3). 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).

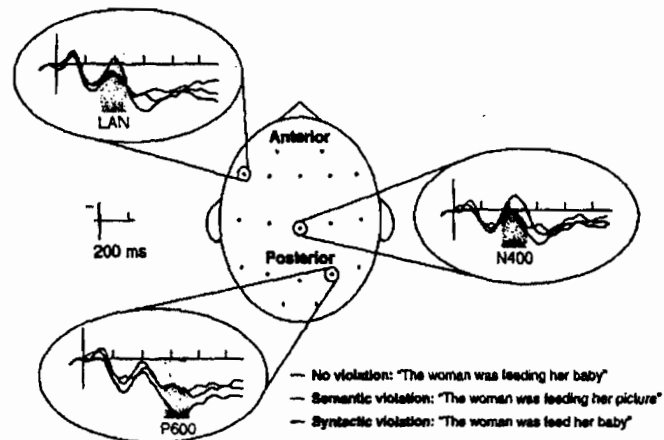


Figure 5.3 ERP responses to normal sentences and sentences with either semantic or syntactic anomalies show distinct distribution and polarity differences in adults. From Kuhl & Rivera-Gaxiola (2008).

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).

ERP data on sentence processing in children suggest that adult-like components in response to semantic and syntactic violations can be elicited starting in the second year of life, 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 *et al.* 2005; Silva-Pereyra *et al.* 2005a, 2005b, 2007; Oberecker & Friederici 2006). Holcomb, *et al.*, (1992) reported the N400 in response to the semantic anomaly effect in children from 5 years of age to adolescence; the latency of the effect was shown to decline systematically with age (see also Neville *et al.* (1993) and Hahne *et al.* (2004)). Studies also show that syntactically anomalous sentences elicit the P600 in children between 7 and 13 years of age (Hahne *et al.* 2004).

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 (2006) observed an N400-like wave to semantic anomalies in 19- and 24-month-old German-speaking children.

Silva-Pereyra *et al.* (2005b) 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 *et al.* (2005a) used the same stimuli and observed late positivities distributed broadly at posterior electrode sites in response to syntactic anomalies and anterior negativities in response to semantically anomalous sentences. In each case, the 30-month-old children's responses had longer latencies than seen in the older children and in adults (Figure 5.4) – a pattern observed repeatedly and attributed to the immaturities and inefficiencies of the developing processing mechanisms.

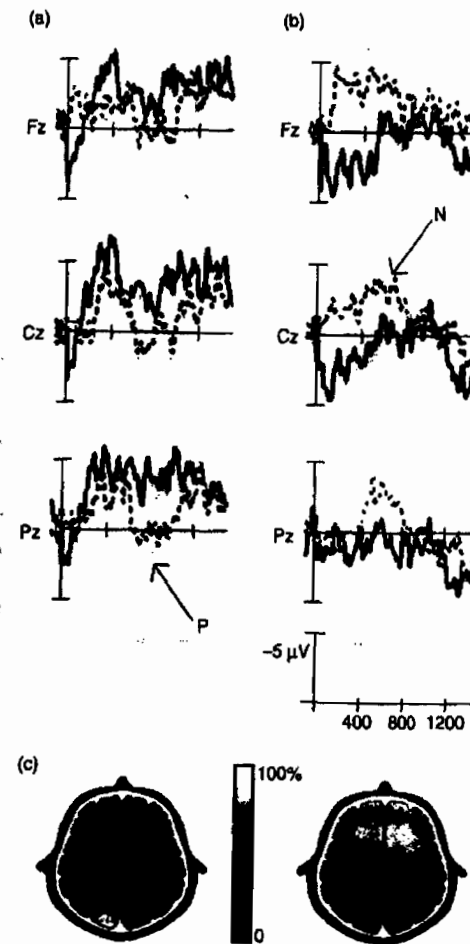


Figure 5.4 ERP waveforms elicited from 30-month-old children in response to sentences with syntactic (a) or semantic (b) violations. Children's ERP responses resemble those of adults (see Figure 5.3), but have longer latencies and are more broadly distributed (c).

From Silva-Pereyra *et al.* (2005a).

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 versus the same violations in real sentences differed. Two negative components, one from 750–900 ms and the other from 950–1050 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



Munte *et al.* 1997; Canseco-Gonzalez 2000; Hahne & Jeschenick 2001) have also reported negative-going waves for jabberwocky sentences, though at much shorter latencies.

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

Scientific discoveries on the progression towards 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 social interest in speech – are revealing a tight coupling between social interaction skills and language acquisition in children with ASD. 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.

