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REPORT

Brain potentials to native and non-native speech contrasts in 7- and 11-month-old American infants

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Abstract

Behavioral data establish a dramatic change in infants' phonetic perception between 6 and 12 months of age. Foreign-language phonetic discrimination significantly declines with increasing age. Using a longitudinal design, we examined the electrophysiological responses of 7- and 11-month-old American infants to native and non-native consonant contrasts. Analyses of the event-related potentials (ERP) of the group data at 7 and at 11 months of age demonstrated that infants' discriminatory ERP responses to the non-native contrast are present at 7 months of age but disappear by 11 months of age, consistent with the behavioral data reported in the literature. However, when the same infants were divided into subgroups based on individual ERP components, we found evidence that the infant brain remains sensitive to the non-native contrast at 11 months of age, showing differences in either the P150–250 or the N250–550 time window, depending upon the subgroup. Moreover, we observed an increase in infants' responsiveness to native language consonant contrasts over time. We describe distinct neural patterns in two groups of infants and suggest that their developmental differences may have an impact on language development.

Introduction

It is widely accepted that linguistic experience exerts a profound effect on an individual's ability to identify and discriminate speech sounds (Jusczyk, 1997; Kuhl, 2000a; Werker & Tees, 1984a) and that adults have great difficulty perceiving some foreign language contrasts (for review, see Strange, 1995). The well-established difficulty adults have in distinguishing the phonetic contrasts of foreign languages has recently been interpreted as an effect of 'interference' by the native language (Kuhl, 2000b; Iverson *et al.*, 2003). This view suggests that extensive experience with a primary language causes *neural commitment* to the acoustic properties of that language, and that consequently, processing a second language whose acoustic patterns do not conform to the previously learned ones becomes difficult.

Both behavioral and brain measures indicate that while adults have difficulty, they do not experience a complete loss in the ability to discriminate foreign language contrasts. Behavioral studies show that adults' performance on foreign language contrasts remains above chance, but far below performance by native speakers on the same task (Carney, Widin & Viemeister, 1977; Werker & Tees, 1984a). Data obtained using electrophysiological techniques yield additional support for this idea, and also suggest that event-related potentials (ERPs) may provide a more sensitive index of speech perception abilities when compared to behavioral measures. Rivera-Gaxiola, Csibra, Johnson and Karmiolff-Smith (2000a, 2000b), for example, demonstrated that native English-speaking adults exhibit discriminatory ERPs to a difficult non-native Hindi dental/retroflex contrast, adding support to the idea that the ability to detect differences in foreign language speech sounds is not lost. Moreover, the data show that when the same participants were tested behaviorally, they did not provide evidence of discrimination. Tremblay, Kraus and McGee (1998), Tremblay, Kraus, McGee, Ponton and Otis (2001) and Tremblay and Kraus (2002) had previously shown in phonetic training studies that ERP measures can reflect learning prior to the time that behavioral measures reflect learning.

ERPs provide an opportunity to study the time course of neural processes with great temporal resolution. In very broad terms, ERP components are classified according to the time in milliseconds of the occurrence of peaks and valleys (latency), the polarity – positive or negative – of the deflections observed within the waveforms, and the topographic distribution of the components

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over the scalp. It is believed that ERPs reflect net electrical fields in open configurations, that is aligned in a parallel orientation, associated with the activity of sizeable populations of neurons that are synchronously active (Coles & Rugg, 1995).

ERP patterns recorded during the perception of speech stimuli may reflect different levels of representation or information processing (Kutas, 1997). For example, in their study, Rivera-Gaxiola and colleagues (2000a) reported that the detection of phonetic differences in the dental/retroflex contrast were observable in the waveform amplitudes during the first few hundred ms after the stimulus was changed, that is, in the N1–P2 auditory complex as well as in the mismatch negativity (MMN). The MMN is an ERP component that reflects a pre-attentive detection of stimulus change to a 'deviant' stimulus when it is presented against a background of 'standard' stimuli. In other words, the MMN represents the neural detection of a 'mismatch' between the deviant and the memory trace formed by the standard in a classic passive 'oddball paradigm' (Näätänen, Gaillard & Mäntysalo, 1978). Evidence of discrimination at the MMN level that precedes evidence of discrimination at the behavioral level suggests that this neural measure may be valuable in determining the effects of linguistic exposure on human speech perception (Cheour *et al.*, 1998b). However, less is known about the precise functionality and origin/development of the N1–P2 complex *per se* regarding speech discrimination in infancy. Developmental studies on the evolution of compulsory ERP components have typically described responses to non-speech stimuli (Kushnerenko, 2003) or to a single syllable (Novak, Kurtzberg, Kreuzer & Vaughan, 1989). The study by Novak *et al.* described the evolution of what was called the P2–N2 complex from birth to 3 and 6 months, showing that by 3 months of age, two positive peaks could be observed. A prominent N1 between the two positive peaks could be observed by 6 months of age. Kurtzberg, Vaughan and Novak (1986) had previously reported that between 6 and 9 months of age, the amplitude of the second major positive peak had decreased and that the amplitude of the bifurcating N1 had increased by 9–12 months of age. We believe that studying the changes typically observed in infants in the auditory P–N complex *within a discriminatory task*, exploring the responses to both deviants and standards, will add information about the functionality of this neural process in the first years of life as well as reveal how it reflects infants' neural development as they are exposed to natural speech.

The goal of the present study was to use ERP measures to test infants in the first year of life to determine whether ERPs would reflect the behavioral changes established in previous studies. Behavioral measures on infants suggest that they develop language-specific perception in the second half of the first year of life (Kuhl, 2000a). Early in life infants show 'categorical perception', the ability to perceptually partition a consonant continuum at the boundaries between categories, both for native and foreign speech stimuli (Eimas, Siqueland, Jusczyk & Vigorito, 1971; Eimas, 1975). Behavioral studies suggest a dramatic change in infants between 6–8 months of age and 10–12 months of age. Specifically, by 10–12 months of age, behavioral studies suggest that infants can no longer discriminate consonant contrasts that do not confer differential meaning in the language of their community (Werker & Tees, 1984b). The question raised, however, is whether more sensitive measures, ones that tap infants' neural responses such as ERPs, would provide evidence that infants retain the ability to discriminate foreign-language consonant sounds, like adults.

