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Bilingual language learning: An ERP study relating early brain responses to speech, language input, and later word production

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ABSTRACT

Research on the development of speech processing in bilingual children has typically implemented a cross-sectional design and relied on behavioral measures. The present study is the first to explore brain measures within a longitudinal study of this population. We report results from the first phase of data analysis in a longitudinal study exploring Spanish-English bilingual children and the relationships among (a) early brain measures of phonetic discrimination in both languages, (b) degree of exposure to each language in the home, and (c) children's later bilingual word production abilities. Speech discrimination was assessed with event-related brain potentials (ERPs). A bilingual questionnaire was used to quantify the amount of language exposure from all adult speakers in the household, and subsequent word production was evaluated in both languages. Our results suggest that bilingual infants' brain responses to speech differ from the pattern shown by monolingual infants. Bilingual infants did not show neural discrimination of either the Spanish or English contrast at 6–9 months. By 10–12 months of age, neural discrimination was observed for both contrasts. Bilingual infants showed continuous improvement in neural discrimination of the phonetic units from both languages with increasing age. Group differences in bilingual infants' speech discrimination abilities are related to the amount of exposure to each of their native languages in the home. Finally, we show that infants' later word production measures are significantly related to both their early neural discrimination skills and the amount exposure to the two languages early in development.

1. Introduction

Studies of speech perception in monolingual infants have shown that the ability to differentiate native speech sounds improves with language exposure (Bosch & Sebastián-Gallés, 2001; Kuhl et al., 2006; Sundara, Polka, & Genesee, 2006; Tsao, Liu, & Kuhl, 2006), suggesting that language learning results in *neural commitment* to the sounds of an infant's native language early in development (Kuhl, 2004). Infants exhibit a perceptual narrowing during the first year of life, showing increasing sensitivity to native speech sounds and decreasing sensitivity to non-native speech sounds (Best & McRoberts, 2003; Kuhl et al., 2006; Velleman & Vihman, 2002; Werker & Tees, 1984; for reviews see Kuhl et al., 2008; Werker & Curtin, 2005).

This pattern of perceptual change in monolingual infants leads to questions regarding the development of speech perception in infants exposed to more than one language from birth (i.e., simultaneous bilinguals). Only a few studies have addressed this question and results have been mixed, perhaps due to differences in methodology, differences in the amount of language exposure to the two languages in individual bilingual participants, and the specific characteristics of the languages and speech contrasts studied. In a behavioral cross-sectional study, Bosch and Sebastián-Gallés (2003a) compared 4-, 8- and 12-month-old infants from Spanish monolingual households, Catalan monolingual households, and Spanish-Catalan bilingual households on a vowel contrast that is phonemic in Catalan but not in Spanish (/ε/ vs. /e/). Their results showed that all groups, monolingual and bilingual, discriminated the vowel contrast at 4 months of age. However, at 8 months of age, only Catalan monolingual infants successfully discriminated the vowel contrast. Interestingly, bilinguals at 12 months of age also demonstrated the ability to discriminate the speech contrast. The authors reported the same developmental pattern in bilingual infants in a study of consonants (Bosch & Sebastián-Gallés, 2003b) and interpreted the results as evidence that different processes

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may underlie bilingual vs. monolingual phoneme category formation (at least for speech sounds with different distributional properties in each of the two languages).

In more recent work, Sebastián-Gallés and Bosch (2009) tested bilingual and monolingual Spanish/Catalan infants in their ability to behaviorally discriminate two vowels (/o/ vs. /u/), which are common to and contrastive in both languages. The results showed the same U-shaped pattern reported by Bosch and Sebastián-Gallés (2003a). That is, 4-month-old bilinguals and 12-month-old bilinguals were able to discriminate the acoustically similar sounds but 8-month-old bilinguals failed to do so. In other words, even though the vowels /o/ and /u/ are phonemic in both languages, 8-month-old bilinguals appeared to perceptually merge the two sounds into a single phonetic category. Sebastián-Gallés and Bosch also tested bilingual and monolingual Spanish/Catalan infants in their ability to behaviorally discriminate a second pair of vowels that are common to and contrastive in both languages, but acoustically more salient (i.e., /e/ vs. /u/). Eight-month-old bilinguals were able to discriminate this acoustically distant contrast. The authors interpreted these data as supporting the idea that differences may exist in monolingual and bilingual phonetic development and that factors in addition to the distributional frequency of phonetic units in language input, such as lexical similarity, may play an important role.

In contrast, other investigations have found that bilingual infants discriminate phonetic contrasts in their native languages in the same way as monolingual infants. For example, Burns, Yoshida, Hill, and Werker (2007) tested voice-onset time consonant discrimination using English-relevant as well as French-relevant values at 6–8, 10–12, and 14–20 months in English monolingual and English-French bilingual infants. As expected, 6–8-month-old English monolingual infants behaviorally discriminated both contrasts while 10–12- and 14–20-month-old English monolingual infants discriminated only the English contrast. In bilingual infants, all age groups were able to discriminate both contrasts. The authors interpreted the data as evidence that bilingual infants' phonetic representational systems develop at the same pace as monolingual infants. Similarly, Sundara, Polka, and Molnar (2008) found that 10–12-month-old French-English bilingual infants were able to behaviorally discriminate a French /d/ from an English /d/, while age-matched French monolingual infants were unable to do so, a pattern the authors interpreted as indicating that monolingual and bilingual infants develop phonetic representations at the same pace (for a similar result using vowel contrasts see Sundara & Scutellaro, 2011).

The conflicting results reported in the bilingual literature described above might be explained by the fact that Spanish and Catalan share more cognates than French and English. Therefore, Spanish and Catalan have greater phonemic overlap, and thus more similar speech sounds, than French and English (see Bosch & Ramon-Casas, 2011). However, in a recent study using an anticipatory eye movement paradigm, Albareda-Castellot, Pons, and Sebastián-Gallés (2011) demonstrated that 8-month-old Catalan-Spanish bilinguals were as good as their Catalan monolingual peers in discriminating /e/ vs. /ε/, a speech contrast previously reported as not discriminated by 8-month-old bilinguals by Bosch and Sebastián-Gallés (2003a). Albareda-Castellot and colleagues note that the Catalan language and the Spanish language share many cognates and hypothesize that the familiarization-preference methodology used by Bosch and Sebastián-Gallés (2003a) may have obscured bilinguals' discrimination abilities. Although the findings of Albareda-Castellot et al. await replication, they suggest that bilingual infants' development of phonetic perception abilities occurs in the same time frame as their monolingual peers.

In the present study we broaden the investigation of the development of bilingual speech discrimination by: (1) using an electrophysiological measure of phonetic discrimination which reduces the potential effects of cognitive factors, such as attention; (2) quantifying language exposure concurrently in the home based on duration of infants' exposure to English and to Spanish using in-home interviews and a bilingual questionnaire administered as part of the interview; and (3) employing a longitudinal design that combined cross-sectional assessments of phonetic discrimination at two early ages (6–9 and 10–12 months), assessment of language exposure at those two ages, and longitudinal follow up assessment of subsequent word production in all infants in both languages, allowing investigation of concurrent and predictive relationships among these measures. This is the first ERP study of speech perception in bilingual infants that combines concurrent and longitudinal methods to assess early phonetic perception, early language exposure, and later word production (see Conboy & Mills, 2006; Vihman, Thierry, Lum, Keren-Portnoy, & Martin, 2007 for bilingual ERP data regarding words).