Kuhl *et al.* (2005a) conducted the first study examining phonetic perception in preschool children with autism using ERP methods. 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 children with autism to choose motherese or non-speech 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 to one direction versus 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 sub-grouped 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 listened to both signals, children with autism strongly preferred the non-speech 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 non-speech analogue did not show an MMN response to the change in a speech syllable.

These results underscore the importance of 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 (Kuhl *et al.* 1997; Burnham *et al.* 2002; Liu *et al.* 2003, 2007; Englund 2005). 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.

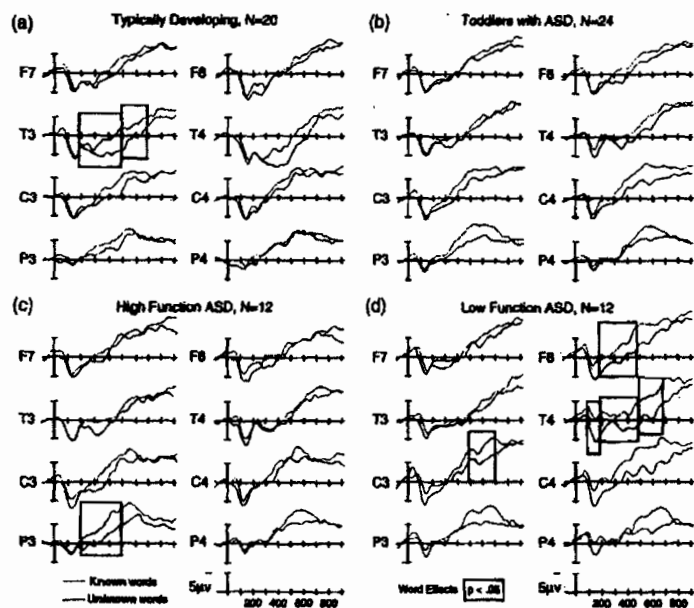
ID speech also produces unique brain responses in typically developing infants. Brain measures of typical infants' response to ID speech, used by Peña *et al.* (2003) in the first study using NIRS, showed more activation in left temporal areas when infants were presented with ID speech as opposed to backward speech or silence. Bortfeld *et al.* (2007) obtained analogous results using NIRS in a sample of 6–9-month-old infants presented with ID 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 non-speech signals. In children with ASD, brain activation to carefully controlled speech versus non-speech 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 *et al.* 2007, 2008). In this study, 24 toddlers with ASD 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 backwards. They were compared to ERPs elicited from a group of 20 typically developing toddlers between the ages of 20 and 31 months.

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 5.5a). These data replicate previous studies of typically developing children published by Mills *et al.* (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 elicited a greater negativity than unknown words across all electrode sites, and at a longer latency than age-matched typically developing children (Figure 5.5b). This pattern of more diffuse activation and longer response latency has been 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 5.5c). In contrast, ERP waveforms of low-functioning toddlers with ASD exhibited a diffuse response to words. ERPs for known words were significantly more negative than those for unknown words at multiple electrode sites and in all measurement windows (Figure 5.5d).

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. Towards that end, we note that children with ASD exhibited highly significant correlations between their ERP components at the initial test time and their verbal intelligence quotient (IQ) scores measured one year after ERP data collection (Figure 5.6).



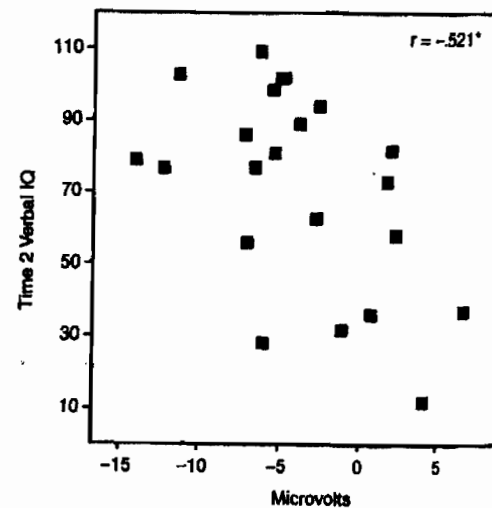
**Figure 5.5** Group data showing ERP waveforms for typically developing toddlers (a) and toddlers with autism spectrum disorder (b). TD toddlers exhibit a localized response with significant differences between known and unknown words at the left temporal electrode site (T3). Toddlers with ASD exhibit a diffuse response to known and unknown words but the differences are significant across all electrode sites in the 500–700 ms measurement window. Subgroup analysis shows that ERP waveforms for high-functioning toddlers with ASD are similar to those of typically developing children, exhibiting a localized response with significant differences between known and unknown words at a parietal electrode site in the left hemisphere (P3) (c). Low-functioning toddlers with ASD exhibit a diffuse response to known and unknown words with significant differences in multiple time windows and electrode sites, a significant effect when collapsed across all electrode sites in the 500–700 ms measurement window (d).