Only one study has employed ERP techniques to examine cross-language speech perception and the study was conducted with vowel stimuli. Cheour *et al.* (1998a) used the recording of ERPs to examine discriminatory responses to vowels in infants at 6 and at 12 months of age. When tested behaviorally in the standard discrimination paradigm, vowel stimuli do not follow the exact same developmental pattern shown by consonants; infants retain the ability to discriminate foreign language vowel stimuli at 10–12 months of age (Polka & Werker, 1994). On the other hand, vowel perception does show a pattern of language specificity by 6 months of age when tested in behavioral studies that tap the internal organization of native versus foreign language speech categories; in these studies, discrimination is shown to be reduced around the category's best instances, an effect that has been shown to be language-specific by 6 months of age (e.g. Kuhl, 1991; Kuhl, Williams, Lacerda, Stevens & Lindblom, 1992). Cheour *et al.* (1998a) report MMN data from a sample of Finnish infants studied longitudinally at 6 and then at 12 months of age, and a sample of Estonian infants (evaluated only at 12 months of age). The results show that infants at 6 months showed a discriminatory response to both of these vowel stimuli, but that by 12 months, infants' responses to the non-native vowel contrast were attenuated. The differences between the time course of language-specific perception seen in the ERP versus the behavioral tasks could be due to the stimuli used or to the methods of assessment. In both cases, however, the literature shows that language-specific perception can be observed by the end of the first year of life. The present study focused on consonants and the goal was to establish the developmental pattern of consonant perception between 6 and

12 months of age using ERP methods. As reviewed, previous data suggest that this period is one of dramatic change for consonants; non-native perception sharply decreases (Werker & Tees, 1984a). Much less is known about the pattern of change for native language consonant contrasts between 6 and 12 months of age. Recent studies in our laboratory suggest that native language consonant contrasts show a dramatic increase in speech perception between 6 and 12 months (Kuhl *et al.*, under review). In fact, studies in our laboratory show that infants at this age readily acquire phonetic information from natural conversation and will learn phonetically at 9 months from short-term exposure to foreign language speakers reading books and playing with toys (Kuhl, Tsao & Liu, 2003). We therefore additionally hypothesized that ERP responses to native language speech sounds would show increased discriminatory ability with increasing age.

In the present study, ERP responses to native and non-native CV-syllable contrasts were examined using a longitudinal design in normally developing 7- and 11-month-old American infants who were acquiring English. We hypothesized that (1) similar to adults, infants at 10–12 months of age would exhibit electrophysiological evidence of discrimination for non-native phonetic contrasts, indicating that infants do not completely lose the ability to discriminate foreign language consonant contrasts; and (2) that neural responsiveness to native language contrasts would show a significant increase over time, reflecting phonetic learning, while neural responsiveness to the non-native consonant contrast would show a decline in neural responsiveness over time.

Methods

Participants

Twenty-eight 7-month-old infants were recruited through the Infant Studies Subject Pool at the University of Washington. Criteria for inclusion in the study were that infants were being raised in monolingual households, had no known visual or auditory deficits, were full term (born ± 14 days from due date) and normal birth weight (2.7–4.5 kg), had normal pregnancies and deliveries, and that members of their immediate families had no history of hearing loss or language impairment. Parents were paid $30 for their participation.

Seven-month-old infants

EEGs from 28 infants (15 girls) were recorded. Data from 14 infants were eliminated due to a low number of trials. ERPs from the remaining 14 infants (8 girls; mean age = 6.7 months; range = 6.24–7.2 months) were further processed and analyzed.

11 month-old infants

The same 14 infants accepted for analyses at 7 months were followed up at 11 months of age and data from 12 infants (7 girls; mean age = 10.5 months; range = 10.23–11.6 months) were further processed and analyzed.

Stimuli

Three consonant–vowel (CV) syllables differing in voice-onset time (VOT), the critical cue distinguishing voiced from voiceless phonetic contrasts, were used: voiced /da/ that is phonemic in Spanish but not in English, a voiceless unaspirated alveolar consonant that is phonemic both in Spanish (heard as /ta/) and in English (heard as /da/), and voiceless aspirated /ta/ that is phonemic in English but not in Spanish. VOT is a measure of the time between the onset of vocal chord vibration (which marks the onset of voicing) and the onset of the plosive burst in the consonant (which marks the release of the consonant). When voicing precedes release, VOT is a negative value; when voicing follows the burst, VOT is a positive value. The three syllables differed in VOT (Spanish /ta/-English /da/ = +12 ms VOT, Spanish /da/ = –24 ms VOT, English aspirated /ta/ = +46 ms VOT). The CV syllables were produced naturally by a female Spanish/English bilingual speaker, and manipulated by using Praat and SoundForge 4.0 software to obtain a match or very close to equal duration (229.65 ± 0.3 ms), intensity, average root mean square power and vowel. The average fundamental frequency was 180 Hz. Pilot studies confirmed the expected pattern of adult discrimination: adult native English speakers behaviorally discriminated the English contrast (voiceless aspirated versus voiceless unaspirated), but not the Spanish contrast (voiceless unaspirated versus voiced). The latter was behaviorally discriminated by native Spanish listeners with ease.

Design

An important feature of these tests was the use of a cross-linguistic double-oddball paradigm within the same time series. The double-oddball paradigm allowed us to test the two deviant stimuli under exactly the same conditions within the same experiment so that fatigue or other external conditions could not affect the two conditions differentially. We used the phoneme common to both languages, the voiceless unaspirated alveloar sound, as the standard, and the two language-specific

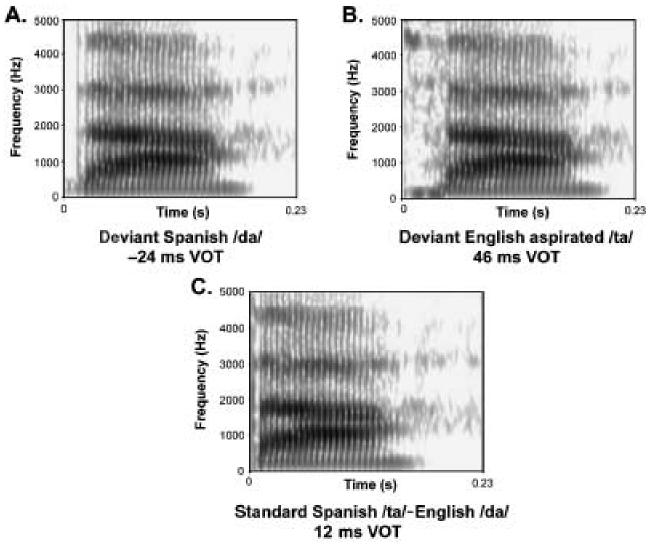

Figure 1 *Spectrograms of the syllables used in the present study showing VOT values for each.*

sounds, voiceless aspirated /ta/ and voiced /da/, as the two deviants. The standard voiceless unaspirated syllable was presented 80% of the time and the remaining two deviant syllables were each presented 10% of the time in a semi-random fashion: presentation restrictions were that at least three standards occurred between presentations of a deviant. The interstimulus (offset to onset) interval was 700 ms.