We employed event-related potentials (ERPs) to assess discriminative responses to phonetic changes in the form of the mismatch negativity (MMN). The MMN is automatically elicited by infrequent stimuli (deviants) that are embedded in a repeating background stimulus (standards) (Näätänen, 1990, 1992). The MMN, a negative deflection observed about 250 ms after the deviant stimulus is presented, has been shown to reflect neural activity associated with phonetic discrimination in adults (Näätänen et al., 1997). Infant studies also show a discriminatory response to a change in speech syllables that often appears as a negative wave (Alho, Sainio, Sajaniemi, Reinikainen, & Näätänen, 1990; Čeponienė et al., 2000; Cheour et al., 1998, 1999; Kuhl et al., 2008; Rivera-Gaxiola, Silva-Pereyra, & Kuhl, 2005; Rivera-Gaxiola, Klarman, Garcia-Sierra, & Kuhl, 2005; Rivera-Gaxiola et al., 2007). However, a number of studies in infants have reported a positive component in the difference wave in response to tones, native and non-native phonemes, and native and non-native stress patterns (Dehaene-Lambertz & Dehaene, 1994; Friederici, Friedrich, & Christophe, 2007; Friederici, Friedrich, & Weber, 2002; Friedrich, Herold, & Friederici, 2009; He, Hotson, & Trainor, 2007; Morr, Shafer, Kreuzer, & Kurtzberg, 2002; Pang et al., 1998; Shafer, Yu, & Datta, 2011; Trainor et al., 2003). This positive component has not been reported in adults. Because of the differences in polarity seen in infant studies, the term Mismatch Response (MMR) has been used to reflect a discriminatory neural response to an auditory change that can be either positive or negative.

Morr et al. (2002) recorded electric brain potentials associated with tones varying in frequency in infants and pre-school aged children. The results showed that infants between 3 and 12 months exhibited positive MMRs; toddlers between 13 and 30 months also showed a positive MMR but at reduced amplitude; and children between 31 and 44 months old elicited clear adult-like negativities characteristic of the adult MMN. It has been suggested that the positive MMR represents a less mature MMN response since it has been shown that the positivity declines with age (Morr et al., 2002) and because the adult-like MMN response emerges later in development (Friedrich, Weber, & Friederici, 2004; Friedrich et al., 2009).

Various reports of positive MMR responses to native and non-native speech sounds in monolingual and bilingual infants have appeared. Several studies of ERP responses to native and non-native stress patterns in monolingual populations have reported a positive MMR for the non-native stress pattern (Friederici et al., 2007; Friedrich et al., 2009). The positive MMR was interpreted as reflecting an enhanced effort in perceptually processing non-native stress patterns due to the involvement of weaker or less activated (immature) memory structures (see also Friederici et al., 2007, 2009). In contrast Shafer et al. (2011) recorded electric brain responses associated with the English vowel contrast /ɪ/ vs. /ɛ/ from English monolingual infants and English/Spanish bilingual infants. The results showed a positive MMR in monolingual infants that decreased in amplitude and latency with increasing age, similar to that reported for tones by Morr et al. (2002). Bilingual infants showed a different pattern of response exhibiting a largely negative mismatch. The authors attributed their results on bilingual infants to attention, with the negative mismatch associated with increased attentional demands experienced by bilingual infants and the positive mismatch related to the reduced attentional demands experienced by monolingual infants.

To summarize, across studies of speech discrimination that vary the age of the participants, there is evidence that a positive mismatch response in infants tends to decrease in amplitude with increasing age, becoming a negative mismatch similar to the adult response. However, the positive MMR in infants is not completely understood. Some investigators suggest that a positive mismatch in infants is the result of an enhanced effort in non-native phoneme discrimination (Friederici et al., 2007; Friedrich et al., 2009), while others suggest that the positive mismatch reflects the low attentional demands of native-language phoneme discrimination (Shafer et al., 2011). While more research is needed to better understand the positive mismatch, the above review indicates that observation of an increasingly negative mismatch to native-language phonetic contrasts over time is widely reported and is taken as evidence of a perceptual narrowing based on neural commitment to native language sounds. Moreover, a more negative mismatch response to native-language sounds has been linked in longitudinal studies to more advanced language skills later in development (Kuhl et al., 2008).

The present study was designed to allow comparisons between monolingual and bilingual infants by using the same stimuli and methods used previously in studies in this laboratory on monolingual infants. Rivera-Gaxiola, Silva-Pereyra et al. (2005) recorded ERPs from monolingual English-learning infants at 7 ($N=14$) and 11 ($N=12$) months using two deviant consonants (one unique to English and another unique to Spanish) embedded in a repetitive standard consonant that was common to both languages. Rivera-Gaxiola, Silva-Pereyra et al. showed that, as a group, English-learning monolingual infants showed neural discrimination in the form of a negativity to both the English and Spanish contrast at 7 months, but only for the English contrast at 11 months, as expected. Moreover, English-learning infants showed improvement in neural processing of the English contrast in the form of an increasingly negative mismatch response, or MMN, between 7 and 11 months of age.

The present study extends the work of Rivera-Gaxiola, Silva-Pereyra et al. (2005) to a bilingual population. In this study, two groups of simultaneous Spanish-English bilingual infants, one aged 6–9 months and another aged 10–12 months were tested on their ability to neurally discriminate the sounds of English and Spanish. We hypothesized that if monolingual and bilingual infants develop phonetic representations at the same pace, both younger and older bilingual infants assessed in this study would exhibit patterns of discrimination for English and Spanish contrasts. However, if monolingual and bilingual phonetic development differs substantially, because the basic process of bilingual development is different or because bilingual development exhibits a different time course of development, bilingual infants would show a distinct pattern when compared to monolingual infants.

A second issue examined in the present study is the relationship between exposure to the two languages in infants' home environments and their neural discrimination abilities. It is widely accepted that bilingualism is difficult to quantify due to the diverse ways in which children can become bilingual. Infants raised in bilingual households typically have different amounts of exposure to each of their native languages, and these differences have been linked to vocabulary, grammar, and other aspects of development in each language (David & Wei, 2008; De Houwer, 2007, 2009; Pearson, Fernandez, Lewedeg, & Oller, 1997). There is also behavioral and electrophysiological evidence that phoneme processing in bilingual infants may vary with relative amounts of exposure to each of their native languages. For example, Sebastián-Gallés and Bosch (2002) studied infant sensitivity to permissible combinations of phonemes (phonotactics). Ten-month-old infants raised in monolingual households showed a preference for the phonetic strings that were consistent with the phonotactic rules of their native language, whereas infants raised in bilingual households showed a preference for the legal phoneme combinations of their dominant language. Conboy and Mills (2006) reported that the amplitude, latency and distribution of ERP effects to known vs. unknown words varied with relative vocabulary size and parent reports of language dominance in bilingual toddlers. Toddlers who knew more words in Spanish than in English showed more mature patterns of language-relevant brain activity to known words in Spanish than to known words in English, and the opposite was true of toddlers with a larger English vocabulary size. There were earlier onsets, larger amplitudes, and more focalized patterns of distribution in the ERP waveforms of the dominant vs. the non-dominant language within the same children, reflecting more efficient processing of the stronger language. No studies have examined this relationship for phonetic contrasts; that is, we do not know how bilingual infants' exposure to the two languages in their homes is related to their abilities to neurally discriminate the phonetic contrasts in the two languages. Prior investigations suggest that bilingual infants' neural commitment to the two languages may vary in accordance with the amount of exposure to each language.

