CHAPTER 2

Event-related potential studies of early language processing at the phoneme, word, and sentence levels

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1 Introduction

The use of event-related potentials (ERPs) in studies of language processing in infants and children is increasing in popularity. The high temporal resolution of ERPs makes them ideally suited for studying the fine-grained, temporally ordered structure of spoken language, and ERP experiments can be completed without overt participation from subjects, thereby reducing the cognitive demands inherent in behavioral paradigms. Thus the use of ERPs in child language research will most likely continue to grow over the next several years, and findings from such studies will become increasingly important for building theories of early language development.

In this chapter we discuss three ways in which ERPs have been applied to the study of child language development. In the first section we review behavioral studies of cross-linguistic phoneme processing during the first year of life, and how ERP studies of infants have elucidated the effects of language experience on speech perception beyond what was known from the behavioral studies. We discuss the similarities and differences between results obtained from ERP and behavioral experiments using the same stimuli. In the second section we review ERP studies of word processing in toddlers, and what these show about the effects of differential language experience on word learning. In the third section we review ERP studies of sentence processing in 2-, 3- and 4-year-old children, which have revealed both similarities to and differences from ERP studies of sentence processing in adults.

2 Phoneme processing in the first year [1]

2.1 Insights from behavioral studies

Several decades of research on infant speech perception have shown how infants process phonetic information that either is or is not phonologically contrastive in their native language. More than 30 years ago, Eimas and colleagues used a non-nutritive high-amplitude sucking technique to show that infants as young as 1 – 4 months of age discriminate stop consonants in a categorical manner (Eimas, Siqueland, Jusczyk, and Vigorito 1971). Since then, research on infant speech perception has employed a variety of behavioral techniques. These have included: *high-amplitude sucking* (e.g., Bertoncini, Bijeljac-Babic, Jusczyk, Kennedy and Mehler 1988; Eilers and Minifie 1975; Eimas 1974, 1975; Jusczyk, Copan and Thompson 1978; Kuhl and Miller 1982; Morse 1972; Streeter 1976; Swoboda, Morse and Leavitt 1976; Trehub and Rabinovich 1972); *heart rate measures* (e.g., Lasky, Syrdal-Lasky and Klein 1975; Leavitt *et al.* 1976; Miller and Morse 1976; Miller, Morse and Dorman 1977; Moffitt 1971); *visual habituation/dishabituation paradigms* (e.g., Best, McRoberts, LaFleur and Eisenstadt 1995; Miller and Eimas 1996; Polka and Werker 1994); and *conditioned (operant) head turn testing* (e.g., Anderson, Morgan and White 2003; Aslin *et al.* 1981; Eilers, Wilson and Moore 1977, 1979; Kuhl 1991, 1993; Liu, Kuhl and Tsao 2003; Polka and Bohn 1996; Tsao, Liu and Kuhl 2006; Werker, Gilbert, Humphrey and Tees 1981; Werker and Tees 1984a). These behavioral techniques have revealed differences in discrimination of contrasts that are phonemic in the language infants are exposed to (native language) versus those that are phonemic in a nonnative language (Best *et al.* 1995; Best and McRoberts 2003; Eilers, Gavin and Wilson 1979; Eilers, Gavin and Oller 1982; Kuhl *et al.* 1992, 2005, 2006; Pegg and Werker 1997; Polka and Werker 1994; Werker and Lalonde 1988; Werker and Tees 1984a).

From the behavioral research has emerged the now widely accepted tenet that infants are born with general auditory perceptual abilities that are subsequently shaped by listening experience in the first year of life. Language experience produces changes in infants' performance on native and nonnative contrasts. Recent studies show that performance on native contrasts shows a statistically significant increase while performance on nonnative contrasts shows a decline, but one that is not statistically significant, and remains above chance (Kuhl *et al.* 2006; Tsao *et al.* 2006). For example, the /r/ and /l/ phonemes are used to contrast meaning in the English words "rock" and "lock", but are not used contrastively in Japanese and

1. The term "phoneme processing" is used in this chapter to refer to the differential processing of speech sound contrasts that are phonemic in the listener's language vs. those that are not phonemic.

several other Asian languages. Infants raised in Japanese-speaking homes discriminate the English /r/ from /l/ at 6–8 months but their discrimination declines by 10–12 months (Kuhl *et al.* 2006). The pattern of a decline in nonnative contrasts, first documented by Werker and Tees using Hindi and Nthlakampx syllables as nonnative stimuli (1984a), is mentioned in virtually every introductory textbook on child language development, and has stimulated the lay public's enthusiasm for exposure to foreign languages during infancy. Yet the mechanisms underlying the shift from broad perceptual abilities to more selective ones that are more and more attuned to the native language remain in question. Early proposals that infants possessed innate linguistic information that was either maintained or lost based on their language experience (e.g., Eimas 1975; Liberman and Mattingly 1985) were revised based on the finding that adults could behaviorally detect various nonnative contrasts under sensitive test conditions (Carney, Widin and Viemeister 1977; Werker and Logan 1985; Werker and Tees 1984b) or after phonetic training (Jamieson and Morosan 1986,1989; Logan, Lively and Pisoni 1991; McClaskey, Pisoni and Carrell 1983; McClelland, Fiez and McCandliss 2002; Morosan and Jamieson 1989; Pisoni, Aslin, Perey and Hennessy 1982; Tees and Werker 1984). It has become clear that a variety of patterns of developmental change exist; current studies are focusing on relating the timeline of developmental change for individual speech sounds to mechanistic models that purport to explain this variance.

Recent studies of the early transition in speech perception have shown that discrimination of native and nonnative speech sound contrasts may be influenced by a host of factors including the acoustic/perceptual salience of the stimuli (Burnham 1986; Polka 1991, 1992; Polka, Colantonio and Sundara 2001), the relationship of the stimuli to phoneme categories in the native language (Anderson *et al.* 2003; Best 1994; Best and Roberts 2003; Best McRoberts and Sithole 1988; Best *et al.* 1995; Kuhl *et al.* 2006; Polka 1991, 1992), the extent to which infants have advanced in native phoneme discrimination (Kuhl 2000a,b; Kuhl *et al.* 2005, 2006; Kuhl, Conboy, Coffey-Corina, Padden, Rivera-Gaxiola and Nelson, 2007), and infants' other cognitive abilities (Conboy, Sommerville and Kuhl, submitted; Lalonde and Werker 1995). The decline in discrimination of nonnative contrasts is not immutable: even at 8–10 months, when the decline in perception of nonnative sounds is well underway, infants can discriminate contrasts from another language after 5 hours of naturalistic, conversational exposure (Kuhl, Tsao and Liu 2003) and can discriminate contrasts from within a native language category after only a few minutes of structured laboratory exposure (Maye, Werker and Gerken 2002; McMurray and Aslin 2005). In addition, infants do not simply maintain perception of all native phonetic contrasts given experience with language. For example, infants with simultaneous exposure to two languages from birth have been shown to display a temporary decline in perception of contrasts that are phonemic in one of

their languages (Bosch and Sebastián-Galles 2003). Infants have shown improvement in discrimination of native contrasts from 7 to 11 months (Kuhl *et al.* 2006), and difficulty discriminating some native contrasts even at 12 months of age (Polka *et al.* 2001).

2.2 Insights from ERP studies

2.2.1 *ERP indices of phonetic processing*

The use of the ERP technique in infant speech perception research is resulting in another restructuring of ideas regarding how shifts in native vs. nonnative phoneme processing unfold over the first year. ERPs can be described as a more sensitive technique for studying phonetic processing than behavioral methods. They provide a non-invasive neurophysiological measure of processing, and have a high temporal resolution, on the order of milliseconds, that makes them ideal for studying the time course of speech processing. Passive ERP tasks can be completed without overt participation from participants, and thus reduce the cognitive demands of behavioral paradigms. ERP studies of speech perception in adults have revealed discrimination of nonnative phonetic contrasts in the absence of behavioral responses to the same stimuli (Rivera-Gaxiola, Csibra, Johnson and Karmiloff-Smith 2000a,b; Tremblay and Kraus 2002; Tremblay, Kraus and McGee 1998). As will be described in the next section, a similar picture is emerging from ERP studies of infants.