The session consisted of the presentation of 1000 stimuli. After every two minutes of stimulation, a 1-minute silence was inserted to allow for 'regular conversation' with the baby, and to improve the signal level. A variety of studies suggest that short breaks prevent habituation of the MMN (McGee *et al.*, 2001; Woods & Elmasian, 1986; Dehaene-Lambertz & Dehaene, 1994). McGee *et al.* showed that short breaks result in the recovery of the MMN or other discriminatory ERP components. Although the habituation timing is around 15–20 minutes of stimulation, they report a rapid decline in the amplitude of the MMN in the populations they studied, namely young adults, guinea pigs and school-age children, who are normally tested in longer sessions than infants. Woods and Elmasian (1986) have also reported up to 60% of amplitude habituation of auditory cortical responses even after the second or third presentation of the same stimulus. Dehaene-Lambertz and Dehaene (1994) reported an important decrease in the amplitude of auditory electrophysiological responses in 2-month-old infants when presented with consonant–vowel (CV) syllables by the second repetition of the standard stimulus. Our preliminary studies showed that infants' ERPs were cleaner (more artifact-free segments per condition) when the pauses and interaction were inserted during the session. The syllables were delivered by computer to two loudspeakers placed approximately 1 m in front of the child, at a level of 69 dB SPL.

Procedure

Infants sat, either on their mothers' laps (at 7 months) or in a highchair with the parent next to them (at 11 months), in a sound proof chamber. In front of the infants, a toy waver would entertain the babies using toys and/or a silent movie played on a television monitor. Parents were asked to praise their child and touch them whenever there was a silent gap. Ten seconds before restarting stimulation, the toy waver was informed via headphones and she would regain the infant's attention. The entire session, including fitting the cap, the 1-minute silences and a 5-minute break in the middle of the session, lasted 45 minutes to 1 hour.

EEG recording

The electroencephalogram (EEG) was recorded using the electrocaps with pre-inserted tin Ag/AgCl electrodes and referenced to the left mastoid from Fp1, Fp2, F3, F4, C3, C4, P3, P4, O1, O2, F7, F8, T3, T4, T5, T6, Fz, Cz, Pz and the active right mastoid of the 10/20 International system. The amplifier bandwidth was set between 0.1 and 40 Hz. All electrode impedances were kept at or below 5KΩ. Signals were amplified with a gain of 20000. EEG was sampled every 4 ms and stored on a hard disk for further analysis. EEG segments of 650 ms with a prestimulus time of 100 ms were selected and averaged off-line to obtain the ERPs. Further low-pass filtering was set at 15 Hz as most of the components that have been described for infants' ERPs are reported within this range (Kushnerenko, 2003; Ceponiene *et al.*, 2002; Cheour *et al.*, 1998a, 1998b). The vertical electro-oculogram (VEOG) was recorded from one infra-orbital electrode placed on the infant's left cheek. Automatic rejection of segments was carried out (electrical activity +/– 150 uV at any electrode site was considered artifact and the whole segment was rejected). Baseline correction was performed in relation to the prestimulus time mentioned above. ERP data were accepted for analyses when clear auditory P–N complexes within the first 600 ms were displayed (minimum number of trials in all channels = 80) and at least 17 out of the 19 recording sites were acceptable.

Data analyses

The waveforms obtained were explored within two time windows, the first positive peak [P-peak (150–250 ms), P150–250] and the following negativity [N-peak (250–550 ms), N250–550]. Peak amplitude values within each window for responses to predeviant and deviant syllables for each child were considered for the analyses. We did not use difference waveforms. The number of responses to predeviant and deviant stimuli analyzed in each condition (native and non-native) were equal or close to equal (mean = 85, range = 80–90). One four-way repeated measures ANOVA was calculated for the whole group. The factors were Condition (native deviant versus non-native deviant), lateral sensor Position (left versus right hemisphere), anterior-posterior Location (frontal-polar, frontal, central, parietal, frontal-lateral and temporal) and Age (7 and 11 months). Subsequently, each of the ages was analyzed separately and two independent three-way ANOVAs were calculated. The factors were the same as before, excluding the age factor. Confirmatory non-parametric statistics were also carried out: Wilcoxon's matched-pairs signed ranks tests between responses to predeviant standards and deviant stimuli within each condition were carried out. Amplitude values (*not* the average) from five consecutive samples around the largest peak for each P150–250 and/or N250–550 time window (i.e. peak amplitude value and the two adjacent values at either side of the peak) were used in the comparisons. Alpha levels were also corrected for multiple comparisons (Bonferroni). The same non-parametric test was used when each age group was subdivided.

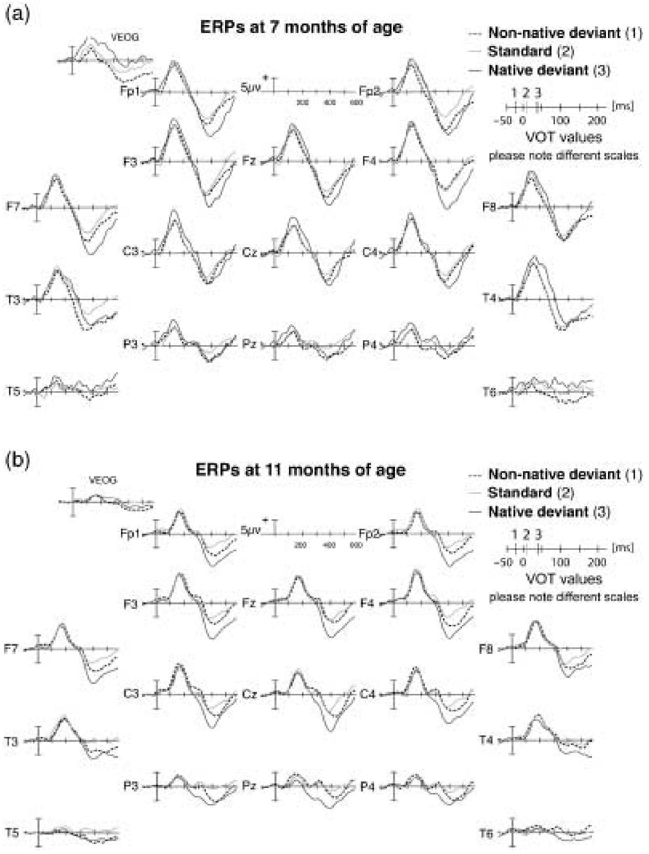

Figure 2 *ERP (auditory P150–250/N250–550 complexes) responses to the standard voiceless unaspirated syllable common to both languages, and the deviant Spanish voiced (non-native) and English aspirated (native) syllables: (a) ERPs at 7 months of age (whole group,* n *= 14, eight girls). (b) ERPs at 11 months of age (whole group,* n *= 12, seven girls). Positive is plotted up.*