We quantified language exposure in the home based on the reported duration of infants' exposure to English and to Spanish obtained during in-home interviews that included a wide variety of components, one of which was a bilingual questionnaire. The bilingual questionnaire was designed to assess the amount of exposure to each language (English and Spanish) allowing calculation of a composite score which took into account language exposure by the nuclear family and other adults living in the home (e.g., extended family, caregivers and friends) (Conboy, 2002; Conboy & Mills, 2006). Simultaneous bilinguals grow up in families where there is much variability in language usage (for reviews, see De Houwer, 2009; Werker & Byers-Heinlein, 2008). For example, the father may speak only English to the infant and the mother only Spanish, or both parents may use both languages equally, and other relatives living in the home also speak to the infants using one or both languages. We hypothesized that the pattern of infants' brain responses to the phonetic units of their two languages would depend on the amount of exposure to each of the two languages.

Finally, a third goal was to examine longitudinal associations between the early measures of neural discrimination and early measures of language exposure to later word production scores in bilingual infants' two languages. While we know of no reports of predictive relationships between early neural responses to speech and later language in bilingual infants, our previous studies on monolingual infants indicate that infants' early responses to speech sounds, whether measured behaviorally (Kuhl, Conboy, Padden, Nelson, & Pruitt, 2005; Tsao, Liu, & Kuhl, 2004) or neurally (Kuhl et al., 2008; Rivera-Gaxiola, Klarman et al., 2005), predict infants' later language abilities. The most recent data from our laboratory suggest that a behavioral measure of speech discrimination taken at 6 months of age predicts phonemic awareness scores in the same cohort of children 4.5 years later, at the age of 5 years (Cardillo-Lebedeva & Kuhl, 2009; Cardillo, 2010). We therefore hypothesized that bilingual infants' word production in their two languages would be linked to their early brain measures of phonetic processing and language exposure.

In summary, the present experiment combines cross-sectional assessments of phonetic discrimination and language exposure in bilingual infants with follow up longitudinal assessment of subsequent word production in both languages, allowing investigation of concurrent and predictive relationships among these measures.

Three research questions were investigated in this study. First, do bilingual infants discriminate speech contrasts in both of their native languages at 6–9 and 10–12 months of age? Second, do bilingual infants' neural skills in discriminating the phonetic units of their two languages vary as a function of language exposure to the two languages in the home? And third, are bilingual infants' later word production scores in both languages related to their early ERP responses and language exposure in the home?

2. Materials and methods

2.1. Participants

The participants were 27 typically developing bilingual infants recruited for participation in a longitudinal study of bilingual infants in San Antonio, Texas. Nineteen of the participants were enrolled in a Head Start[1] program and 8 were recruited from flyers posted at The University of Texas at San Antonio. Of the 27 infants, 12 (7 girls; 5 boys) were between 6 and 9 months of age and 15 (6 girls; 9 boys) were between 10 and 12 months of age. Mean age for the 6–9 month age group was 7.36 months ($SD=.81$); mean age for the 10–12 month age group was 10.87 months ($SD=1.36$). Criteria for participation included regular exposure to both English and Spanish (see below) and no known physical, sensory, or mental handicaps.

2.2. Socio-economic status

Demographic variables such as level of education, cultural background, and socio-economic status were assessed during the in-home interviews. Here we report only on the income level of the parent(s), because it was the most reliably obtained measure in the interviews. Parent(s) income was categorized based on the U.S. Bureau of the Census (2009), which takes into account the number of people living in the home. Three categories were defined: Low, below poverty guidelines; Middle, above poverty guidelines, but below the threshold for median income; High, above median threshold.

Eighteen of the 27 participants responded to questions regarding demographic information during the in-home interview. Seventy-eight percent reported living with 4 or more people in their homes and an annual income between $1500 and $21,000 (Low group); 11% reported living with 5 people in their homes and an annual income between $27,000 and $30,000 (Middle group); and 11% reported living with 2 or 3 people in their homes and an annual income higher than $50,000 (High group). Based on the SES distributions, we divided our sample into two groups based on an income level median-split (Low SES group mean=$11,200, $SD=5056$ and Medium SES group mean=$38,562, $SD=32,566$). A Mann–Whitney U-test demonstrated that the two groups differed significantly (Mann–Whitney $U=0$, $p<.0001$).

2.3. Brain measurements of speech discrimination

Event-related potentials were recorded at the University of Texas at San Antonio (UTSA). Parents were informed about the procedures, signed approved consent forms, and were paid $15 for participating in the study.

2.3.1. Stimuli

The three consonant–vowel syllables created by Rivera-Gaxiola, Silva-Pereyra et al. (2005) were used in this study: one Spanish native speech sound ("da"), one English native speech sound ("ta"), and one speech sound that is phonetically native to both languages, but phonemically different ("da" in English and "ta" in Spanish).[2] The Spanish /da/ had −24 ms of voice-onset time (VOT), the English /ta/ had 46 ms of VOT, and the sound common to both languages had 12 ms of VOT. Stimuli were naturally produced by a female Spanish/English bilingual speaker and manipulated to obtain a match in duration (229.65 ± .3 ms) and average RMS power. The average fundamental frequency was 180 Hz. Previous studies have confirmed that adult native English speakers (Rivera-Gaxiola, Silva-Pereyra et al., 2005) and English-learning monolingual infants (Conboy, Rivera-Gaxiola, Klarman, Aksoylu, & Kuhl, 2005; Conboy, Sommerville, & Kuhl, 2008) behaviorally discriminate the English but not the Spanish contrast.

2.3.2. Design

A double-oddball paradigm was used. The speech sound common to both languages was used as the standard, and the two language-specific sounds served as deviants in an 80/10/10 presentation format. Deviants appeared in a semi-random fashion with at least three standards between deviants. The interstimulus interval (offset to onset) was 700 ms and a maximum of 900 stimuli were presented. A 1 min silent period was inserted after every 2 min of stimulus presentation. Stimuli were delivered at 69 dBA SPL via two loudspeakers placed 1 m in front of the child.[3]

2.3.3. Procedure

Infants were awake and tested inside a quiet room. The child sat in the parent's lap. In front of them, a research assistant entertained the child with quiet toys while a muted movie played on a TV. The research assistant and the parent wore headphones with masking music during testing. The electroencephalogram (EEG) was recorded using electro-caps (ECI, Inc.) with pre-inserted tin electrodes referenced to the left mastoid from Fp1, Fp2, F3, F4, C3, C4, P3, P4, F7, F8, T3, T4, Fz, and Cz, in the 10/20 International System. Blinking was monitored by recording the electrooculogram from 1 infraorbital electrode placed on the infant's left cheek. The amplifier bandwidth was set between .1 and 40 Hz.

The EEG amplifier used was the isolated bioelectric amplifier system (SC-16/24 BA; SA Instrumentation San Diego, CA). Signals were amplified with a gain of 20,000. EEG was sampled every

[1] Head Start is a national program that promotes school readiness by enhancing the social and cognitive development of children through the provision of educational, health, nutritional, social and other services to enrolled children and families.

[2] We use the term phonetic to indicate sounds with distinct acoustic properties and articulatory patterns.

[3] We are aware that the language used by the experimenter might influence phoneme perception (see Garcia-Sierra, Diehl, & Champlin, 2009; Mattock, Polka, Rvachew, & Krehm, 2010). Therefore, during the one-minute pause the researcher continued silent distraction of the infant, and mothers were instructed to minimize interaction with their infant.

4 ms. Electrode impedances were kept below 5 KΩ. Segments with electrical activity ±70 mV at any electrode site were rejected. EEG segments of 700 ms with a pre-stimulus baseline time of 50 ms were selected and averaged offline to obtain the ERPs. Baseline correction was performed in relationship to the pre-stimulus time. The final ERP wave forms were band-pass filtered offline from .1 to 15 Hz.