From Coffey-Corina *et al.* (2008).

In new studies with the siblings of children with ASD, we are now exploring whether these early brain and behavioural responses to syllables and words, 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.

### 5.9 Mirror neurones and shared brain systems

Neuroscience studies focussed on shared neural systems for perception and action have a long tradition in speech research (Lieberman & Mattingly 1985; Fowler 2006). The discovery of ‘mirror neurones’ for social cognition (Gallese 2003; Meltzoff & Decety 2003;



**Figure 5.6** 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 1 year later. A more negative response predicted significantly higher verbal IQ ( $r = -.521$ ,  $p = 0.013$ ).

From Coffey-Corina *et al.* (2008).

Rizzolatti & Craighero 2004; Pulvermuller 2005; Rizzolatti 2005) has re-invigorated 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 (Imada *et al.* 2006; Bosseler *et al.* 2008).

In speech, the theoretical linkage between perception and action came in the form of the original *Motor Theory* (Lieberman *et al.* 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 (Lieberman & Mattingly 1985). Alternatively, it was viewed as being forged early in development through experience with speech motor movements and their auditory consequences (Kuhl & Meltzoff 1982, 1996). Two new infant studies shed some light on the developmental issue.

Imada *et al.* (2006) used MEG, studying newborns, 6-month-old infants and 12-month-old infants while they listened to non-speech signals, harmonics, and syllables (Figure 5.7). Dehaene-Lambertz *et al.* (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, etc.) in response to auditorially presented speech. Imada *et al.* reported synchronized activation in response to speech in auditory and motor areas at 6 and 12 months, and Dehaene-Lambertz *et al.* reported activation in motor speech areas in response to sentences in 3-month-olds.

Is activation of Broca’s area by speech sounds present at birth? Newborns tested by Imada *et al.* (2006) showed no activation in motor speech areas for any signals, whereas auditory areas responded robustly to all signals, suggesting the possibility that perception–action linkages for speech develop by 3 months of age as infants produce vowel-like sounds.

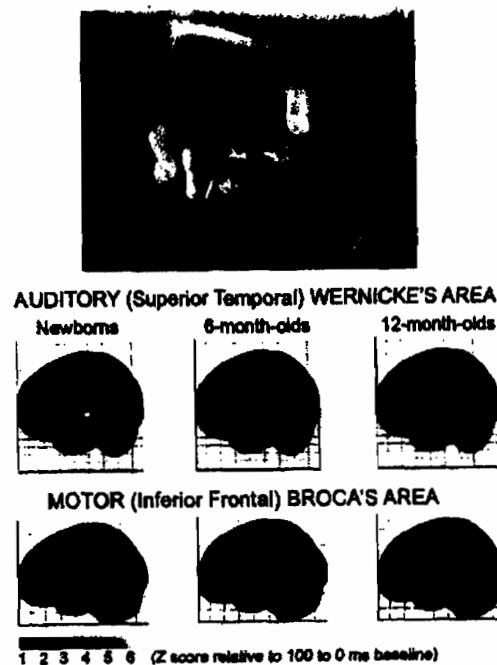


Figure 5.7 Neuromagnetic signals were recorded using MEG in newborns, 6-month-old, and 12-month-old infants while listening to speech (shown) and nonspeech auditory signals. Brain activation recorded in auditory (*top row*) and motor (*bottom row*) brain regions revealed no activation in the motor speech areas in the newborn in response to auditory syllables. However, activation increased in the motor areas in response to speech (but not non-speech) in 6- and 12-month-old infants, and it was temporally synchronized between the auditory and motor brain regions. From Imada *et al.* (2006).

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.

### 5.10 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 native-like manner to two different codes?

Bilingual language experience could potentially have an impact on development – both 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 could depend on factors such as the number of people in the infants' environment producing the two languages in speech directed towards 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,b). 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, others studies report no change in the timing of the developmental transition in phonetic skills in the two languages of bilingual infants (Burns *et al.* 2007; Sundara *et al.* 2008). For example, Sundara *et al.*, 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 *et al.* 2005b).

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- to 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).

Researchers have 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.

### 5.11 A theoretical model and future research

How do we integrate the body of work showing the effects of early language experience on the brain? From the early brain measures recorded at 7 months in response to phonetic units to those recorded at 30 months in response to sentences that are syntactically correct versus anomalous, infants’ brain responses show that the brain is altered by exposure to a language.