ERP studies of speech perception typically employ the auditory "oddball paradigm", which has been shown to elicit a P300 when the participant is required to respond overtly to the stimuli (see Picton *et al.* 2000) and a preattentive "Mismatch Negativity" (MMN), (Näätänen, Lehtokoski, Lennes, Cheour, Huotilainen, Iivonen, Vainio, Alku, Ilmoniemi, Luuk, Allik, Sinkkonen and Alho 1997). In the auditory oddball paradigm, subjects are presented with a background or "standard" stimulus (e.g., a tone, click, or syllable), repeated with a high frequency of occurrence (typically, 85% of the time), and a "deviant" stimulus (a tone, click, or syllable differing from the standard stimulus on one or more acoustic parameters such as frequency, intensity, or duration) that is randomly presented with a lower frequency of occurrence (e.g., 15% of the time). In speech perception studies, the difference between the standard and deviant is a single phonetic feature in the consonant or vowel of a syllable that results in a minimal pair (e.g., the English pair /pa/ vs. /ta/ involves acoustic cues that signal a difference in the place of articulation feature). The ongoing electroencephalogram (EEG) is time-locked to the onset of presentation of each stimulus (syllable). Epochs of the EEG for each stimulus type (standards and deviants) are digitized and averaged off-line, after trials with artifact from muscle and eye movement have been removed. Auditory ERPs are

typically characterized by a series of positive and negative waveforms peaking within the first few hundred ms after stimulus onset and reflecting different sensory, perceptual, and cognitive processes. The term "Mismatch Negativity" or MMN refers to a negative component observed when the responses to the standard are subtracted from the responses to the deviant, presumably reflecting the brain's "automatic change-detection response" (Näätänen *et al.* 1997; Näätänen, Gaillard and Mäntysalo 1978). Generators in both auditory and frontal cortex are believed to underlie the MMN, reflecting the formation of traces in auditory sensory memory and subsequent involuntary preattentional switches to the deviant stimulus, respectively (Näätänen 2001). There is evidence that the MMN can reflect long-term memory traces such as the representation of phonemes, and that the sources of the MMN elicited by minimal phoneme pairs are neural generators in the left auditory cortex (Näätänen *et al.* 1997; Rinne, Alho, Alku, Holi, Sinkkonen, Virtanen, Bertrand and Näätänen 1999). Thus, the MMN is well suited to studying language-specific phonetic representations (see Cheour, Leppanen and Kraus 2000 and Näätänen 2001, for reviews). However, it is important to note that the MMN is not the only ERP effect elicited by passive listening to phonetic contrasts. For example, differences in the ERPs to deviants vs. standards have been noted in the N1-P2 auditory complex and as a "Late Positive Deflection" in addition to the MMN in adults (Rivera-Gaxiola, Csibra, Johnson and Karmiloff-Smith 2000a).

2.2.2 *ERP studies of phoneme processing in infants*

Using a habituation/dishabituation ERP paradigm, Dehaene-Lambertz and Dehaene (1994) provided the first ERP evidence of a CV-syllabic "mismatch" response in infants, a recovery of ERP amplitude reflecting discrimination of a phonetic contrast. In their study of 2- to 3-month-old infants they presented trains of 5 syllables with the 5th syllable being either the same or different from the previous 4. Infants displayed a left posterior positivity to the new syllable (/ga/) compared to the previous 4 standard syllables (/ba/), at around 400 ms. A later negative effect was also noted, with a bilateral frontal distribution. Cheour and colleagues reported that a component resembling the MMN could be elicited in infants by presenting phonetic contrasts in an oddball paradigm (Cheour-Luhtanen, Alho, Kujala, Sainio, Reinikainen, Renlund, Aaltonen, Eerola and Näätänen 1995). In that research, ERPs were recorded from sleeping newborns who were presented with a vowel contrast. The deviant elicited a larger amplitude negative component than the standard, peaking at approximately 200–250 ms after stimulus onset. Subsequent studies have shown increased negativity in similar time windows to the deviant vs. standard throughout the first year. This increased negativity has been found for vowel contrasts (Cheour-Luhtanen, Alho, Sainio, Sainio, Rinne, Reinikainen, Pohjavuori, Renlund, Aaltonen, Eerola and Näätänen 1996; Cheour,

Alho, Sainio, Reinikainen, Renlund, Aaltonen, Eerola and Näätänen 1997; Cheour, Alho, Ceponiene, Reinikainen, Sainio, Pohjavuori, Aaltonen and Näätänen 1998; Cheour, Ceponiene, Lehtokoski, Luuk, Allik, Alho and Näätänen 1998; Friederici, Friedrich and Weber 2002, and consonant contrasts (Dehaene-Lambertz and Baillet1998; Kuhl *et al.* 2007; Pang, Edmonds, Desjardins, Khan, Trainor and Taylor 1998; Rivera-Gaxiola, Klarman, García-Sierra and Kuhl 2005; Rivera-Gaxiola, Silva-Pereyra and Kuhl 2005). However, the MMNs reported for the infants in those studies had longer latencies and different scalp distributions than those reported for adults (for a review, see Cheour, Leppanen and Kraus 2000).

ERPs have also been used to study changes in the brain's response to phonetic units that arise from experience with language over the first year (Cheour, Ceponiene *et al.* 1998; Kuhl *et al.* in press; Rivera-Gaxiola, Silva-Pereyra and Kuhl 2005). For example, Cheour, Ceponiene and colleagues (1998) recorded ERPs to Finnish and Estonian vowel contrasts in Finnish infants at 6 and 12 months and in Estonian infants at 12 months. Results indicated that the ERPs of 6-month-old infants showed a discriminatory response to both vowel contrasts, that is, regardless of language experience, whereas the ERPs of 12-month-old infants were attenuated for the contrast that was nonnative.

Rivera-Gaxiola and colleagues conducted a series of studies of consonant processing in infants from monolingual English-speaking homes in the U.S. and monolingual Spanish-speaking homes in Mexico using a double-oddball paradigm. Two "deviants," the coronal stop-initial syllables [da] and [t^ha], were contrasted with a single standard syllable, [ta], that represents phonetic features occurring in the subjects' ambient native languages, English or Spanish, as well as in their nonnative language. The phonetic feature that was contrasted across the three syllables was voice onset time, i.e., the timing of onset of vocal fold vibration relative to the burst portion of the stop consonant. For the English-learning infants, native and nonnative contrasts were English /da/ – /ta/ and Spanish /ta/ – /da/, respectively. The standard stimulus, unaspirated [ta] (VOT= +12 ms), was identified as /da/ by adult English speakers and as /ta/ by adult Spanish speakers. The native voiceless aspirated [t^ha] (VOT=+46 ms) was identified as /ta/ by native English speakers, and the nonnative prevoiced [da] (VOT=-24) as /da/ by native Spanish speakers. Both these deviants differed from the standard on voice onset time by the same amount. The standard was presented approximately 80% of the time, a total of 700 trials, and each deviant was presented approximately 10% of the time, a total of 100 trials each. During testing, each infant sat on his or her parent's lap in a sound attenuated test booth and watched moving puppets, toys, or silent videos.

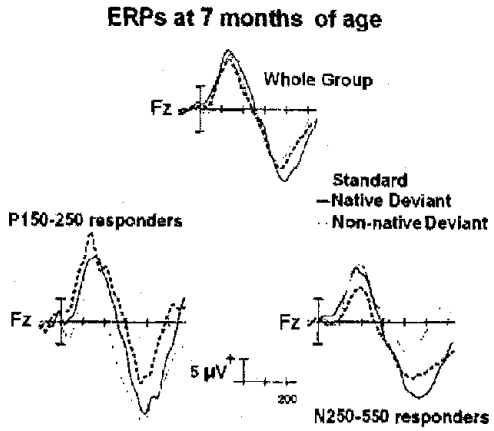

Figure 1. ERPs to native and nonnative deviant syllables (English aspirated [t^{h}a] and Spanish prevoiced [da]) and a standard syllable (voiceless unaspirated [ta]) recorded in a double-oddball passive discrimination paradigm (frontal-central site displayed, positive plotted upwards). At the group level, 7-month-old infants show larger negativities to both the native and nonnative deviant compared to the standard (top of figure), but individual infants responded to the native and nonnative contrasts with either a positivity (P150–250-responders, bottom left) or a negativity (N250–550-responders, bottom right) (adapted with permission from Rivera-Gaxiola, M., Silva-Pereyra, J. and Kuhl, P.K. (2005), Brain potentials to native and non-native speech contrasts in 7- and 11-month-old American infants. *Developmental Science, 8*, 162–172)

In the first study (Rivera-Gaxiola, Silva-Pereyra and Kuhl 2005) infants were tested longitudinally, at 7 months and again at 11 months of age. Group results were consistent with the behavioral literature. At 7 months, infants showed evidence of discrimination for both the native and nonnative contrasts, whereas at 11 months, they showed a significant discriminatory effect only for the native contrast (Figure 1). However, when individual infants' ERPs were further examined, two subgroups emerged, and indicated that even at 11 months, some infants showed evidence of above-chance discrimination of the nonnative contrast (see also Cheour, Ceponiene *et al.* 1998). One subgroup, labeled the "N250-550 responders" (henceforth, N-responders), evidenced an enhanced negativity to both the native and the nonnative deviants compared to the standard syllable in the negative-going portion of the wave between 250–550 ms. The other group, labeled the "P150–250 responders" (henceforth, P-responders), showed an enhanced positivity to both the native and the nonnative deviants in the earlier positive deflection occurring between 150 and 250 ms (Figure 1). Interestingly, at 11 months, the infants who were P-responders at 7 months continued to be P-responders to the nonnative deviant, but showed an N response to the native deviant. The infants who were

N-responders at 7 months continued to show an N response to both the nonnative and native deviant at 11 months, although the effect was smaller for the nonnative contrast. Thus, all infants showed the N250–550 ERP effect for their native contrast by 11 months of age, an effect that is probably analogous to a late MMN.