2.3.4. Data analyses

ERP data were accepted when clear auditory P–N complexes within the first 600 ms were displayed (at least 30 artifact-free trials for each standard and deviant types required). The standard and deviant ERP responses were analyzed by obtaining the most negative peak within the time window 250–550 ms after stimulus onset. Individual MMN-values (Näätänen et al., 1997) were obtained by subtracting the standard ERP-responses from the deviant ERP-responses (i.e., English Deviant ERP minus Standard ERP and Spanish Deviant ERP minus Standard ERP). The MMN was analyzed by obtaining the most negative peak within the time window from 250 to 550 ms after stimulus onset. Adults typically respond to a deviant stimulus with a negative wave that is observed at approximately 250 ms. The infant response is slightly later at approximately 300–500 ms after stimulus onset (Cheour et al., 1998; Rivera-Gaxiola, Silva-Pereyra et al., 2005). Better discrimination is indicated by greater negative amplitudes.

2.4. Language exposure

The infants' language exposure was assessed by means of the bilingual questionnaire designed by Conboy (2002) and implemented in Conboy and Mills (2006). The bilingual questionnaire was administered during the in-home interview. The questionnaire included questions about the amount of exposure to English and Spanish the infant received from the nuclear family, extended family, and other adults living in the home. The questionnaire assessed the amount of interaction time between each individual in the household and the infant using a scale ranging from 1 to 10, where 1 is low exposure (i.e., the person interacted with the infant a few days a year), 5 is medium exposure (i.e., the person interacted with the infant 6–8 months a year), and 10 is high exposure (i.e., the person interacted with the infant every day, all day). In addition, the questionnaire collected information about the language each person spoke when interacting with the infant (i.e., English, Spanish, or both). Exposure patterns ranged from infants who experienced constant daily exposure to both languages to infants whose primary caregiver spoke only one language to the child, with exposure to the second language occurring far less frequently.

Language exposure was quantified as follows: First, Spanish and English language exposure scores for each adult interacting with the child in the home were created. Most of our infant participants lived in homes with multiple relatives. The amount of exposure, on a scale of 1–10, was assigned to English and Spanish. A given score was assigned only to Spanish if the person spoke only Spanish when interacting with the baby, assigned only to English if the person spoke only English when interacting with the baby, and assigned to both Spanish and English if the person spoke both languages when interacting with the baby. For example, if the mother indicated that she spent every day, all day with the infant and spoke only Spanish, then a score of 10 was given to Spanish language exposure; likewise if the mother only spoke English, then a 10 was given to English; and finally if the mother spent all day, every day with the infant and spoke both English and Spanish, a score of 10 was given for both English and Spanish. Each adult in the home was given a score, and all scores were summed to reflect language input from all individuals who interacted with the infant. Home language exposure scores were obtained for 25 infants. The data for two additional infants were excluded (i.e., one female from the younger group and 1 male from the older group) because the questionnaire was incomplete.

The observed language exposure scores for English were normally distributed and ranged from 16 to 168 with a group mean of 61 ($SD=37$). The Spanish language exposure scores were also normally distributed and ranged from 13 to 150 with a group mean of 55 ($SD=29$). The raw language scores for English and Spanish were not significantly different, $t(24)=.81$, $p=.42$, $d=.17$.

Infants were divided into high and low language exposure groups for English and Spanish based on a median split of the language exposure scores. The median scores were 56 and 51 for English and Spanish (respectively). Eight participants fell into the top half of the distribution for English, indicating high exposure, and also into the top half of the distribution for Spanish indicating high exposure to that language as well. Eight participants fell into the lower half of the distribution for English, indicating low exposure for English and also fell into the low exposure for Spanish distribution, indicating low exposure to Spanish. Four participants showed high exposure to English and low exposure to Spanish and 5 participants showed low exposure to English and high exposure to Spanish.

The statistical comparison across high and low exposure groups within each language showed a significant difference. Specifically, the English high exposure group (mean=90, $SD=32.4$) differed from the English low exposure group (mean=34.6, $SD=13.2$), $t(23)=5.6$, $p=.0001$; $d=2.2$. The Spanish high exposure group (mean=75.2 $SD=26$) also differed significantly from the low Spanish exposure group (mean=33.6 $SD=11.6$), $t(23)=5.1$, $p=.0001$; $d=2.1$. However, the comparison across high exposure groups (English vs. Spanish) and low exposure groups showed no statistical difference (high groups: $t(23)=1.24$, $p=.23$; $d=.5$; low groups: $t(23)=.21$, $p=.84$; $d=.08$).

2.5. Degree of language exposure

We generated an index from the language exposure scores indicating relative exposure to English and Spanish for each participant. The English score was divided by the scores obtained in both English and Spanish. Infants with scores closer to 1 had strong English exposure and infants with scores closer to 0 had strong Spanish exposure. For example, if the language exposure total was 20 in both English and Spanish, 20 was divided by 40. The final score, which we refer to as the Language Exposure-Index, was .5 when an infant experienced equal exposure to English and Spanish. The observed language exposure-index scores were normally distributed ranging from .2 to .8 with a group mean of .52 ($SD=.16$) (5 of the 25 participants scored between .20 and .40, 13 participants scored between .41 and .60, and 7 participants scored between .61 to .80). Data from the present investigation, showing that bilingual infants' daily exposure to English and Spanish ranged from .2 to .8, is consistent with previous investigations (Sundara & Scutellaro, 2011; Ramon-Casas, Swingley, Sebastián-Gallés, & Bosch, 2009).

2.6. Language dominance in word production

Word production was assessed using the MacArthur-Bates Communicative Development Inventory (CDI). Parents completed the English and the Spanish versions of the survey at the same point in time with assistance provided by one of the investigators (SO), and received $10 for completing the inventories. The CDI: Words and Gestures (Fenson et al., 1993) and its adaptation to Spanish (Jackson-Maldonado et al., 2003) are reliable and valid parent surveys for assessing vocabulary comprehension, vocabulary production, gesture production, and other communication skills from 8 to 18 months of age. Only the vocabulary production section (a checklist of 396 words) was used in this study. The parent who provided the primary input in each language was asked to help complete the inventory for that language.

Completed Words and Gestures (CDI-WG) for each language were obtained for 20 participants at 15 months of age (mean = 15 months, $SD = 3.3$). Data from 7 additional subjects (i.e., 3 females and 4 males from the younger group) was excluded because questionnaires were incomplete. Participants produced an average of 36.4 ($SD = 68.0$) words in English and 26.4 ($SD = 61.4$) words in Spanish. This overall difference in English and Spanish word production was not statistically significant, $t(19) = 1.0$, $p = .31$, $d = .15$. The large variability in expressive vocabulary across infants observed in our sample is consistent with that reported in the CDI norming studies (Fenson et al., 1994, 2000).