A theory developed in my laboratory, NLM-e (*Native Language Magnet-Expanded*), provides a framework for understanding these data and makes specific predictions that will structure future research. The framework described by NLM-e indicates that early exposure to a specific language establishes a neural architecture – specific connections and tissue – that is ‘neurally committed’ to the acoustic patterns typical of that language.

This *Native Language Neural Commitment* (NLNC) hypothesis captures the idea that learning results in the formation of new neural networks that are specialized for a specific language. Dedicated networks do two very interesting things: first, the neural networks detect patterns (such as those typical of phonetic units in the language) that promote the development of higher order language units (such as words), and second, these neural networks allow infants to begin to inhibit responses to linguistic units that are characteristic of other languages. These two factors promote attentional focus, which produces rapid advancement in language acquisition.

NLM-e is schematically described in Figure 5.8, and it encompasses four phases of development. In Phase 1, early in life, infants discriminate all phonetic units in the world’s languages, and factors such as acoustic salience and directional asymmetries explain the degree to which infant performance varies across phonetic contrasts. Infants’ initial performance leaves room for substantial improvement, especially for those contrasts that are acoustically fragile. In Phase 1, infants’ phonetic abilities are relatively crude, reflecting general auditory constraints (see Kuhl *et al.* (2008) for more details). The critical feature of the initial state stipulated by the model is that infants begin life with a capacity to discriminate the acoustic cues that code differences among phonetic units. Infants’ initial ability to discriminate phonetic units, albeit crudely, assists their language development in Phase 2.

Phase 2 represents the core of the NLM-e model. At this stage in development, infants’ sensitivity to the distributional patterns (Kuhl *et al.* 1992; Maye *et al.* 2002) and exaggerated cues of ID speech (Liu *et al.* 2003) causes phonetic learning. As depicted, learning occurs earlier for vowels than consonants (e.g. Werker & Tees 1984; Kuhl *et al.* 1992; Polka & Werker 1994; Best & McRoberts 2003). This difference could reflect the availability of exaggerated cues in ID speech: consonants are not as easily exaggerated as vowels, because exaggeration can change the category (e.g. stretching the formant transitions of /b/ produces /w/). Alternatively, there may be differences in the availability and/or prominence of distributional differences for consonants (e.g. consonants like /tb/ occur in function words, which are lower in energy and do not capture infant attention, see Sundara *et al.* (2006)). Understanding how these two aspects of environmental input – exaggerated

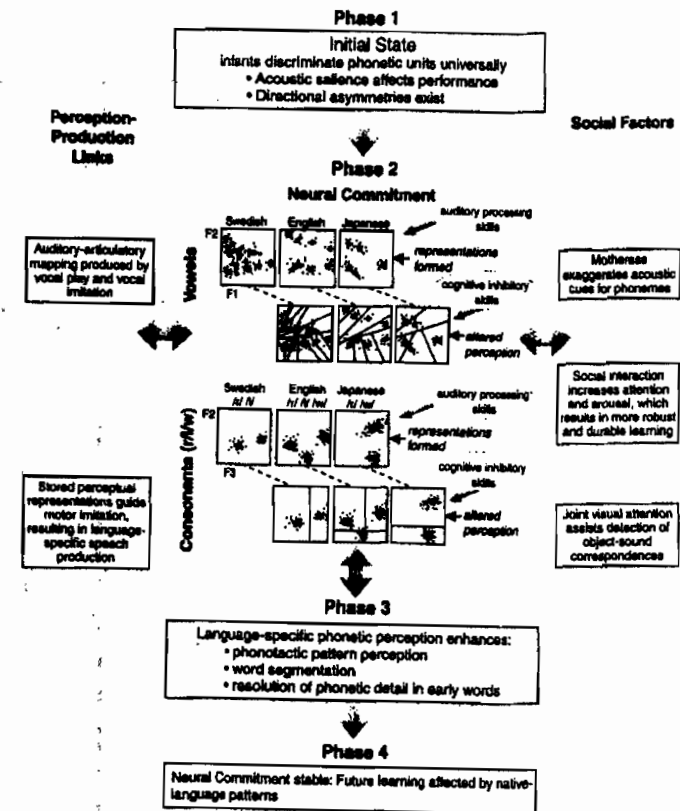


Figure 5.8 The four phases posited by NLM-e. (see text for description).  
From Kuhl *et al.* (2008).

acoustics and distributional properties – interact to support infants’ perception of categories will be important for future studies.