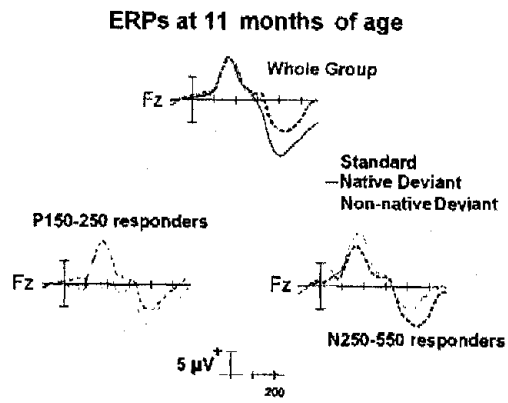

Figure 2. ERPs to native and nonnative deviant syllables (English aspirated [tʰa] and Spanish prevoiced [da]) and a standard syllable (voiceless unaspirated [ta]) recorded in a double-oddball passive discrimination paradigm (frontal-central site displayed, positive plotted upwards). At the group level, 11-month-old infants show a larger negativity only to the native deviant (top of figure), but individual infants responded to the nonnative sound with either a positivity (P150–250-responders, bottom left) or a negativity (N250–550 -responders, bottom right) (adapted with permission from Rivera-Gaxiola, M., Silva-Pereyra, J. and Kuhl, P.K. (2005), Brain potentials to native and non-native speech contrasts in 7- and 11-month-old American infants. *Developmental Science, 8*, 162–172)

In a second study (Rivera-Gaxiola, Klarman *et al.* 2005), a larger sample of infants was tested at 11 months and the pattern of a negative ERP effect for the native contrast and either a P or an N response for the nonnative contrast was replicated (Figure 2). These results indicate that infants continue to exhibit sensitivity to nonnative phonetic contrasts at 11 months, but many do so in the early positive component rather than the later negativity that is thought to index processing at a linguistic level. Also, the infants who continue to show a negativity to a nonnative contrast at 11 months do so to a lesser extent than for a native contrast. Using the same stimuli and testing procedures, Rivera-Gaxiola and colleagues also encountered P- and N-responders in a sample of 10–13 month-old Mexican infants learning Spanish in monolingual households (Rivera-Gaxiola, Silva-Pereyra, Klarman, García-Sierra, Lara-Ayala, Cadena-Salazar and Kuhl, 2007).

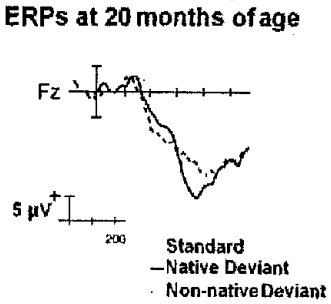

Figure 3. ERPs to native and nonnative deviant syllables (English aspirated [tʰa] and Spanish prevoiced [da]) and a standard syllable (voiceless unaspirated [ta]) recorded in a double-oddball passive discrimination paradigm (right fronto-polar site displayed, positive plotted upwards). At the group level, all 20-month-old infants show larger negativities to both the native and nonnative deviants compared to the standard

Finally, Rivera-Gaxiola and colleagues (in press) found that at 20 months of age, all participants were N-responders to both native and nonnative contrasts; however, the negativity to the native deviant was stronger and had a larger amplitude than that to the nonnative deviant (Figure 3). The P150–250 and the N250–550 were also found to differ in scalp distribution across ages. Rivera-Gaxiola and her colleagues argued that these are two distinct discriminatory components that differ in polarity, latency, scalp distribution, developmental pattern, and have different implications for later language development (see next section).

Two recent behavioral studies using either an English /ɹ/-/l/ contrast with infants from monolingual Japanese-speaking homes (Kuhl *et al.* 2006) or a Mandarin alveolo-palatal affricate-fricative contrast with infants from monolingual English-speaking homes (Tsao *et al.* 2006) have also indicated that nonnative discrimination remains above chance levels at this age, at the group level. However, behavioral methods do not provide adequate temporal precision for distinguishing between levels of processing in the same way that ERP methods do. Thus the use of ERPs may help determine whether there are differences in the perceptual and cognitive processes involved in the discrimination of native and nonnative contrasts during infancy.

2.2.3 *ERP phoneme processing measures as predictors of early language development*

One important question regarding changes in speech perception during the first year is how these shifts relate to other aspects of language acquisition. Do these shifts in speech sound perception facilitate subsequent language learning? Do they constitute a step in a continuous process in language acquisition? Early speech

perception abilities may underlie the ability to recognize and segment words from ongoing speech (Jusczyk 1993, 1994, 1997; Kuhl 2000a; Mehler, Dupoux, and Segui 1990; Werker and Yeung 2005), and those abilities may in turn facilitate other aspects of language acquisition (Newman, Ratner, Jusczyk, Jusczyk and Dow 2006; Weber, Hahne, Friedrich and Friederici 2004). Continuity across domains of language learning has previously been shown in the relationships between early expressive lexical development and subsequent expressive grammatical development (e.g., Bates, Bretherton and Snyder 1988; Bates and Goodman 1997), and between early expressive phonological and lexical development (Locke 1989; MacNeilage and Davis 2000; MacNeilage, Davis and Matyear 1997; McCathren, Yoder and Warren 1999; McCune and Vihman 2001; Oller, Eilers, Neal and Schwartz 1999; Stoel-Gammon 1989; Vihman 1993; Vihman, Ferguson and Elbert 1986). Models of early word acquisition have suggested links between the development of language-specific phonetic representations and the formation of lexical representations (Jusczyk 1993, 1994, 1997, 2003; Werker and Curtin 2005; Werker and Tees 1999; Werker and Yeung 2005).

Few studies have linked early phonetic perception to later language outcomes. Molfese, Molfese and colleagues (Molfese 2000; Molfese and Molfese 1985, 1997; Molfese, Molfese and Espy 1999) recorded ERPs to syllables shortly after birth and showed that these measures predicted language scores at 3, 5, and 8 years and reading disabilities at 8 years. In addition, maturation of the ERP response to speech and nonspeech stimuli from 1 to 8 years was related to reading scores at 8 years (Espy, Molfese, Molfese and Modglin 2004). That research was retrospective in that children were classified according to language or reading ability at later ages and this classification was then linked to previous ERP results. Prospective studies more directly test whether ERPs recorded at an early age have predictive value for later outcomes.

In order to prospectively investigate the association between native and nonnative phoneme processing and later language functioning, Rivera-Gaxiola, Klarman, Garcia-Sierra and Kuhl (2005) obtained parent reports of expressive vocabulary development using the MacArthur-Bates Communicative Development Inventory (CDI; Fenson *et al.* 1993) at 18, 22, 25, 27, and 30 months in the same infants from whom they had recorded ERPs at 11 months (see previously). Recall that at 11 months all infants showed a negative ERP effect for the native contrast, but for the nonnative contrast they either showed a negative (N250–550) or a positive (P150–250) effect. Results indicated that the infants who at 11 months showed a larger P150–250 to the nonnative deviant than to the standard had larger vocabulary sizes at every age than the infants who showed a larger N250–550 to the nonnative deviant compared to the standard. Topographical analyses further indicated that the P150–250 and N250–550 responses differed in scalp distribution. The P150–

250 amplitudes were largest over frontocentral sites, while the N250–550 amplitudes were largest over parietal sites. These different scalp distributions support the hypothesis that the P150–250 and N250–550 effects reflect different neural processing of the nonnative contrast, which are associated with different rates of subsequent vocabulary learning (Rivera-Gaxiola *et al.* 2007). Using the same sample of children, Klarman, Rivera-Gaxiola, Conboy, and Kuhl (2004) elaborated further on how the CDI language scores of P- and N-responders developed beyond word production. N-responders consistently showed lower scores for the Mean of the Three Longest Utterances (M3L), which is a measure of a child's longest reported utterances in morphemes, compared to P-responders. N-responders also showed lower sentence complexity scores compared to P-responders.

Using different stimuli and a different analysis technique, Kuhl and colleagues (2005) recorded ERPs in monolingual English infants at 7.5 months and collected CDIs at 14, 18, 24, and 30 months. ERPs were recorded to a native place contrast (standard /ta/ – deviant /pa/) and one of two nonnative contrasts: a Spanish prevoiced-voiceless unaspirated contrast (standard /ta/ – deviant /da/) or a Mandarin fricative-affricate contrast (standard /ɕi/ – deviant /tɕʰi/). Infants were tested in two separate auditory oddball sessions, one for the native and one for the nonnative contrast. Testing was conducted on the same day, and the contrast order was counterbalanced. For each session, the standard stimulus occurred 85% of the time and the deviant occurred 15% of the time. Mismatch responses were calculated for the native and nonnative contrasts in the negative-going portion of the waveform between 300 and 600 ms. Results indicated a significant negative correlation between the size of the mismatch response (negativity to the deviant vs. the standard) for the native and nonnative contrasts, regardless of whether the Mandarin nonnative or the Spanish nonnative contrast was tested. Infants with more negative amplitudes for the native /ta/-/pa/ contrast tended to have less negative values for the nonnative contrast (either Mandarin or Spanish). Infants' MMN-like responses for the native and nonnative contrasts were differentially associated with language skills between 14 and 30 months. A larger native-language MMN-like response at 7.5 months was associated with a larger number of words produced at 18 and 24 months, greater sentence complexity scores at 24 months, and a longer M3L at 24 and 30 months. The opposite pattern of associations was observed between infants' mismatch responses for the nonnative contrast and their future CDI scores. A more negative amplitude effect for the nonnative contrast was associated with a smaller number of words produced at 24 months, lower sentence complexity scores at 24 months, and a shorter M3L at 30 months. The rate of growth over time in expressive vocabulary size from 14 to 30 months was also related to the native and nonnative contrast mismatch responses. A larger native-contrast MMN-like response at 7.5 months was linked to larger vocabulary

sizes at 24 months and a steeper slope in vocabulary growth from 14 to 30 months. The opposite pattern was obtained for the nonnative-language contrast: a larger nonnative-contrast MMN-like response at 7.5 months was related to smaller vocabulary sizes at 24 months and slower growth in vocabulary size.