3. Results

3.1. Bilingual infants' neural responses to both languages as a function of age

Our first question was: Do bilingual infants show a negative MMR in response to both of their native sounds at 6–9 and at 10–12 months of age? Rivera-Gaxiola, Silva-Pereyra et al. (2005) demonstrated that monolingual infants showed neural discrimination (in the form of a negativity) of the native phonetic contrast at both 7 and 11 months of age, using the same stimuli used in the present tests. Using the same ERP analysis techniques as Rivera-Gaxiola, Silva-Pereyra et al., we measured peak amplitude of the standard and deviant ERP responses in the 250–500 ms measurement window. Repeated measures ANOVAs were performed comparing

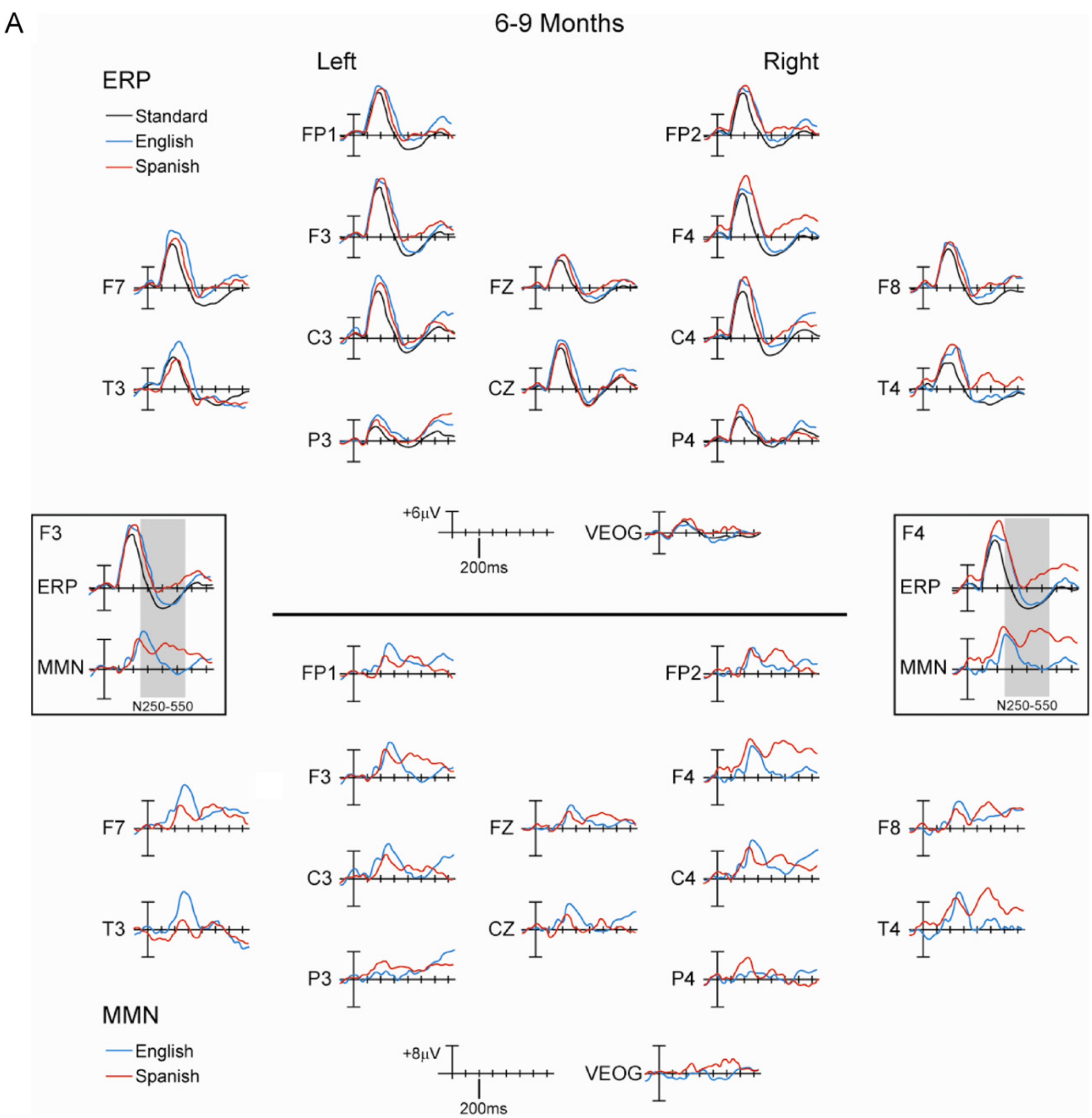

Fig. 1. Brain event-related potentials associated with speech discrimination in bilingual infants. Panel A shows the standard ERP-response and both deviant ERP-responses for the 6–9-month-old group in the upper section and the MMN responses to both speech contrasts in the lower section. Panel B shows the standard ERP-response and both deviant ERP-responses for the 10–12-month-old group in the upper section and the MMN responses to both speech contrasts in the lower section. F3 electrode is magnified in the left side of the figure and F4 electrode is magnified in the right side of the figure.

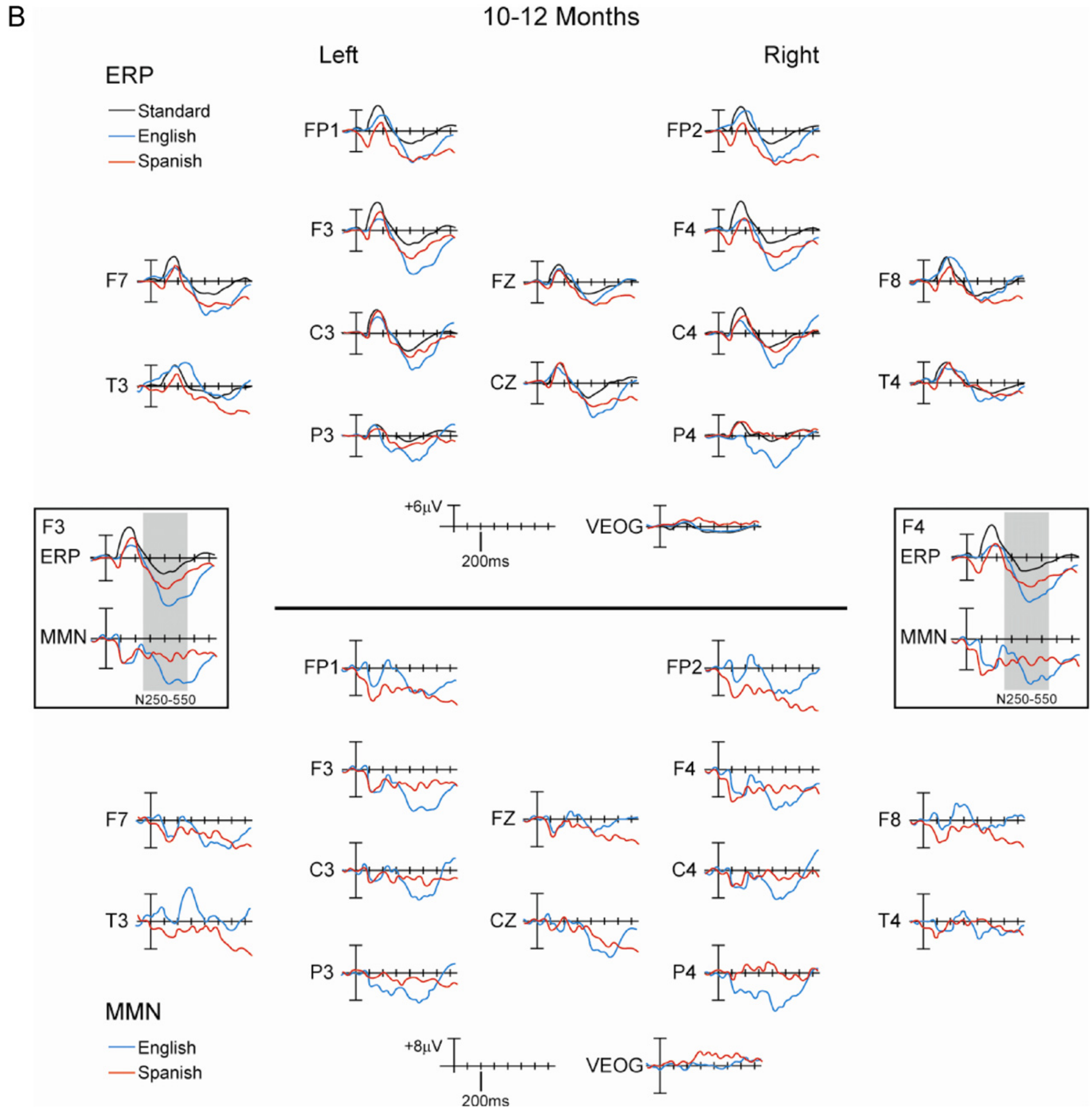

Fig. 1. (*continued*)

the amplitude of the standard response with the amplitudes of the English deviant and the Spanish deviant independently for each age group (Fig. 1).