Results

Group data show that normally developing American infants acquiring English, when tested at 7 and 11 months of age, show different patterns of electrical responses to native and non-native phonetic contrasts as a function of age over the N250–550 time window. The analyses showed main effects for Condition ($F(2, 11) = 5.77$, $p = 0.022$, $\eta^2 = 0.536$, observed power = 0.742), Age ($F(1, 11) = 8.25$, $p = 0.015$, partial $\eta^2 = 0.429$, observed power = 0.744) and Location ($F(5, 7) = 8.113$, $p = 0.008$, partial $\eta^2 = 0.853$, observed power = 0.937). No hemispheric differences were found and no interactions were found. We will limit our discussion to the Condition main effect, that is, the statistical differences observed in the ERPs to the native as opposed to the non-native contrast.

As shown in Figures 2a and b, the group ERP results for the two groups, 7- and 11-month-old infants, show that at 7 months of age, infants' neural responses provide evidence of discrimination of both the native and the non-native phonetic contrasts, as expected, given the large literature attesting to the fact that between 6 and 8 months of age, infants are capable of discriminating both native and non-native phonetic contrasts. We had also predicted, given our behavioral findings, that between 7 and 11 months of age, infants would show improvement in their responses to native language sounds, and this was also verified by the ERP measures at the two ages. By 11 months of age, ERP responses over the N250–550 time window to the native deviant appear to have improved; compare 7 months' ($F(1, 13) = 5.56$, $p = 0.035$, partial $\eta^2 = 0.3$, observed power = 0.588) to 11 months' ($F(1, 11) = 18.58$, $p = 0.001$, partial $\eta^2 = 0.628$, observed power = 0.974) N250–550 values. We were particularly interested in infants' response to the non-native contrast. We had predicted that ERP measures, being more sensitive, would reveal that infants retain neural responsiveness to the non-native contrast. However, the group results showed that neither P150–250 or N250–550 neural responses to the non-native contrast reach significance at 11 months

(N250–550 $F(1, 13) = 3.901$, $p = .05$ at 7 months, and $p > .10$ at 11 months of age for both time windows).

Nonparametric tests were also conducted on the group data. At 7 months of age, these tests confirmed that American infants discriminate both syllable contrasts. In the N250–550 time window, significance is reached ($p < 0.05$ in all cases) for the native deviant versus standard over FP1, FP2, F3, C4, F7, T3, T4 and midline ($z \in [-.94, -2.55]$). For the non-native deviant versus standard, significance is reached over F3, T3, P3 and P4 $z \in [-1.54, -2.12]$). In the P150–250 time window, significance was reached over fronto-polar, central and parietal recording sites for the native deviant versus standard comparison $z \in [-1.6, -2.34]$). No sites were significant for the non-native deviant versus standard comparison. At 11 months of age, nothing was significant for the non-native deviant versus standard comparison, whereas all recording sites except T4 were significantly different for the native contrast within the N250–550 time window $z \in [-0.89, -2.31]$).

Detailed examination of individual ERPs, however, suggested that infants differed dramatically with respect to the pattern of polarity in their responses to the deviants. About half the infants responded to the deviant stimuli with a larger early positivity, whereas other infants responded with a larger later negativity. Combining responses across these two groups cancelled the effect in the group average. A subdivision of our sample was therefore carried out, based on the polarity of the infants' ERP responses to the deviant.

Half of the 7-month-old infants (henceforth Group 1) showed significantly larger P150–250 discriminatory responses for both the native and non-native contrasts (native contrast: $p < 0.05$ over FP1, F3, F4, C3, C4, P3, P4, F8, T4 and midline, $z \in [-1.68, -2.51$, positive ranks], non-native contrasts: $p < 0.05$ over FP1, F3, F4, C3, C4, P3, Fz and Cz, $z \in [-1.68, -2.24]$. Nothing was significant for this group in the N250–550 time window. Parametric statistics were also calculated: $F(1, 6) = 10.88$, $p = 0.01$ for the native contrast and $F(1, 6) = 8.11$, $p = 0.02$ for the non-native contrast over the P150–250 time window See Figure 3a.

The other half of the infants (henceforth Group 2) showed significantly larger amplitudes for the N250–550 component for both the native and the non-native deviants. Significance was shown with nonparametric statistical analyses over all electrode sites except C4, T4 and F8 for the native contrast ($p < 0.05$ $z \in [-1.12, -2.38]$) and over all sites except F3 for the non-native contrast ($p < 0.05$ $z \in [-1.54, -2.52]$). Parametric analyses yielded analogous results ($F(1, 6) = 19.12$, $p = 0.01$ for the native contrast, and $F(1, 6) = 35.9$, $p = 0.001$ for the non-native contrast). See Figure 4a.