In sum, recent ERP studies using two different types of speech sound contrasts have revealed that infants' neural responses to speech sounds during the first year of life predict subsequent achievements in language development over the next two years. Infants who respond to a native phonemic contrast with a strong negative ERP effect at 7.5 months show an advantage in later vocabulary development over infants who either do not show this effect or show a weaker effect to that contrast. Infants who respond to nonnative contrasts with a negative ERP effect at 7.5 or 11 months show slower subsequent growth in vocabulary and grammatical development than infants who do not show this negativity to nonnative contrasts at that age. Further research is needed to determine whether early attunement to the relevant features of speech sounds for the infant's native language serves as a bootstrapping mechanism for learning at the word and sentence levels, or if the relationships between rates of learning in each of these domains derive solely from other factors, such as amounts and types of input and more general cognitive abilities.

2.2.4 *Behavioral phoneme processing measures and language outcomes*

The Kuhl *et al.* (2007) and Rivera-Gaxiola, Klarman, Garcia-Sierra and Kuhl (2005) studies indicate that ERPs reflect the shifts in speech sound processing during the first year of life that have been reported in the behavioral literature. Additionally, ERPs capture important individual variability in brain activity that is linked to future advances in language acquisition. Of interest is whether ERPs and behavioral methods capture similar patterns of individual variability. Three behavioral studies from our research group have linked phonetic discrimination scores during the first year to later vocabulary and/or utterance length and complexity. In the first study, Tsao, Liu, and Kuhl (2004) tested 6 month-old infants from monolingual English-speaking homes on a native vowel contrast using the conditioned head turn paradigm, and subsequently followed the infants using the CDI at 4 time points between 14 and 30 months. The results indicated that the 6-month head turn scores positively correlated with later vocabulary size, utterance length, and utterance complexity. In a second study, Kuhl and colleagues (2005) tested 7.5 month-old monolingual English infants on the native English /ta/-/pa/ contrast and the nonnative Mandarin fricative-affricate /ɕi/-/tɕʰi/ contrast using head turn, and subsequently administered the CDI at 4 time points between 14 and 30 months. In striking similarity to the ERP study described above in which the same phonetic contrasts were used, the head turn scores for the native contrast were positively correlated with later language scores, and head turn scores for the

nonnative contrast at 7.5 were negatively correlated with later language scores. In addition, in this study, native and nonnative contrast discrimination were negatively correlated, indicating that as infants improve in native language skills, they attend less to information that is irrelevant for that language. In a third study, Conboy, Rivera-Gaxiola, Klarman, Aksoylu, and Kuhl (2005) conducted a double-target conditioned head turn test with 7.5 and 11 month-old infants from monolingual English backgrounds using the same English and Spanish stimuli used by Rivera-Gaxiola, Silva Pereyra and Kuhl and Rivera-Gaxiola, Klarman, Garcia-Sierra and Kuhl (2005). At the group level, the 7.5 month-old infants performed at similar levels for the English and Spanish contrasts, whereas the 11 month-old infants performed at higher levels on the English than on the Spanish contrast. Because the infants were tested on both contrasts simultaneously, performance factors such as fatigue and inattentiveness would be expected to affect both contrasts equally. Thus the design controlled for such factors. At both ages there were individual differences in performance across contrasts, and these were linked to 11-month vocabulary size. Infants who displayed a larger difference between scores for the native (English) and nonnative (Spanish) contrasts tended to have higher receptive vocabulary sizes as measured by the CDI.

The finding that better language skills are linked to better discrimination of native contrasts and worse discrimination of nonnative contrasts seems to reflect infants' ability to attend to acoustic cues that are relevant for the language they are acquiring while disregarding irrelevant or misleading cues. Conboy, Sommerville and Kuhl (submitted) hypothesized that this ability may involve more general developing cognitive skills which would also be evident in infants' performance on nonlinguistic tasks (see also Lalonde and Werker 1995). To explore this, Conboy and colleagues administered the double-target head turn test, a detour-reaching object retrieval task (based on Diamond 1990), and a means-ends object-reaching task (based on Sommerville and Woodward 2005) to a group of 11-month-old infants. These cognitive tasks required infants to inhibit attention and motoric responses to irrelevant, misleading information in the visual domain. Parent reports of receptive vocabulary were obtained using the CDI. The head turn results replicated those of the previous study, showing better discrimination of the native vs. the nonnative contrast. Discrimination of the native contrast was positively associated with CDI receptive vocabulary size. In addition, discrimination of the nonnative contrast was negatively associated with performance on each of the nonlinguistic cognitive tasks, but not related to vocabulary size. We can conclude that the low head turn responses to the nonnative target were not due to a general reduction in attention during the testing for two reasons. First, because we used a double-target design, fatigue and other factors would be expected to affect performance in both languages, but this was not the case. Second, low head turn

performance for the nonnative contrast was associated with *higher* performance on the cognitive tasks, in keeping with previous findings reported by Lalonde and Werker (1995). Thus, advances in cognitive control abilities that allow infants to ignore irrelevant information may also influence the extent to which infants tune out phonetic information that is not relevant for their ambient language. Ongoing research is exploring whether ERP responses to these stimuli are linked to the same cognitive tasks (Conboy, Sommerville and Kuhl, submitted). Because ERPs can tap preattentive processes, we are interested in whether they are linked to performance on the cognitive tasks in the same way as the head turn scores, reflecting shifts in processing of irrelevant information across domains (Conboy, Sommerville and Kuhl, unpublished data; Kuhl *et al.* 2007).

2.3 Future directions for phoneme processing studies using ERPs

Taken together, these studies suggest that infants who show earlier attunement to the features of speech sounds that signal phonemic differences in their native language, and relatedly, earlier *tuning out* of nonnative contrasts that are not relevant for the native language, show faster growth in early language development. The same overall pattern of association between the native vs. nonnative contrast have been obtained using behavioral and ERP methods, across different sets of stimuli. However, the ERP findings further elucidate differences in the neural processes involved in sensitivity to the native vs. nonnative contrast. An important area for future research is the use of direct comparisons of ERP and head turn responses to native and nonnative contrasts in the same infants. Such studies will provide a better understanding of the functional significance of ERPs elicited by a variety of phonetic contrasts. One study that used behavioral and ERP measures with the same group of infants from monolingual English-speaking homes has already shown significant correlations between the ERP mismatch effect and head turn sensitivity scores for both native and nonnative contrasts (Kuhl *et al.* 2005; see also, Kuhl *et al.* 2007).

Studies across a wider range of populations and language learning environments would be useful for determining how these ERP effects are linked to experience with language. In addition, longitudinal studies of phoneme processing throughout the period of early lexical development are needed for determining how the emerging use of contrastive phonology in words affects the brain's responses to speech sounds, and to determine the predictive power of individual ERPs to speech sounds recorded during the first year and later language achievements.

Finally, ERP phoneme processing studies of infants exposed to two or more languages during the first year of life will help us understand how the auditory-perceptual space is shaped in the bilingual brain and allow us to test specific

hypotheses regarding neural commitment to language arising from individual variation in language experience. Our group has been conducting ERP studies of bilingual infants from two different language backgrounds (Spanish/English, Mandarin/English). We predict that by 11 months of age infants exposed to both Spanish and English will respond with larger N250–550s to both the Spanish and English contrasts used in the studies described above, reflecting the linguistic relevance of both contrasts. Differences in the latencies, scalp distributions, and amplitudes of these effects may arise with respect to the specific language dominance of each infant. An analogous pattern would be expected for the Mandarin/English infants. Of interest would be to test them in a third language that they have not heard. Will they show the expected pattern of decline for perception of the nonnative contrast over the first year, or will their systems remain more flexible or "open" to nonnative contrasts as a result of their experience with two languages?