Twenty of the 27 infants had acceptable ERP data. The 6–9-month-old infants (N=10, 6 females) did not show significant neural discrimination for either the English or Spanish contrast. Differences between the peak amplitudes of the standard (mean= −5.3 μV, SD=2.6) and the English deviant (mean= −5.7 μV, SD=4.0; $F(1, 9)=.20$, $p=.70$, $\eta_p^2=.02$) and between the standard and the Spanish deviant (mean= −4.3 μV, SD=4.1; $F(1, 9)=.31$, $p=.60$, $\eta_p^2=.03$) were not significant. The 10–12-month-old infants (N=10, 4 females) showed a significant difference in peak amplitude between the standard (mean= −4.2 μV, SD=4.1) and the English deviant (mean= −9.5 μV, SD=4.3; $F(1, 9)=17.4$, $p=.002$, $\eta_p^2=.66$) and a marginally significant difference between the standard and the Spanish deviant (mean= −8.34 μV, SD=6.7; $F(1, 9)=4.3$, $p=.06$, $\eta_p^2=.32$). These results showed an increasing negativity (reflecting better phoneme discrimination) with increasing age. English and Spanish deviants elicited ERP responses that were more positive than standards in the 6–9-month-old age group, although not significantly so, whereas English and Spanish deviants elicited ERP responses that were more negative than standards in the 10–12-month-old age group (see Panel A and Panel B, Fig. 1 upper section). We also examined the amplitude of the standard and deviant as a function of SES. Subjects were divided in two groups based on an income level median-split. Amplitudes of the standards or of the deviants did not differ as a function of SES when collapsing age groups or when doing the analyses separately by age.

To examine the effects of age as a continuous variable, we averaged the responses at the electrode sites showing the strongest effects (F3 and F4) and plotted the relationship between the MMN amplitude and age. Significant negative correlations between MMN values and age were obtained for both languages (English, $r=-.52$, $p=.018$; Spanish, $r=-.50$, $p=.026$), indicating a pattern of increasing neural discrimination for both languages between 6 and 12 months of age (Fig. 2).

3.1.1. Summary

Our results comparing standards and deviants at all electrode sites across age show that at 6–9 months bilinguals do not show neural discrimination of the Spanish or the English contrasts. However, by 10–12 months, infants show neural discrimination of both native contrasts. The MMN averaged across electrodes F3 and F4 corroborate these findings by showing a continuous improvement in neural discrimination for both native phonetic contrasts over time.

3.2. MMN and language exposure

We posed a second question: Is the strength of bilingual infants' neural responses to the phonetic units of their two languages, as measured by MMN amplitude, related to language exposure in the home? We hypothesized that neural commitment to the sounds of English and Spanish would be related to language exposure in the home, and that the pattern of the relationship would be influenced by age. More specifically, we hypothesized that neural discrimination would vary as a function of language exposure and age.

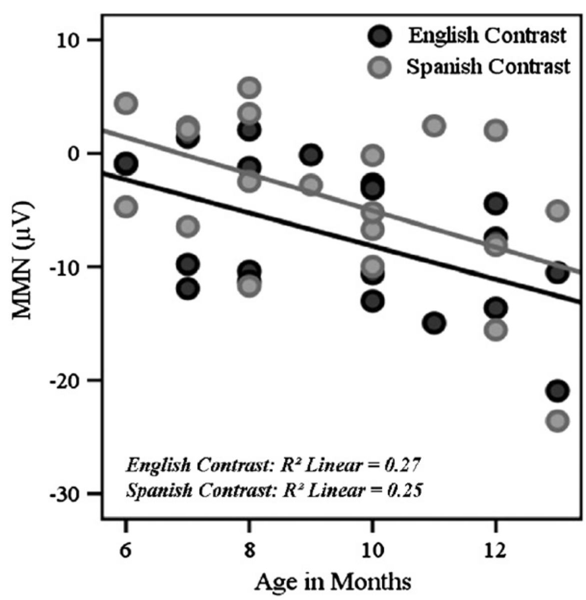

Fig. 2. Scatterplot showing MMN responses to Spanish and English contrasts as a function of age. The MMN values represent the average of F3 and F4.

ERP data and language exposure data were available for 9 infants at 6–9 months of age (5 females) and 10 infants at 10–12 months of age (4 females). To reduce the variability typical of small samples, we averaged the mean amplitude of 6 data points before and 6 points after the peak amplitude at F3 and F4 for each infant (Luck, 2005). Infants were divided into high and low language exposure groups for English and Spanish based on a median split of the language exposure scores (see Section 2.4). The relationship between ERP, language exposure, and age was evaluated independently for English and Spanish using a 2 (high vs. low exposure) $\times$ 2 (6–9 month vs. 10–12 month age group) analysis of variance.

The pattern of results showed that, for the older group of infants, high exposure to the language was associated with a strong (negative) MMN effect for both English and Spanish, whereas low exposure to either Spanish or English did not result in an MMN effect. For the younger group of infants, high exposure to Spanish produced a positive MMR (a less mature pattern of response), whereas high exposure to English produced neural responses that were comparatively more negative (see Fig. 3). This could be due to the fact that the English contrast is inherently easier to discriminate or that infants in our sample were exposed more to English, given that they were living in the United States, even though our questionnaire suggests equal exposure. The main effect of age was significant for both English, $F(1, 15)=11.4$, $p=.004$, $\eta^2_p=.43$, and Spanish, $F(1, 15)=11.5$, $p=.004$, $\eta^2_p=.43$. The age by language exposure interaction was significant for Spanish, $F(1, 15)=8.5$, $p=.01$, $\eta^2_p=.36$, and approached significance for English, $F(1, 15)=3.4$, $p=.08$, $\eta^2_p=.19$.