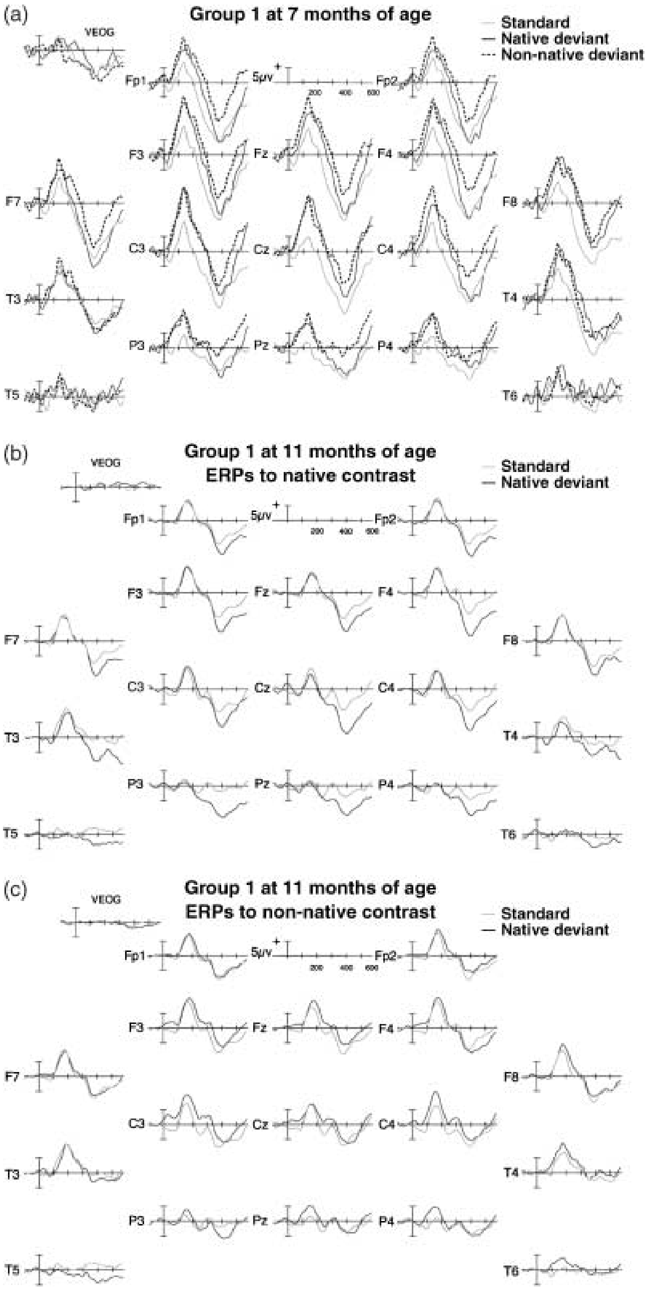

Figure 3 *ERP responses displayed by Group 1: (a) at 7 months of age, infants from Group 1 (*n *= 7, three girls) display a larger positivity (between 150–250 ms after stimulus onset) to both deviants with respect to the standard, (b) at 11 months of age (*n *= 5, one girl), these infants display a larger N250–550 to the native deviant, and (c) a larger P150–250 to the non-native deviant.*

When these infants were followed up at 11 months of age, their neural responses demonstrated that both groups continued to discriminate both the native and the non-native contrasts. Infants in Group 1, who at

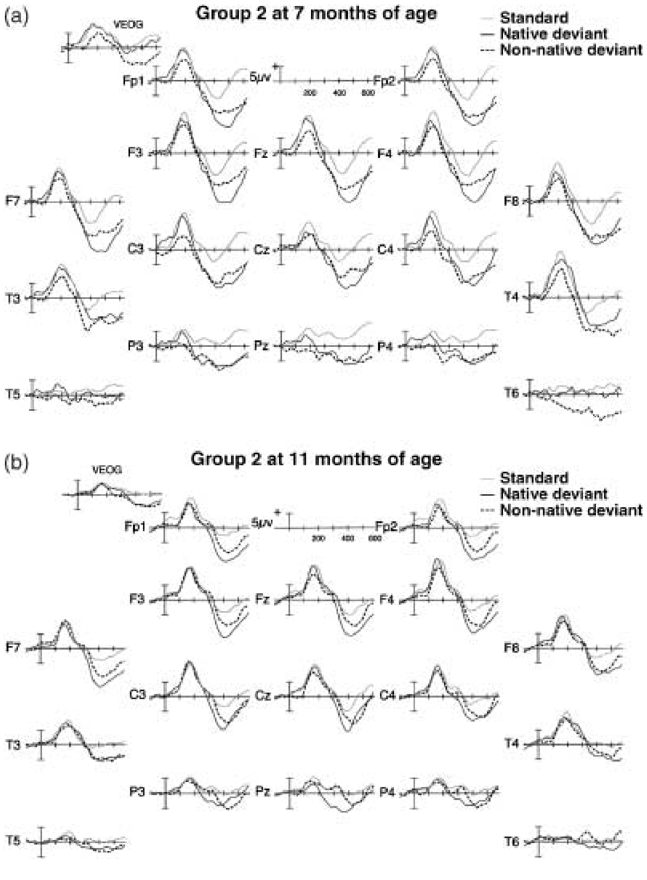

Figure 4 *ERP responses displayed by Group 2: (a) at 7 months of age, infants from Group 2 (*n = 7*, five girls) display a larger N250–550 to both native and non-native deviants with respect to the standard, (b) at 11 months of age (*n = 7*, six girls), the same infants display a larger and more robust N250–550 to the native deviant, and a smaller (but still significant) N250–550 to the non-native deviant.*

7 months showed differences in the amplitudes of the positivity to both the native and the non-native contrast, now demonstrated a significant N250–550 difference to the native contrast; they continued to show a larger amplitude to the non-native deviant in the positivity. For the N250–550 time window, non-parametric tests showed $p < 0.05$ over fronto-polar, frontal, central and parietal recording sites, $z \in [-1.99, -2.2]$; parametric tests showed an $F(1, 4) = 7.48$, $p = 0.05$ to the native contrast. For the non-native contrast, Group 1 infants continued to show a large P150–250 bilaterally over temporal and central recording sites. For the non-native contrast, non-parametric statistics showed $p < 0.03$, $z \in [-.9, -2.2]$; parametric statistics: $F(1, 4) = .48$, $p = 0.05$). See Figures 3b and 3c.

Infants in Group 2, who at 7 months showed a larger negativity to both the native and the non-native contrast, remained 'N250–550 discriminators'. For the native contrast, they showed a significant effect over all electrode sites (non-parametric statistics values: $p < 0.01$, $z \in [-1.96, -2.52]$; parametric values: $F(1, 6) = 13.45$, $p = 0.001$. For the non-native contrast, they showed significant differences over FP1, F3, F4, C3, C4, P3, T3, Cz and Pz (non-parametric statistics values: $p < 0.05$, $z \in [-1.54, -2.52]$; parametric statistics values: $F(1, 6) = 6.145$, $p = 0.048$. See Figure 4b.