3 Word processing in the second year

3.1 Insights from behavioral studies

An important aspect of early language acquisition involves the ability to recognize words in the speech stream and to link those words to meaning. Infants are faced with the challenge of segmenting words early on; it has been estimated that more than 90% of the speech addressed to 6 to 9 month-old infants consists of multiword utterances (van de Weijer 1998). Behavioral experiments have revealed shifts in strategies for segmenting words from connected speech in the input between 6 and 12 months, from an initial focus on familiar prosodic and sequential cues to increasing integration of prosodic, segmental, and statistical cues (e.g., Bortfield, Morgan, Golinkoff and Rathbun 2005; Christophe, Dupoux, Bertoncini and Mehler 1994; Friederici and Wessels 1993; Goodsitt, Morgan and Kuhl 1993; Houston, Santelmann and Jusczyk 2004; Johnson and Jusczyk 2001; Jusczyk, Hohne and Bauman 1999; Jusczyk, Houston and Newsome 1999; Mattys and Jusczyk 2001a,b; Mattys, Jusczyk, Luce and Morgan 1999; Morgan and Saffran 1995; Saffran, Aslin and Newport 1996). In addition to this ability to segment words from ongoing speech, behavioral experiments have shown that infants retain long-term memory for new words. For example, using a head turn preference procedure, Hallé and de Boysson-Bardies (1994) found that by 11 months, infants prefer words that are frequent in the input over less frequent words. Using a similar procedure, Jusczyk and colleagues have shown that by 7.5 months infants listen longer to passages containing word forms they have previously heard either in passages or as isolated words, compared to passages containing words to which they have not been

previously exposed (Jusczyk and Aslin 1995; Jusczyk and Hohne 1997). Even by 4.5 months, infants show recognition of their own names, as measured by a preference for listening to those names over other words (Mandel, Jusczyk and Pisoni 1995).

Other behavioral techniques have shown that some ability to map word forms to meaning is in place by the first months of the second year, and possibly earlier. These techniques include parent reports of infants' reliable responses to words (e.g., Fenson *et al.* 1993, 1994), naturalistic observations of appropriate responses to verbal commands (Benedict 1979), and visual attention to and/or manipulation of objects or pictures that are labeled during experimental tasks (e.g., Hollich, Hirsch-Pasek and Golinkoff 2000; Oviatt, 1980; Pruden, Hirsh-Pasek, Golinkoff and Hennon 2006; Schafer 2005; Waxman and Booth 2003; Waxman and Braun 2005; Werker, Cohen, Lloyd, Stager and Casasola 1998; Woodward, Markman and Fitzsimmons 1994). Using a preferential looking paradigm, Tincoff and Juszcyk (1999) showed that infants as young as 6 months of age comprehended highly familiar words associated with animate beings (i.e., "mommy" and "daddy").

In spite of these early advances in word learning, infants' lexical processing skills are limited. For example, Hallé and de Boysson-Bardies (1996) reported that 11-month-old infants preferred to listen to nonsense words that were phonetically similar to real, highly frequent words over dissimilar nonsense words, leading to the suggestion that early word representations are phonetically underspecified. Stager and Werker (1997) found that at 14 months, infants were able to link two dissimilar nonsense words to different referents (e.g., "leef" and "neem"), but not two similar sounding nonsense words that they could easily tell apart in a discrimination task (e.g., "bih" and "dih"), suggesting they treated the two word forms as instances of the same label during the more cognitively demanding word-learning task (see also Pater, Stager and Werker 2004). However, by 14 months infants with larger vocabulary sizes succeeded on this task (Werker, Fennell, Corcoran and Stager 2002). By 17 – 20 months infants easily map phonetically similar nonsense words to different referents (Bailey and Plunkett 2002; Werker *et al.* 2002), except when the minimal difference is in a vowel rather than a consonant (Nazzi 2005), and by 14 months they can map similar sounding words to different referents when both words are highly familiar (e.g., "doll" and "ball") (Fennell and Werker 2003). At both 18–23 (Swingley 2003; Swingley and Aslin 2000) and 14–15 months (Swingley and Aslin 2002), infants are slower to fixate visually to a picture of a familiar object (e.g., baby) vs. a foil in a looking preference task when they hear a mispronunciation of that word (e.g., "vaby") compared to when they hear a correct pronunciation of that word. Also, at 14 months infants look longer to pictures matching correct pronunciations of novel words compared to foils, but not mispronunciations of those target words (Ballem and Plunkett 2005). Finally, there

is evidence that even younger infants can access phonetic detail in their representations of words: Jusczyk and Aslin (1995) found that 7.5 month-old infants showed a listening preference for familiarized words (e.g., "cup") over unfamiliarized words, but not when the initial consonant of the familiarized word was changed ("tup"); Stager and Werker (1997) reported that 8-month-old infants succeeded in detecting a switch from "bih" to "dih" in a single sound-object pairing, a task at which 14-month-old infants failed; Swingley (2005) showed that 11-month-old infants preferred correct pronunciations to word-onset (but not word-offset) mispronunciations of familiar words, although they did not prefer onset or offset mispronunciations of the familiar words to nonwords; and Vihman and colleagues reported that changing the initial consonants of the accented syllables of familiar words blocked recognition of those words in 11-month-old infants, whereas changing the initial consonants of the unaccented syllables of those same words did not block recognition, but did delay recognition of the words (Vihman, Nakai, De Paolis and Hallé 2004). It has been suggested that the results with younger infants are tapping into simple recognition of word forms rather than the more difficult process of mapping of word form to meaning (Hallé and de Boysson-Bardies 1996; Pater *et al.* 2004; Stager and Werker 1997; Werker and Curtin 2005).

Taken together, the behavioral research on early word processing suggests that phonetic detail is available to infants in their earliest word representations, but due to limited cognitive resources, more holistic representations may be used when mapping words to meaning in demanding word-learning and processing tasks (Fennell and Werker 2003; Pater, Stager and Werker 2004; Stager and Werker 1997; Werker and Tees 1999). This explanation has also been extended to account for phonological errors in the early stages of word production (Fikkert 2005).

Throughout the second year, infants become more efficient at learning, producing, and processing words. Evidence of this is also found in fine-grained analyses of eye movements during looking preference tasks, which have reflected increases in the efficiency of lexical access during the second year (Fernald, Perfors and Marchman 2006; Fernald, Pinto, Swingley, Weinberg and McRoberts 1998; Fernald, Swingley and Pinto 2001; Zangl, Klarman, Thal, Fernald and Bates 2005).

3.2 Insights from ERP studies

3.2.1 *Infants growing up with one language*

Given these early advances in word segmentation, recognition, and comprehension, words with which infants have had repeated experience from their language input would be expected to elicit different neural responses than unfamiliar words. In a series of ERP studies, Molfese and colleagues showed that brain responses reliably discriminated between known and unknown words that infants passively

listened to as young as 12 -16 months (Molfese 1989,1990; Molfese and Wetzel 1992; Molfese, Wetzel and Gill 1993). Molfese, Morse and Peters (1990) additionally showed that ERP effects linked to the acquisition of names for novel objects could be obtained as young as 14–15 months.

Mills, Coffey-Corina and Neville (1993, 1997) reported different brain responses for children as young as 13–20 months of age to words that parents reported to be known words, unknown words, and known words that were played backwards. Additionally, they found that the scalp distributions of these effects varied according to vocabulary size, with higher vocabulary children showing more focal ERP effects (an enhanced negativity to known vs. unknown words between 200 and 400 ms), only at left temporal and parietal electrode sites, compared to lower vocabulary children who showed more symmetrical, broadly distributed effects. More recently, ERPs have been shown to differentiate familiar from unfamiliar words by 250 ms in infants as young as 11 months (Thierry, Roberts and Vihman 2003), and as young as 9–11 months in infants who have high CDI receptive vocabulary scores (Sheehan and Mills, this volume). The finding that ERPs linked to word familiarity and meaning are modulated by experience with individual words was further demonstrated by Mills, Plunkett, Prat, and Schafer (2005). In that research, ERPs were recorded in 20 month-old infants as they listened to known and unknown words, and nonwords that were phonotactically legal English words. ERPs were then recorded during a brief training session in which half of the nonwords were presented with an unknown object referent, and the other half were simply repeated without any pairing of word to referent. Subsequently, ERPs were recorded to all 4 word types, without any pairing of word form to a visual referent. The amplitude and distribution of the ERPs to the nonwords that had been paired with a referent were strikingly similar to those of the previously known words and different from the ERPs to the nonwords that had not been paired to a referent. These results indicate that short-term learning of new word forms may be encoded in the same neural regions as words that were previously learned.

To investigate whether phonetic specificity in words is reflected in ERP known-unknown word effects, Mills and colleagues recorded ERPs to words that children knew, phonetically similar words, and dissimilar words (Mills, Prat, Stager, Zangl, Neville and Werker 2004). The results indicated that ERPs are sensitive to shifts from holistic to phonetically specific lexical representations between 14 and 20 months. At 14 months, infants displayed the ERP effect that has previously been shown to index word meaning, an enhanced negativity between 200 and 400 ms (N200–400), to known vs. dissimilar nonsense words (e.g., "bear" vs. "kobe"), but not to known vs. phonetically similar nonsense words ("bear" vs."gare"). Moreover, they showed the N200–400 effect to words that were similar to the known words vs. dissimilar words ("gare" vs. "kobe"), suggesting that they processed

mispronunciations of known words in the same way as correct pronunciations. By 20 months, there was an N200–400 effect to known vs. dissimilar words and known vs. similar words, but no effect in the ERPs to words that were similar to known words vs. dissimilar words (i.e., "gare" vs."kobe"). These results are consistent with the behavioral literature reviewed above indicating that novice word learners have difficulty attending to phonetic detail in words under processing conditions in which they link the words to meaning.