3.2.1. Summary

We find an interesting developmental pattern of brain activity as a function of age and exposure to language. Specifically, only infants who have high exposure to English or Spanish show an MMN response at the older age and also show a positive MMR at the earlier age. This developmental pattern of change from

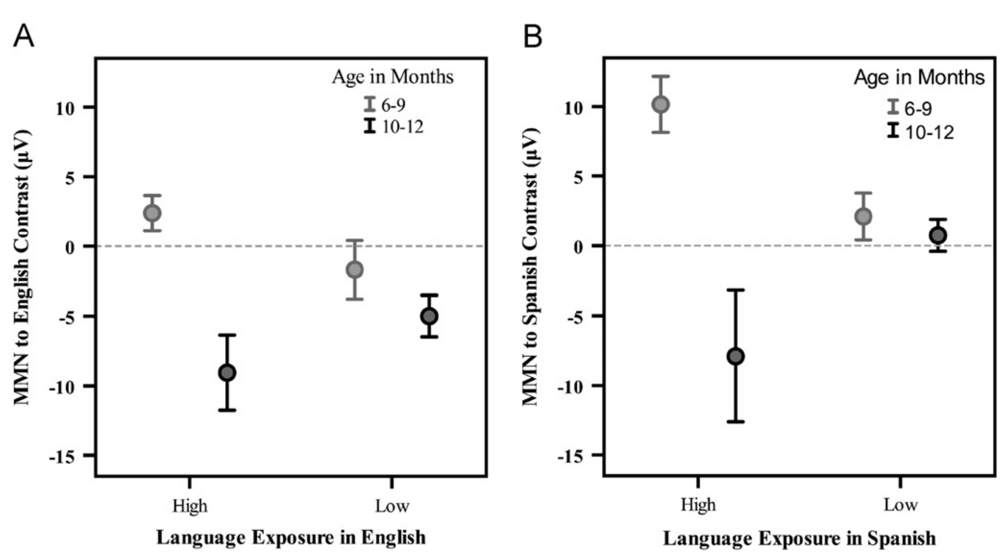

Fig. 3. MMN as a function of high and low exposure to English and Spanish. Panel A shows the English MMN scores as a function of high and low exposure to English. Panel B shows the Spanish MMN scores as a function of high and low exposure to Spanish. The MMN values represent the average of F3 and F4. Error bars represent ± 1 standard error of the mean.

positive MMR to MMN (or negativity) has been documented in other studies (Friedrich et al., 2009; He et al., 2007; Morr et al., 2002; Trainor et al., 2003) and has been interpreted as a reflection of an enhanced ability to perceptually process the deviant speech contrast over time (Friederici et al., 2007; Friedrich et al., 2004).

3.3. MMN, language exposure and language dominance in word production

A third question was posed in the present study: Are bilingual infants' later word production scores in both languages related to their early ERP responses and language exposure? In order to test this question we calculated indices to represent the relative exposure to English and Spanish in the home (Language Exposure-Index), the relative strength of the ERP response to English and Spanish (MMN-Index), and the relative number of words produced in English and Spanish (Word Production-Index).

All indices were calculated in a similar way. The first step was to normalize the data using an approach described by McCarthy and Wood (1985). For language exposure and word production, the minimum score was subtracted from each individual measurement. The adjusted measurement was then divided by the difference between the maximum and minimum score, assigning a value of 1 to the maximum and 0 to the minimum. This procedure was inverted for the MMN so that the most negative value had the value of 1 and the most positive value had a value of 0. The index is the ratio obtained by dividing the normalized English measurement by the sum of the normalized Spanish and the normalized English measurements. The index shows the contribution, in percent, of the English response to the overall response for each subject. Index values closer to 1 represent a stronger English contribution to the total, while index values closer to zero represent a stronger Spanish contribution to the total; index values close to .5 represent comparable contributions from English and Spanish. The MMN-Index was calculated from the MMN peak amplitude at F3 and F4 for English and for Spanish, the Language Exposure-Index was calculated from the quantified results of the bilingual questionnaire, and the Word Production-Index was calculated from the number of words produced in English and Spanish at 15 months of age. Infants were then divided into two groups based on a median split of their Word Production-Indices: Spanish dominant in word production or English dominant in word production. The English and Spanish word production groups did not differ in annual income level.

3.3.1. MMN and word production

Are early ERP responses to English and Spanish in bilingual infants related to later dominance in word production? We hypothesized that children who are English dominant in word production at 15 months would have early MMN-Indices closer to 1, indicating a stronger English language ERP response, while children who are Spanish dominant in word production at 15 months would have early MMN-Indices closer to 0, indicating a stronger Spanish language ERP response. MMN data and word production data were available for 13 infants. The English dominant word production group had higher MMN-Index scores, indicating relatively better discrimination of the English contrast (mean=.64, SD=.20, N=7), and the Spanish dominant word production group had lower MMN-Index scores, indicating relatively better discrimination of the Spanish contrast (mean=.40, SD=.16, N=6) (Fig. 4). This difference between word production groups was significant, $t(11)=2.34$, $p=.04$, $d=1.32$.

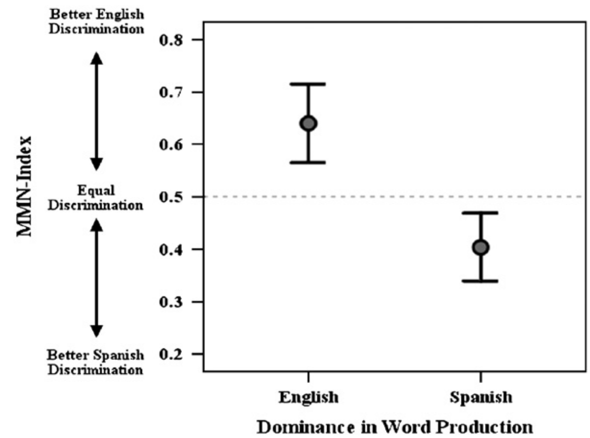

Fig. 4. MMN-Index as a function of dominance in word production. Error bars represent ±1 standard error of the mean.

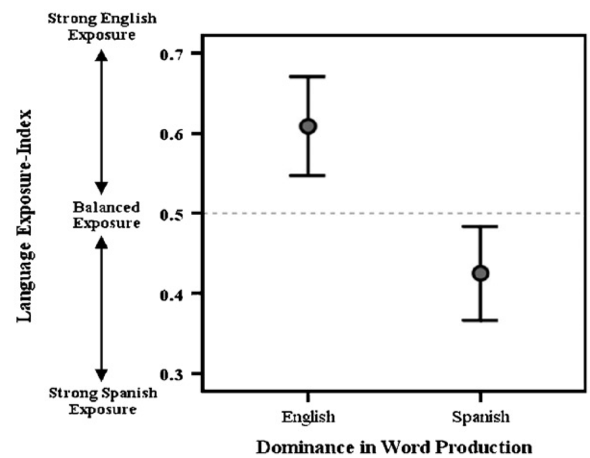

Fig. 5. Language Exposure-Index as a function of dominance in word production. Error bars represent ±1 standard error of the mean.

3.4. Language exposure and word production

Are bilingual infants' later word production scores in both languages related to their early language exposure? We hypothesized that children who are English dominant in word production at 15 months would have early Language Exposure-Indices closer to 1, indicating stronger English language exposure, while children who are Spanish dominant in word production at 15 months would have early Language Exposure-Indices closer to 0, indicating stronger Spanish language exposure. Language exposure-index data and word production data were available for 6 infants at 6–9 months of age (5 females) and 13 infants at 10–12 months of age (5 females). The English dominant word production group had higher Language Exposure-Index scores, indicating relatively stronger English language exposure (mean=.61, SD=.18, N=9), and the Spanish dominant word production group had lower Language Exposure-Index scores, indicating relatively stronger Spanish language exposure (mean=.42, SD=.18, N=10) (Fig. 5). This difference between word production groups was significant, $t(17)=2.1$, $p=.05$, $d=1.0$.

3.4.1. Summary

These findings demonstrate an overall consistency in the patterning of results relating language exposure, phonetic discrimination, and later word production in children from bilingual families. As predicted, language exposure, neural commitment as evidenced by ERP brain measures of phonetic discrimination, and language dominance in word production at 15 months of age are interrelated in a statistically significant manner.

4. Discussion

Three research questions were investigated in this study. The first question explored the effects of age on neural responses to the phonetic units of language in bilingual infants. The second question examined the relationship between neural responses to speech in both languages and the degree of language exposure in the home to the two languages. The third question examined the relationships among later word production in Spanish and English and two other variables, early ERP responses to speech and the amount of early language exposure to both languages.