Discussion and conclusions

It is widely accepted that infants have an innate capacity to acquire linguistic information from exposure to language. However, although humans are born with highly complex capacities that allow them to discriminate speech sounds, we are an altricial species and will – under normal circumstances – be exposed to the language(s) of our community. In order to organize those speech sounds into categories, segment the speech stream, acquire words, understand and produce sentences, and later on, engage in full discourse, both biological endowments and experience are pivotal. Studies on speech perception show a developmental change early in infancy, one that diminishes foreign language processing. Though foreign language processing is diminished, adults remain capable of discriminating speech contrasts that do not confer differential meaning in the person's native language (Werker & Tees, 1984b; Carney, Widin & Viemeister, 1977; Rivera-Gaxiola *et al.*, 2000a; Rivera-Gaxiola *et al.*, 2000b). To further our understanding of the mechanisms underlying speech perception and the way in which neurological development and exposure to language interact, evaluation of neural responses to native and non-native contrasts over time provides valuable information.

In the present study, American monolingual infants aged 7 months were followed longitudinally until they were 11 months, and their auditory event-related potentials to native and non-native contrasts were examined. The findings demonstrated that, at the group level, infant ERPs at 7 months of age reveal discrimination of both native and non-native phonetic contrasts; by 11 months of age, infants' ERPs show increased responsiveness to a phonetic contrast that conveys meaning in the language of their community, but show a failure to discriminate the non-native contrast. These results are overall in agreement with Cheour *et al.*'s (1998a) study, in which 6-month-old Finnish infants showed MMNs when presented with either a native Finnish vowel contrast or a non-native Estonian, acoustically larger vowel contrast. The acoustically more salient non-native contrast showed a larger (but not significantly different) MMN when compared to the native contrast. At 11 months of age, the same Finnish babies displayed a much larger MMN for the native contrast, than for the non-native – and acoustically larger – contrast. The authors claimed an enhancement in the MMN response to the native contrast from 6 to 12 months of age because of the stronger statistical results at 12 months when compared to 6 months. As stated before, the interesting finding here is that infants show a more robust discriminatory response to a contrast that conveys differential meaning in their native language with age, although an MMN can be recorded at earlier ages. In our study, when individual infants' ERP components were examined, two subgroups were formed on the basis of the amplitude and polarity of their responses. Analysis of these data demonstrated that both groups of 11-month-old infants showed discriminatory ERP responses to the non-native contrast.

The literature also documents differences in the polarity in the ERP responses that infants display when presented with speech contrasts at different ages within the first year of life. Dehaene-Lambertz and Dehaene (1994) and Dehaene-Lambertz and Baillet (1998), for example, report significant differences in the positive components of the auditory ERPs they observed in infants under 6 months of age. Pinkho *et al.* (1999) and Leppänen, Pihko, Eklund and Lyytinen (1999) reported a significant positivity and remarked on the absence of a negativity in response to a speech change from /kaa/ to /ka/ in 6-month-old infants. Other researchers (Cheour-Luhtanen *et al.*, 1995; Cheour *et al.*, 1998a, 1998b; Kushnerenko *et al.*, 2001, 2002a, 2000b; Ceponiene *et al.*, 2002; Pang *et al.*, 1998) report a negativity (the MMN) in infants as a response to speech changes during the first year of life. Kushnerenko *et al.* (2002a), in a developmental study using pitch detection in tones, reported a negativity (the MMN) that increased with age (from birth to 1 year of age); however, they also observed high individual variability and a large positivity over C3 in their 3- and 6-month-old infants. The differences observed across studies could be attributable to the stimuli employed in the test, or age differences, and support the idea that both significantly larger positivities to deviants, when compared with standards, as well as significantly larger negativities have been observed across studies in response to auditory stimuli in the first year of life.

We argue that these differences in components and polarity are important because they indicate individual variability that cannot be observed when ERPs are observed only at the group level. It is well known that ERP responses are multifactorially determined: Different levels of maturity, different listening strategies and even different generators contribute to the waveforms of individual infants' auditory responses to speech, and we believe that these differences may be important in speech perception development.

In the present study, analysis of individual subjects' data suggested that infants fell into two separate groups, with each group providing evidence that infants at 11 months still have the capacity to discriminate non-native contrasts or, in other words, the acoustic difference that is phonemic in Spanish. Infants were grouped according to the amplitudes of each of the components observed (P150–250 and N250–550). At 7 months of age, Group 1 infants presented a significantly larger P150–250 for both the native and non-native deviants when compared to the predeviant standard. In the follow-up tests at 11 months of age, these same infants displayed a significant N250–550 for the native contrast and continued to show a significant response in the P150–250 time window to the non-native contrast. Group 2 infants, who displayed a significantly larger N250–550 to the deviants of both contrasts at 7 months of age, exhibited what we believe is a stronger and more consistent N250–550 to the native contrast at 11 months of age, and a smaller N250–550 (though still significant) to the non-native contrast. In other words, analysis of individual neural patterns of response demonstrated discrimination of the non-native contrast by both groups of infants. These data suggest that infants retain the capacity, at a neural level, to differentiate non-native contrasts. The relationship between the two responses (P and N) here described remains to be studied further. We speculate that all infants will present larger N250–550s for both contrasts later in life but probably with different peak latencies and strengths. The P-peak may continue to reflect acoustic differences as well as the number and salience of the acoustic cues.

Moreover, there is support in both groups for the notion that infants' native language phonetic processing improves over time, consistent with the behavioral data obtained in this laboratory on infants at this age (Kuhl *et al.*, under review). Both the large proportion of subjects who could discriminate the native contrast at the N250–550 level at 11 months of age – seven infants at 7 months of age and then all 12 infants at 11 months of age – and the statistical results suggest improvement over time. We interpret this finding as suggesting that the period between 6 and 12 months is one in which infants show strong phonetic learning and begin a process of *neural commitment* to the auditory patterns that typify their native language (Kuhl, 2000b). Evidence in support of this idea stems from the previously mentioned studies showing that first-time exposure to a foreign language between 9 and 10 months of age results in rapid phonetic learning of foreign language contrasts by the infants (Kuhl *et al.*, 2003). Neural commitment to the auditory patterns frequent in native language reduces the brain's response to the acoustic differences that do not conform to the learned patterns, such as those contained in non-native speech. The present results suggest large individual differences in ERP responses to speech by young infants. The question prompted by the results is: of what significance are the different patterns seen in infants at this early age? Given that the N250–550 is the response that all infants show for the native contrast at 11 months of age, it is possible that stronger N250–550 differences may mirror a more mature pattern of response, whereas the earlier P150–250 responses reflect a more acoustic form of analysis. While all of the 11-month-old infants displayed a large N250–550 for the deviant in the native condition, Group 1 infants evolved from showing 'P' responses for both contrast types to an N250–550 response for the native contrast, and appear to have developed a more complex P-peak (a clearer double positivity peaking at 180 and 300 ms after stimulus onset) especially over central and right frontal recording sites. Group 2 infants showed a stronger N250–550 peak amplitude difference between standard and the deviant for the native contrast, and a smaller response to the non-native contrast, which may reflect 'neural commitment' to the native language; this group of infants already responded at the N250–550 level to both contrasts at 7 months of age. More developmental studies are needed to determine the ontogeny of these two groups and their ERP components, with timing of occurrence of peaks being crucial.