3.2.2 *Infants growing up with two languages*

Infants raised bilingually provide a natural test case for examining the effects of experience with language on the brain activity elicited by known and unknown words. Of interest is whether similar ERP effects are noted for known vs. unknown words in each of the bilingual child's languages, and whether the timing and distribution of these effects vary according to single-language vocabulary size or the child's total vocabulary size. To investigate these questions, Conboy and Mills (2006) recorded ERPs to known and unknown Spanish and English words in 19- to 22-month-olds who received naturalistic input in both Spanish and English on a regular basis, starting within the first 6 months of life. Following the procedure of Mills *et al.* (e.g. 1993, 1997, 2004), known words were determined by asking parents to rate a list of words in each language on a 4-point scale, with a rating of 1 indicating that the parent was absolutely certain the child did not understand the word and a 4 indicating the parent was very certain the child understood the word. The words on this list were selected based on normative data from studies of early language acquisition in English (Fenson *et al.* 1993) and Spanish (Jackson-Maldonado *et al.* 1993). Each child's individualized known stimulus word list was made up of 10 English and 10 Spanish words that received ratings of 3 or 4 for that child, and the unknown words were low frequency words in each language reported as unfamiliar to the child and matched in syllable structure to the known words. In addition, a picture-pointing task was used to ensure that infants comprehended the particular word forms used in the ERP task, rather than derived forms (e.g., the dimunitive form *carrito* for *carro*). No two words on any child's list were translation equivalents. All words were recorded in the same voice by a female bilingual speaker, and presented in a randomly mixed order during testing.

Expressive vocabulary sizes were obtained using the CDI and its Spanish language counterpart, the Inventario del Desarrollo de Habilidades Comunicativas (Jackson-Maldonado *et al.* 2003). These scores, along with parent reports of children's ability and preference for each language, were used to determine the language of dominance for each child. Approximately equal numbers of children were English- and Spanish-dominant. In addition, a conceptual vocabulary score was calculated by summing the total number of words in both languages and then

subtracting out the number of times a pair of conceptually equivalent words (e.g., "water" and "agua") occurred across the two languages. This conceptual score was used to divide the group into two subgroups, a higher and a lower vocabulary group. Mean conceptual vocabulary sizes were 212 words for the higher producers and 66 words for the low producers.

Across the entire group of 30 children, ERP differences to known and unknown words in the dominant language occurred as early as 200–400 and 400–600 ms, and were broadly distributed over the left and right hemispheres, resembling the pattern observed for 13- to 17-month-old monolingual children (i.e., Mills *et al.* 1997). However, ERP differences for words in the nondominant language of the same children were not apparent until late in the waveform, from 600 to 900 ms. For the dominant language the known-unknown word effect was larger over right hemisphere anterior sites (Figure 4).

These ERP effects were modulated not only by experience with each individual language, but also by overall experience with both languages. When children were divided into higher and lower groups based on their conceptual vocabulary sizes, differences in the timing of ERP known-unknown word effects were noted for the nondominant language. For the higher producers, the ERP effects occurred by 200–400 ms, consistent with the latency observed for the dominant language of the same children, and with that observed in monolingual children at the same and younger ages. For the lower producers, there was no difference in the negativity to known-unknown words at 200–400 or 400–600 ms, but the difference was significant at 600–900 ms.

Different scalp distributions of the ERP known-unknown word effect were also noted in the bilingual 20-month-old children in this study. For the dominant language, N200–400 known-unknown word effects were larger over right frontal regions, in contrast to the left temporal-parietal distribution of this ERP effect in monolingual 20-month-olds. In the bilingual study the stimuli switched randomly between Spanish and English, and this language switching may have elicited more frontal activation than the monolingual testing conditions. Switching between languages has been linked to frontal activation in studies of bilingual adults using fMRI (Hernández, Dapretto, Mazziotta and Brookheimer 2001; Hernández, Martínez and Kohnert 2000) and ERPs (Jackson, Swainson, Cunnington and Jackson 2001; Moreno, Federmeier and Kutas 2002). Moreover, switching may have engaged the right hemisphere to a greater degree, given that the right hemisphere has been shown to be involved in integration of information across domains (Goldberg and Costa 1981). The effects of switching were thus investigated by testing a group of ten 19–22 month-old bilingual toddlers on the same stimuli, but in alternating blocks of 50 English and 50 Spanish trials (Conboy 2002). The children in

this group were matched for total conceptual vocabulary size and approximate English and Spanish vocabulary sizes to 10 infants from the group of 30 toddlers

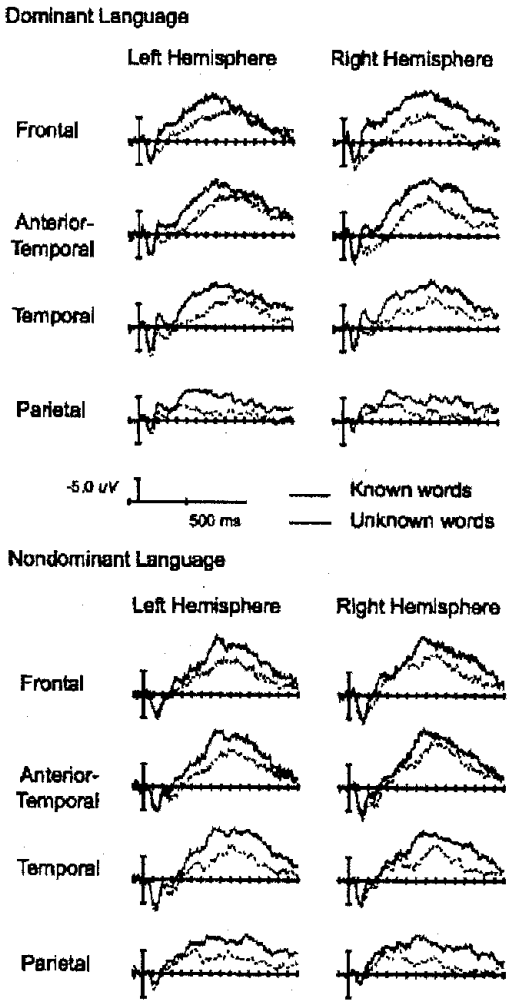

Figure 4. ERPs to known and unknown words in a group of 30 19–22 month-old Spanish-English bilingual toddlers (negative plotted upwards). At the group level, children show greater negativity to known compared to unknown words in both their languages (N200–400, N400–600, and N600–900 effects), The earlier negative effects (N200–400 and N400–600) occur only for the dominant language, whereas the later effects (N600–900) occur for both languages. When the group is subdivided into higher and lower vocabulary groups, children in the higher group show the N200–400 and N400–600 effect for both languages (adapted with permission from Conboy, B.T. and Mills, D.L. (2006). Two languages, one developing brain: Event-related potentials to words in bilingual toddlers. *Developmental Science*, 9(1), F1-F12)

who heard the stimuli in a randomly switched presentation. As predicted, the children in the blocked condition did not show the right frontal asymmetry for their dominant language shown by the children tested in the language-switched group. All other ERP effects were similar across groups, but latencies for all effects were shorter for the children tested in the blocked condition than for those tested in the switched condition.

One ERP component elicited by auditory words in infants as young as 6 months is the P100, an early positivity peaking at approximately 100 ms (Neville and Mills 1997). Due to its similarity to a sensory ERP component observed in adults, the P50, the P100 in infants and toddlers is thought to index a sensory stage of processing auditory words (Mills, Conboy and Paton 2005). In studies of monolingual infants and toddlers, this component was larger over the left vs. the right hemisphere, for both known and unknown words (Mills *et al.* 1997; Mills, Conboy and Paton 2005). However, the P100 asymmetry varied as a function of a child's percentile rank on the MacArthur-Bates CDI. Across studies, the P100 to words was larger in amplitude at left vs. right electrode sites in children who scored above the 50th percentile, but this asymmetry was not present for children with slower vocabulary development, including late talkers as old as 30 months of age (Mills, Conboy and Paton 2005). In bilingual 20-month-olds, the left over right P100 amplitude asymmetry was noted for the dominant language of the children with higher total conceptual vocabulary scores, but was not present for the nondominant language of those same children, nor was it present for either language of the children with lower total conceptual vocabulary scores (Conboy and Mills 2006). Thus, the distribution of this early sensory component appears to be modulated by experience with particular words.