In Phase 2, NLM-e shows an important new component – social interaction – as playing a role in phonetic and early word learning. The new data reviewed earlier show that social factors strongly influence infants’ computational learning in the domain of language (Kuhl *et al.* 2003; Kuhl 2007). Future studies using MEG will allow us to determine whether the increased attention and arousal that occurs during social interaction, the specific information provided during social interaction (such as joint visual attention to an object), or both factors, are responsible for the facilitative effect social interaction has on language learning. Either a general ‘motivational’ explanation involving attention or arousal, or a more specific ‘informational’ explanation could account for the effects of social interaction on learning, and both are likely to play a role (Kuhl *et al.* 2003).

In complex natural communicative settings, social interaction may serve to ‘gate’ computational learning (Kuhl 2007). Why might this be the case? One only needs to watch the

complexity of the social interaction that takes place as infants are exposed to natural language to make the assumption that the attention demanded by interacting with people, and the ability to glean information from those complex social interactions, would prove to significantly modulate language learning in individual children. The dual deficits in social understanding and language acquisition in children with ASD provide further evidence of a deep linkage between social cognition and linguistic processing in humans.

Finally, NLM-e posits that during Phase 2 a link to speech production is forged. Infants develop connections between their own production of speech and the auditory signals this causes as they practice and play with vocalizations, and imitate those they hear. As speech production improves, imitation of the learned patterns stored in memory leads to language-specific speech production. It has been suggested that speech production itself plays a role by encouraging the use of learned motor patterns (DePaolis 2005), and NLM-e depicts bidirectional effects between perception and production in Phase 2 as the link between them is formed. As the MEG data reviewed earlier showed (Imada *et al.* 2006), 6- and 12-month-old infants exhibit synchronized activation in Wernicke's and Broca's area during the perception of speech. This synchronized activation was shown to be unique to speech, and may indicate the inception of a 'mirror system' for speech in human infants.

By the end of Phase 2, infants' perception is altered and attentional focus shifts towards the native language and away from non-native patterns. Language learning has begun. The detection of native language phonetic cues is enhanced, while detection of non-native phonetic patterns is reduced. At this stage, infant perception has been 'warped' by experience and begins to reflect attunement between infant perception and the language and culture in which infants are being raised.

In Phase 3, enhanced speech perception abilities improve three independent skills that propel infants towards word acquisition: the detection of phonotactic patterns (Friederici & Wessels 1993; Mattys *et al.* 1999), the detection of transitional probabilities between segments and syllables (Goodsitt *et al.* 1993; Saffran *et al.* 1996; Newport & Aslin 2004), and the association between sound patterns and objects (Swingle & Aslin 2002; Werker *et al.* 2002; Ballem & Plunkett 2005). Each of these skills – detection of phonotactic patterns, detection of word-like units, and the resolution of phonetic detail in early words – is likely to predict future language, though empirical studies have just begun to test these relationships (Newman *et al.* 2006). Bidirectional effects are indicated at this stage – native language phonetic learning would assist the detection of word patterns, and the learning of phonetically close words would be expected to sharpen awareness of phonetic distinctions.

By Phase 4, analysis of incoming language has produced relatively stable neural representations – and these representations start to restrict the learning of new languages. In infancy, neural networks are not completely 'set,' and do not constrain learning. Infants are capable of learning from multiple languages, as shown in everyday life, and also as shown by experimental interventions in which children learn from exposure to new language material (Maye *et al.* 2002; Kuhl *et al.* 2003). By adulthood, representations are stable, and it is much more difficult to learn by listening to a new language. Thus, exposure to a new language does not automatically create new neural structure as we age. The principle underlying the model is that the degree of 'plasticity' in learning a second language depends on the stability of the underlying perceptual representations, and therefore on the degree of neural commitment.

Future studies will benefit from the tools of modern neuroscience, which will allow us to examine the 'neural commitment' process using both functional MEG measures and structural MRI measures on the developing infant brain. Using functional brain measures, we will also be able to examine how social interaction affects the language areas of the brain, and what defines a 'social agent' for a child. We hypothesize that early language learning in a social context results in a highly robust and very durable form of learning, one that creates patterns of perception and production that will affect us all our lives.

Two populations will be especially interesting as we move towards understanding the neurobiology of language – bilingual children and children with developmental disabilities affecting language. Both will allow us to test the strong assumptions underlying NLM-e and other models of language acquisition.

## 5.12 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 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. Theoretical models, such as NLM-e explain these data and suggest new experiments that will further our understanding of the neurobiology of language. Studies show continuity from the earliest phases of language learning in infancy to the complex processing evidenced at the age of 3 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 2 years later. This is important theoretically but is also vital to the eventual use of these early precursors to speech 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 ASD. 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 (non-native 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. Researchers have 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.

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