We also note that, in a replication study with a much larger sample of 11-month-old infants ($n = 50$), and with Spanish-learning infants ($n = 35$) we have found the same electrophysiological patterns and differences (Rivera-Gaxiola *et al.*, submitted). Two distinct groups of infants, from the standpoint of their neural responses to native and non-native speech, were again observed. We are now following the children in the present study and those in the replication study longitudinally to examine whether the patterns of response seen in Group 1 as opposed to Group 2 infants have a predictive validity for differential later language scores. On the one hand, we are very interested in infants' ERP responses to native speech contrasts, and the degree to which responses to these two kinds of speech sounds may allow us to detect infants at risk of delay/failure in future language. On the other hand, we are also interested in the evolution of the responses to non-native speech contrasts as possible indicators of ease at some levels of second language learning.

We have here illustrated in an electrophysiological longitudinal developmental study that group ERP data may underestimate individual infants' perception of phonetic contrasts. In the present study, infants' neural responses at the group level failed to show discrimination of a non-native contrast. However, we further demonstrated that infants' ERPs are rich in information, and that when infants are considered individually, more detailed information is obtained. The infant brain remains capable of discriminating non-native phonetic contrasts at 11 months of age and the infants' neural patterns we observed suggest that they accomplish this in different ways. Infants may be differentially sensitive to lag/lead contrasts based on purely acoustic features. We argue that the responses observed in the present study are related to the native/non-native status of the contrast. We base this conclusion both on the evidence of the N250–550 at 7 and 11 months of age reported here, and on the results of cross-linguistic comparisons using these same stimuli (Rivera-Gaxiola *et al.*, 2004). Further studies will determine whether the distinct patterns of neural response observed in infants in the present work influence their future language performance.

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References

Carney, A.E., Widin, G.P., & Viemeister, N.F. (1977). Noncategorical perception of stop consonants differing in VOT. *Journal of the Acoustical Society of America*, **62** (4), 961–970.

Ceponiene, R., Shestakova, A., Balan, P., Alku, P., Yaguchi, K., & Näätänen, R. (2002). Maturation of cortical sound processing as indexed by event-related potentials. *Clinical Neurophysiology*, **113** (6), 870–882.

Cheour, M., Ceponiene, R., Lehtokoski, A., Luuk, A., Allik, J., Alho, K., & Näätänen, R. (1998a). Development of language-specific phoneme representations in the infant brain. *Nature Neuroscience*, **1** (5), 351–353.

Cheour, M., Alho, K., Ceponiene, R., Reinikainen, K., Sainio, K., Pohjavouri, M., Aaltonen, O., & Näätänen, R. (1998b).

Maturation of mismatch negativity in infants. *International Journal of Psychophysiology*, **29**, 217–226.

Cheour-Luhtanen, K., Alho, T., Kujala, T., Sainio, K., Reinikainen, K., Renlund, M., Aaltonen, O., Eerola, O., & Naatanen, R. (1995). Mismatch Negativity indicates vowel discrimination in newborns. *Hearing Research*, **82**, 53–58.

Coles, M.G.H., & Rugg, M.D. (1995). Event-related brain potentials: an introduction. In M. Rugg & M. Coles (Eds.), *Electrophysiology of mind*. Oxford: Oxford University Press.

Dehaene-Lambertz, G., & Dehaene, S. (1994). Speed and cerebral correlates of syllable discrimination in infants. *Nature*, **370**, 292–295.

Dehaene-Lambertz, G., & Baillet, S. (1998). A phonological representation in the infant brain. *NeuroReport*, **9** (8), 1885–1888.

Eimas, P.D. (1975). Auditory and phonetic coding of the cues for speech: discrimination of the [r–l] distinction by young infants. *Perception and Psychophysics*, **18**, 341–347.

Eimas, P.D., Siqueland, E.R., Jusczyk, P., & Vigorito, J. (1971). Speech perception in infants. *Science*, **171**, 303–330.

Iverson, P., Kuhl, P.K., Akahane-Yamada, R., Diesch, E., Tohkura, Y., Kettermann, A., & Siebert, C. (2003). A perceptual interference account of acquisition difficulties for non-native phonemes. *Cognition*, **87**, B47–B57.

Jusczyk, P.D. (1997). *The discovery of spoken language*. Cambridge, MA: MIT Press.

Kuhl, P.K. (1991). Human adults and human infants show a 'perceptual magnet effect' for the prototypes of speech categories, monkeys do not. *Perception and Psychophysics*, **50** (2), 93–107.

Kuhl, P.K. (1992). Psychoacoustics and speech perception: internal standards, perceptual anchors, and prototypes. In L.A. Werner & E.W. Rubel (Eds.), *Developmental psychoacoustics* (pp. 293–332). Washington, DC: American Psychological Association.

Kuhl, P.K. (2000a). A new view of language acquisition. *Proceedings of the National Academy of Sciences of the United States of America*, **97** (22), 11850–11857.

Kuhl, P.K. (2000b). Language, mind, and brain: experience alters perception. In M. Gazzaniga (Ed.), *The new cognitive neurosciences* (2nd edn., pp. 99–115). London: MIT Press.

Kuhl, P.K., Williams, K.A., Lacerda, F., Stevens, K.N., & Lindblom, B. (1992). Linguistic experience alters phonetic perception in infants by 6 months of age. *Science*, **255**, 606–608.

Kuhl, P.K., Tsao, F.-M., & Liu, H.-M. (2003). Effects of foreign-language exposure in infancy on phonetic perception. *Proceedings of the National Academy of Sciences of the United States of America*, **100** (15), 9096–9101.