3.3 Future directions for word processing studies using ERPs

ERPs recorded to individual words have been shown to index word familiarity as young as 9 months and word meaning by 13–17 months. These studies suggest that the efficiency of word processing, as reflected in the latency and distribution of ERP effects, is linked both to general language experience and to experience with particular words. Further work is needed to compare the brain's responses to words under different listening conditions, those that may slow processing and those that make processing more efficient, and to investigate the nature of lexical representations tapped by ERPs. In a study of 14–15 month-old infants, Molfese and colleagues (1990) found distinct ERPs to nonsense words that matched objects that the infants had been trained to associate with the words, vs. nonsense words that did not match. Using a different type of cross-modal design, two research groups have reported distinct ERPs to words that are congruous with

pictures of objects vs. those that are incongruous, in 14- and 19-month-olds (Friedrich and Friederici 2004, 2005a, 2005c) and in 13- and 20-month-olds (Mills, Conboy and Paton 2005). In addition, Friedrich and Friederici (2005c) have shown that ERPs reflect phonotactic familiarity and semantic priming effects as early as 12 months (2005c). Additional work using ERPs in cross-modal designs will help reveal the nature of infants' earliest word representations.

4 Sentence processing in the third, fourth, and fifth years

4.1 ERP effects associated with semantic and syntactic processing in adults and school-age children

The processing of semantic and morphosyntactic information in sentences has also been studied in young children using ERPs. These studies have exploited the well-known finding that in adults, semantic and syntactic anomalies elicit ERP components with distinct latencies and scalp distributions. The ERP effect elicited to a word that renders a sentence semantically anomalous is a negative wave occurring between 250 and 500 ms post stimulus onset, peaking around 400 ms and largest over right posterior sites (known as the N400; Kutas 1997; Kutas and Hillyard 1980). In contrast, words that render a sentence syntactically anomalous typically elicit a late positivity beginning around 500 ms with a parietal distribution, known as the P600 (for reviews, see Friederici 2002; Hagoort, Brown and Osterhout 1999). In addition, many studies have reported a negative wave between 300 and 500 ms that is largest over left frontal sites (known as the "left anterior negativity" or LAN; e.g., Friederici 1995, 2002; Münte, Heinze and Mangun 1993) in response to both syntactic and morphological violations, an even earlier left anterior negativity (ELAN) occurring between 150 and 250 ms in response to phrase structure violations (Friederici, Hahne and Mecklinger 1996; Münte and Heinze 1994), and more centrally-distributed frontal negative effects in the same approximate time ranges to morphological violations although this latter effect has been linked to working memory processes, and may not necessarily be specific to morphosyntactic processing (Coulson, King and Kutas 1998a; King and Kutas 1995; Kluender and Kutas 1993a,b). Thus in adults, distinct neural systems are in place for semantic vs. grammatical levels of language processing. This has led researchers to ask how early these ERP effects are noted in children.

In one of the first developmental ERP sentence processing studies, the N400 semantic anomaly effect was replicated in children from 5 years through adolescence, and it was further shown that the peak latency of this component was as long as 620 ms in the youngest children and decreased steadily with age (Holcomb,

Coffey and Neville 1992). Since then, several studies have documented sentence-level N400 effects in school-age children, and in many cases reported longer latencies for these effects than those reported for adults (González-Garrido, Oropeza de Alba, Riestra Castaneda, Riestra Castaneda, Perez Avalos and Valdes Sosa 1997; Hahne, Eckstein and Friederici 2004; Neville, Coffey, Holcomb and Tallal 1993). Adult-like ERP effects to syntactically anomalous sentences have also been replicated in children; both an ELAN and P600 by 13 years and a P600 by 7–13 years (Hahne, Eckstein and Friederici 2004).

4.2 ERP effects associated with semantic and syntactic processing in preschool-age children

Several recent studies have also addressed sentence processing in preschool-age children. Harris (2001) provided ERP evidence of semantic and syntactic processing in 36–38 month-old English-speaking children. In the first study, semantic violations in sentences elicited a larger negativity, but in contrast to the N400 reported for adults, this negative ERP effect was largest over posterior regions of both hemispheres. Phrase structure violations elicited a larger positivity for syntactic anomalies from 500–1500 ms, bilaterally, which resembled the adult P600 in its latency but not in its scalp distribution. In contrast to the P600 in adults, this slow positive shift was largest at anterior sites. In this study there was no evidence of a LAN, which has been interpreted as a component that reflects automatic processing. Thus it was concluded that children this age do not yet use syntactic information in the same ways as adults. However, in the second study, Harris (2001) reported that a different type of phrase structure violation elicited a bilateral negativity between 300 and 600 ms. In addition to the differences in phrase structure violation type, there were differences in how the sentences were produced across these two studies (with pauses between words in the first study, and in a natural, continuous voice in the second), which may have influenced the results. Friedrich and Friederici (2005b; 2006) provided evidence of a prolonged, centroparietal N400-like effect to semantic anomalies in sentences in 19- and 24-month-old German-speaking children. Oberecker, Friedrich, and Friederici (2005) reported both an early negativity and a late positivity to phrase structure violations in 32-month-old German-speaking children, whereas Oberecker and Friederici (2006) observed only a P600 to the same stimuli in 24-month-old children.

Silva-Pereyra, Rivera-Gaxiola, and Kuhl (2005) recorded ERPs to sentences with syntactic and semantic anomalies in 36- and 48-month-old English-speaking children. In order to ensure that children were familiar with the lexical material used in the stimuli, the sentences were constructed using words from the MacArthur-Bates CDI lexical database (Dale and Fenson 1996). Morphosyntactic

anomalies were created by adding the grammatical inflection "-ing" to the verb in the control sentences (i.e., *My uncle will watch +ing the movie*), and sentences with semantic anomalies were created by changing the verb so that it was incongruous with the last word of the sentence (i.e., *My uncle will blow the movie*). Each sentence had the same syntactic structure. All of the sentences were recorded using the same female speaker and were presented via loudspeaker while the child watched a puppet show. For syntactically anomalous sentences, the ERPs were time-locked to the verb, whereas for semantically anomalous sentences, they were time-locked to the sentence-final word (noun). For the control sentences, ERPs were time-locked to both the verb, to serve as a comparison for the syntactically anomalous sentences, and to the final word, as a comparison for the semantically anomalous sentences.

Results indicated different effects for each sentence type at both ages (Figure 5). For the semantically anomalous sentences, there were two negative-going waves that were larger in amplitude than those elicited by the control sentences. In the 36-month-old children, the first of these (N400 effect) started at 400 ms after the onset of the critical word, and peaked at approximately 550 ms. A second negative effect (N600 effect) began at 550 ms, and peaked at 650 ms. In the 48-month-old children, the first negative (N400) effect occurred earlier, beginning at approximately 200 ms and peaking at around 400 ms, and the second negativity (N600) peaked at 600 ms. A third negative effect, from 800–1200 ms (N800 effect), was evident only in the 36-month-olds. For the grammatically anomalous sentences, both age groups displayed a positive wave from 300–600 ms after the onset of the critical word (the verb with the "-ing" inflection), peaking at approximately 400 ms (P400 effect). This effect was broadly distributed across electrode sites but largest at anterior electrode sites. A second positivity from 600–1000 ms (P800 effect) peaked at approximately 800 ms. The effects were more clearly defined at 48 than at 36 months.

In a follow-up study, Silva-Pereyra, Klarman, Lin, and Kuhl (2005) used the same stimuli as in the previous study but with 30-month old children. Similar to the results obtained with 36- and 48-month old children, these younger children displayed anterior negativities to semantically anomalous sentences, but at a longer latency, from 600–800 ms. They also evidenced a broadly distributed late positive shift to morphosyntactic violations from 600–1000 ms (P800 effect), but the earlier frontal positivity (P400 effect) observed in 36- and 48-month-old children was not observed in these younger children (Figure 5).