Kuhl, P.K., Stevens, E., Hayashi, A., Deguchi, T., Kiritani, S., & Iverson, P. (under review). Mechanisms of developmental change in infants' perception of speech.

Kurtzberg, D., Vaughan, H.G. Jr., & Novak, G.P. (1986). Discriminative brain responses to speech sounds in the newborn high risk infant. In V. Gallai (Ed.), *Maturation of the CNS and evoked potentials* (pp. 253–259). Amsterdam: Elsevier.

Kushnerenko, E.V. (2003). Maturation of the cortical auditory event-related brain potentials in infancy. Unpublished doctoral dissertation, University of Helsinki.

Kushnerenko, E., Ceponiene, R., Balan, P., Fellman, V., Huotilainen, M., & Winkler, I. (2001). Event-related potential correlates of sound duration: similar pattern from birth to adulthood. *NeuroReport*, **12** (17), 3777–3781.

Kushnerenko, E., Ceponiene, R., Balan, P., Fellman, V., & Näätänen, R. (2002a). Maturation of the auditory change detection response in infants: a longitudinal ERP study. *NeuroReport*, **13** (15), 1843–1848.

Kushnerenko, E., Ceponiene, R., Balan, P., Fellman, V., Huotilainen, M., & Näätänen, R. (2002b). Maturation of the auditory event-related potentials during the first year of life. *NeuroReport*, **13** (1), 47–51.

Kutas, M. (1997). Views on how the electrical activity that the brain generates reflects the functions of different language structures. *Psychophysiology*, **34** (4), 383–398.

Leppäanen, P.H.Y., Pihko, E., Eklund, K.M., & Lyytinen, H. (1999). Cortical responses of infants with and without a genetic risk for dyslexia: II group effects. *NeuroReport*, **10**, 969–973.

Liu, H.-M., Kuhl, P.K., & Tsao, F.-M. (2003). An association between mother's speech clarity and infants' speech discrimination skills. *Developmental Science*, **6** (3), F1–F10.

McGee, T.J., King, C., Tremblay, K., Nicol, T.G., Cunningham, J., & Kraus, N. (2001). Long-term habituation of the speech-elicited mismatch negativity. *Psychophysiology*, **38**, 653–658.

Miller, J.L., & Eimas, P.D. (1996). Internal structure of voicing categories in early infancy. *Perception and Psychophysics*, **58**, 1157–1167.

Näätänen, R., Gaillard, A.W.K., & Mäntysalo, S. (1978). Early selective attention effects on the evoked potential: a critical review and reinterpretation. *Biological Psychology*, **8**, 81–136.

Novak, G.P., Kurtzberg, D., Kreuzer, J.A., & Vaughan, H.G. Jr. (1989). Cortical responses to speech sounds and their formants in normal infants: maturational sequence and spatiotemporal analysis. *Electroencephalography and Clinical Neurophysiology*, **73** (4), 295–305.

Pang, E.W., Edmonds, G.E., Desjardin, R., Khan, S.C., Trainor, L.J., & Taylor, M.J. (1998). Mismatch negativity to speech stimuli in 8-month-old infants and adults. *International Journal of Psychophysiology*, **29**, 227–236.

Pikho, E., Leppänen, P.H., Eklund, K.M., Cheour, M., Gutorm, T.K., & Lyytinen, H. (1999). Cortical responses of infants with and without a genetic risk for dyslexia: I age effects. *NeuroReport*, **10**, 901–905.

Polka, L., & Werker, J.F. (1994). Developmental changes in perception of non-native vowel contrasts. *Journal of Experimental Psychology: Human Perception and Performance*, **20**, 421–435.

Rivera-Gaxiola, M., Csibra, G., Johnson, M.H., & Karmiolff-Smith, A. (2000a). Electrophysiological correlates of cross-linguistic speech perception in Native English speakers. *Behavioral Brain Research*, **111**, 13–23.

Rivera-Gaxiola, M., Csibra, G., Johnson, M.H., & Karmiolff-Smith, A. (2000b). Electrophysiological correlates of category goodness. *Behavioral Brain Research*, **112**, 1–11.

Rivera-Gaxiola, M., Klarman, L., Garcia-Sierra, A., & Kuhl, P.K. (under review). Neural patterns to speech and vocabulary growth in American infants.

Rivera-Gaxiola, M., Lara-Ayala, L., Cadena, C., & Kuhl, P.K. (2004). Discrimination of voice-onset time speech contrasts in Mexican and American 11-month-old infants: an event-related potential study. Poster presented at the Cognitive Neuroscience Society Meeting, San Francisco, USA.

Samuel, A.G. (2003). Phonetic prototypes. *Perception and Psychophysics*, **22**, 321–330.

Stevens, K.N. (1972). The quantal nature of speech: evidence from articulatory-acoustic data. In P.B. Denes & E.E. David Jr. (Eds.), *Human communication, a unified view* (pp. 51–66). New York: McGraw-Hill.

Strange, W. (1995). Book review: *The development of speech perception: The transition from speech sounds to spoken words* by J.C. Goodman and H.C. Nusbaum. *Language and Speech*, **38** (2), 217–222.

Tremblay, K., Kraus, N., & McGee, T. (1998). The time course of auditory perceptual learning: neurophysiological changes during speech-sound training. *NeuroReport*, **9** (16), 3557–3560.

Tremblay, K., Kraus, N., McGee, T., Ponton, C., & Otis, B. (2001). Central auditory plasticity: changes in the N1-P2 complex after speech sound training. *Ear and Hearing*, **22** (2), 79–90.

Tremblay, K.L., & Kraus, N. (2002). Auditory training induces asymmetrical changes in cortical neural activity. *Journal of Speech Language and Hearing Research*, **45** (3), 564–572.

Werker, J.F., & Tees, R.C. (1984a). Cross-language speech perception: evidence for perceptual reorganization during the first year of life. *Infant Behavior and Development*, **7**, 49–63.

Werker, J.F., & Tees, R.C. (1984b). Phonemic and phonetic factors in adult cross-language speech perception. *Journal of the Acoustical Society of America*, **75** (6), 1866–1878.

Werker, J.F., Gilbert, J.H., Humphrey, K., & Tees, R.C. (1981). Developmental aspects of cross-language speech perception. *Child Development*, **52** (1), 349–355.

Woods, D.L., & Elmasian, R. (1986). The habituation of event-related potentials to speech sounds and tones. *Electroencephalography and Clinical Neurophysiology*, **65**, 447–459.

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