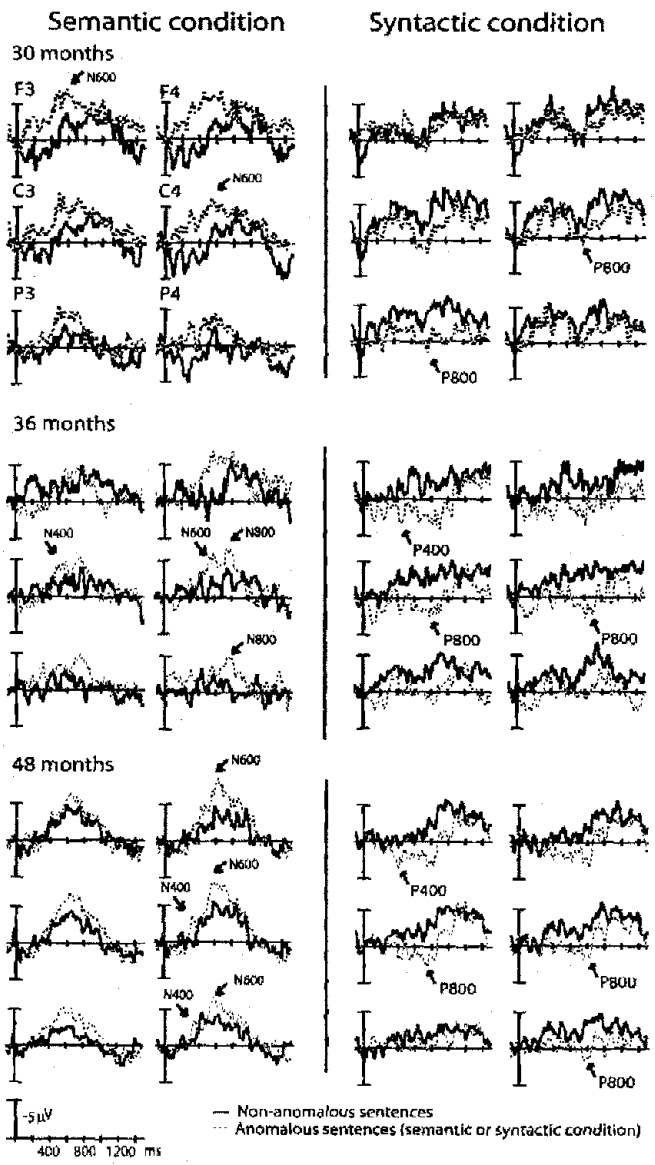

Figure 5. ERPs elicited by anomalous and non-anomalous sentences at 30, 36, and 48 months of age (negative plotted upwards). In the semantic condition all 3 groups show greater negativity to the semantically anomalous sentences compared to non-anomalous sentences (N400 and N600 effects, left side of figure). In the syntactic condition all 3 groups show greater positivity to the syntactically anomalous sentences compared to non-anomalous sentences (P800 effects, right side of figure) (adapted with permission from Silva-Pereyra J., Rivera-Gaxiola M. and Kuhl P. (2005). An event-related brain potential study of sentence comprehension in preschoolers: Semantic and morphosyntactic processing. *Cognitive Brain Research, 23*, 247–258

The results of these two studies indicate that both semantic and syntactic processing mechanisms in young children share many similarities with those reported for adults. Anterior concept-relevant brain areas that are active during spoken sentence processing appear very early in development and are identifiable as specific electrical responses to semantic anomalies. Similar to the longer latencies in the younger children studied by Holcomb and colleagues, the N400-like component in these young children had a longer latency than that reported for adults, suggesting slower rates of processing.

The late positive effects elicited by syntactic anomalies were in the same general time range as the adult P600 component, which has been hypothesized to reflect evaluation and repair processes specific to language processing (Friederici 2002). Silva-Pereyra and colleagues considered a possible interpretation for the presence of the early frontal positivity in preschool children. This effect could reflect attentional processes that were enhanced by the lower probability of the anomalous sentence types during the experiment, similar to the P300 effect that has been linked to probability and expectancy in adults (Coulson, King and Kutas 1998a,b). Although no LAN was observed, it is possible that a LAN-like effect overlapped with the early positivity. Alternatively, the LAN may not have been observed because the automatic mechanism it is believed to index may not yet be developed in children this young. The positive effect to morphosyntactic anomalies was more broadly distributed in 30- and 36-month-old children than in 48-month-old children. This increasing anterior-posterior specialization reflects a move in the direction that is more typical of responses at later stages in development and may reflect the fact that the specialization of brain mechanisms continues to mature until the mid-teen years (Bates, Thal, Finlay and Clancy 2003; Huttenlocher 2003). Such developmental specialization is also reflected in the latency of this effect, which was longer than that reported for the 6-year-old children previously studied by Hahne *et al.* (2004).

It is interesting to note that Oberecker and colleagues (2005) reported both LAN and P600 effects to phrase structure violations in 32-month-old children. In that study, children displayed a late positivity, resembling a P600, with a centroparietal positivity, but starting somewhat later than in adults. Also observed was a LAN between 300 and 600 ms. The peak of this effect, however, was later in the children (513 ms) than in adults (400 ms). Due to its similar distribution, Oberecker and colleagues interpreted this negativity as a child-specific precursor to the ELAN component. The reasons for the discrepancy between the results of this study and the studies of Silva-Pereyra and colleagues are unclear, but it is noteworthy that LAN effects have not been reported in all studies of morphosyntactic violation processing in adults (see Kim and Osterhout 2005). Furthermore, Oberecker and Friederici (2006) failed to observe an early negativity in 24-month-old

children. In a recent study, Silva-Pereyra, Conboy, Klarman and Kuhl (2007) examined ERP responses to phrase structure violations in 36-month-old children. There were two positive ERP effects elicited by the syntactically anomalous vs. non-anomalous real English sentences. The first positivity began at 500 ms and was observed only at left frontal, temporal and posterior temporal electrode sites. The second, later, positive effect was significant only at the left temporal site. While similar to those reported for morphosyntactic violations in 30-, 36-, and 48-month-old children (Silva-Pereyra, Klarman *et al.* 2005; Silva-Pereyra, Rivera-Gaxiola and Kuhl 2005), these results for phrase structure violations showed a more clearly left-lateralized distribution. In contrast, the late positivity to phrase structure violations reported by Oberecker and colleagues (2005) was more right-lateralized.

4.3 ERP effects associated with syntactic processing in the face of reduced lexical-semantic information

In the results reviewed thus far, morphosyntactic anomalies were presented in real sentences that contained intact lexical-semantic information. Of interest is whether preschool-age children show similar syntactic processing effects under conditions of greatly reduced semantic content, or if lexical-semantic information modulates these morphosyntactic effects. Children of preschool age may comprehend word order and other syntactic information in sentences not only because of purely syntactic processing mechanisms but because they also make use of lexical-semantic, pragmatic, and prosodic cues (Hirsh-Pasek and Golinkoff 1996). To this end, Silva-Pereyra and colleagues (2007) recorded ERPs in 36-month-old children to phrase structure violations in "jabberwocky" sentences (i.e., sentences in which content words were replaced with pseudowords while grammatical functional words were retained). Children listened to real English sentences with and without phrase structure violations (as described above) and their jabberwocky counterparts, which contained no cues to sentence meaning other than regular past-tense inflections on pseudoverbs and intact closed class words (determiners and prepositions). The pseudowords differed from the canonical words by only a few phonemes (e.g., My uncle watched a movie about my family / *My macle platched a flovie about my garily*). Certainly, this kind of sentence provides some semantic information, but not complete lexical information. ERPs were time-locked to the final noun phrase, as that was the point at which the phrase structure violation would be detected in the syntactically anomalous sentences (e.g., * *My macle platched about a flovie MY GARILY*).

Silva-Pereyra and colleagues observed two negative effects to the anomalous vs. non-anomalous jabberwocky sentences over the left hemisphere, from 750–900

ms and from 950–1050 ms. Thus the positivities noted to phrase structure violations in real sentences in these same children were not noted in the jabberwocky sentence condition. One possible explanation for this result is that the children did not note any syntactic anomaly because they were interpreting the final noun phrase as the beginning of a reduced relative clause (as in the construction, "My uncle talked about a movie *my family was in*"). However, P600-like positive effects have not been consistently reported for grammatical violation processing in jabberwocky studies with adults (Canseco-Gonzalez 2000; Münte, Matzke and Johannes 1997), and Hahne and Jescheniak (2001), who did report a P600 effect for jabberwocky stimuli, have hypothesized that such effects depend on the presence of very early syntactic effects (i.e., an ELAN). In all three studies of jabberwocky processing in adults, negative effects were reported, although at a much shorter latency than those observed in 36-month-old children. In addition, a study by Harris (2001) using jabberwocky sentences with preschool-age children also reported negative (but no positive) effects, which were bilateral but largest at left anterior electrode sites. As described above, the longer latency of the effects noted in the children studied by Silva-Pereyra and colleagues may be due to their underdeveloped language processing systems. It is also possible that these negativies in children reflected different processes than those observed in adults. Specifically, the children may have been attempting to extract meaning at the level of the pseudowords rather than at the sentence level. Late negativities, albeit with a right-hemisphere distribution, have been reported in ERP studies of word processing in 13–17 month-old infants, 20-month-old toddlers with delayed expressive language development, and 20-month-old bilingual toddlers, and appear to reflect the use of attentional resources during more effortful processing (Mills, Conboy and Paton 2005).

4.4 Future directions for sentence processing studies using ERPs

Together, the studies reviewed above indicate that sentence processing mechanisms develop early in life, but are less efficient in young children compared to adults, as reflected by longer latencies and in some cases, broader distributions of ERP effects. Studies of sentence processing in children have been conducted in English and German; a more complete picture would be obtained through studies of sentence processing across a wider range of typologically distinct languages. In addition, longitudinal studies might be undertaken to determine how the mechanisms involved in grammatical processing develop with age and language experience.

5 Conclusions

The ERP studies reviewed in this chapter suggest that early language processing mechanisms undergo important changes during the first few years of life. ERPs recorded to syllables have shown that within the same infants, the neural mechanisms involved in processing both native and nonnative phoneme contrasts change between 7 and 11 months, and that these early patterns are predictive of later language learning in the second and third years. ERPs recorded to words in the second year have suggested important links between the experience of learning and using words and the neural activity elicited by those words. ERPs recorded to sentences in the third and fourth years suggest that although adult-like semantic and syntactic processing mechanisms are noted at these ages, there are differences in the latencies and scalp distributions of these components between children and adults. Further research using ERPs with infants and young children will complement behavioral approaches by providing a means of observing how changes in brain systems give rise to and are shaped by advances in early language development.

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