Question 1. Do bilingual infants show neural commitment for each of their native languages as a function of age?

We find that bilingual infants' brain responses do not show neural discrimination at 6–9 months of age. However, at 10–12 months of age bilingual infants in our sample do show neural discrimination in the form of a negative wave. These results suggest that bilingual infants in the current study display a pattern of neural response that is different from that of monolinguals previously tested using the same stimuli and methods (Rivera-Gaxiola, Silva-Pereyra et al., 2005; Rivera-Gaxiola, Klarman et al., 2005). Rivera-Gaxiola, Silva-Pereyra et al. (2005) collected brain measures from English monolingual infants at 7 and 11 months of age. As a group, monolingual infants at 7 months showed MMN-like neural discriminatory responses for the native phonetic contrast (English) and the non-native contrast (Spanish). At 11 months, monolingual infants, as a group, showed MMN-like neural discriminatory responses for the native phonetic contrast (English) only. In contrast to monolingual infants, our younger bilingual infants did not exhibit neural discriminatory responses. Discrimination of both native contrasts was shown in our older-aged bilingual group.

Interpretation of the differences observed between bilingual and monolingual infants' speech discrimination in the present study is influenced by previous theoretical arguments we have offered about the process of neural commitment to native language phonetic units (Kuhl, 2004, 2010; Kuhl et al., 2008). Our finding that bilingual and monolingual infants differ at 6–9 months is consistent with the Native-Language-Magnet, expanded (NLM-e) formulation. According to the NLM-e model, infants' phonetic development depends on both statistical learning and social contexts (Kuhl et al., 2008). According to the theory, for both monolingual and bilingual infants, the amount of time required to "transition" from a universal pattern of perception to one in which language experience produces neural commitment will depend on language input and variability. The model predicts that, given greater variability in language input, bilingual infants could remain "plastic" for a longer period of time (Kuhl et al., 2008). Adaptively, bilingual infants could remain more "open"—that is, less neurally committed—when compared to monolingual infants at the same time point in development. By this reasoning, bilingual infants would be expected to show the perceptual narrowing in speech perception development at a later point in time. This strategy provides a distinct advantage to bilingual children who are mapping two languages.

Some evidence that bilingual infants remain "open" longer can be adduced from the present study, in that bilingual infants at 6–9 months of age did not show a negative MMR to either the English or the Spanish contrast. The positive MMRs exhibited by bilingual infants at 6–9 months were not significant, and therefore did not indicate neural discrimination. Bilingual infants' MMRs became more negative over time, suggesting the expected change from a positive to a negative MMR in response to speech with exposure and development. By 10–12 months of age bilingual infants showed negative MMRs for both contrasts.

The pattern shown by the bilingual infants at 10–12 months of age could be described as resembling the "pre-committed" neural responses seen in monolingual infants at 6–9 months of age. However, the pattern we observed could also be said to resemble monolingual infants' responses at 10–12 months—both groups exhibit negative MMRs to their native contrasts at this age. As discussed previously (Kuhl et al., 2008), correct interpretation of the bilingual data requires testing a third phonetic contrast, one that is non-native for the bilingual infants. In an ongoing research project, we are directly comparing bilingual and monolingual infants' speech discrimination abilities at 11- and 14-months of age, and we are testing neural discrimination of three contrasts. For bilingual infants the three contrasts consist of 2 native and 1 non-native, while for monolingual infants the three contrasts consist of 1 native and 2 non-native (see Garcia-Sierra, Ramirez-Esparza, & Kuhl, 2010). Testing a third contrast will advance our understanding of the timetable of neural commitment to phonetic contrasts in bilingual infants by comparing bilingual and monolingual infants on a contrast that is non-native for both groups.

Question 2. Do bilingual infants show differential neural responses to the phonetic units of each of their languages as a function of language exposure?

Our goal was to investigate whether bilingual infants show differential neural commitment as a function of exposure to their two languages. Our findings indicate that infants raised in bilingual households show a significant relationship between language exposure and their neural responses to phonetic units from both languages. Specifically, infants who have high exposure to English or Spanish—but not those with low exposure to the language – show a significant change in the amplitude of their ERP responses with age. In future studies, it will be helpful to have improved measurements of the degree of exposure in the home to bilingual infants' two languages, and we are working on methodological improvements that will achieve this goal (see Section 4.1).

Question 3. Are bilingual infants' later word production scores in both languages related to their early ERP responses to phonetic contrasts in their two native languages and early language exposure?

A third goal was to examine the relationships among early neural commitment, early language exposure, and later word production. In accordance with previous findings in monolinguals (Kuhl et al., 2008; Rivera-Gaxiola, Klarman et al., 2005), we find that early phoneme discrimination is related to dominance in later word production. This is the first study demonstrating a predictive relationship between early brain measures in bilingual infants and later word production in their two languages. We find that infants with relatively stronger early exposure to Spanish in the home subsequently produce more words in Spanish, whereas infants with relatively stronger early exposure to English in the home subsequently produce more words in English. Thus, the study shows two relations: (1) dominance in early brain responses (i.e., MMN-index) predicts later word production, and (2) early language input predicts later word production.

4.1. Limitations of this study

Limitations of the current study include the sample size, which is an inherent problem in longitudinal studies. A small sample size does not permit additional comparisons of interest, such as parental education level or other cultural factors. Additional studies with larger samples will be helpful. Another potential limitation arises from the generally low SES of our sample, though we draw from two sources of evidence to suggest that our results on bilingual infants are not attributable to SES. First, in the present data, median split comparisons did not show ERP differences based on SES. Second, in our on-going research study, we compare monolingual and bilingual infants from higher SES families than in the present study, and a similar pattern of results is emerging. A further limitation of the current study is the use of caregiver reports to assess language exposure, which provides an indirect, ordinal measurement of exposure. In our current study of 11- and 14-month-old monolingual and bilingual infants, we improve the measurement of language exposure by utilizing a digital recorder (Lena technology) that records all auditory input from infants' point of view as they go about their normal activities at home (Ramirez-Esparza, Garcia-Sierra, & Kuhl, 2010).

4.2. Summary

Our investigation explored the development of phonetic perception in bilingual infants using a neural measure of phonetic discrimination and a longitudinal design. The language environment of the bilingual infants was assessed and related to both concurrent neural discrimination data and to later word production in both languages. Our results indicate different patterns of development in monolingual and bilingual infants: At 6–9 months, bilingual infants did not show a significant MMR nor MMN-like neural discrimination of phonetic contrasts in either of their native languages. Previous studies of monolingual infants using the same stimuli and methods have shown MMN-like neural discrimination for both native and non-native phonetic contrasts at 7 months and only the native contrast at 11 months (Rivera-Gaxiola, Silva-Pereyra et al., 2005). By 10–12 months of age bilingual infants exhibited the MMN-like neural discrimination of both their native contrasts. It is of interest to the present study that in a new study directly comparing English monolingual and Spanish-English bilingual infants at 11 and 14 months of age we observe a similar pattern—bilingual infants show negativities to native sounds at a later point in time when compared to monolingual infants (Garcia-Sierra et al., 2010). It will be important in future studies to examine ERPs to the same stimuli in Spanish monolingual infants.

Based on the data available at present from our studies, we put forward the hypothesis that bilingual and monolingual infants show a different timetable for developmental change, with bilingual infants remaining "open" to the effects of language experience longer than monolingual infants, a highly adaptive response to the increased variability of language input that bilingual infants experience.

Second, our findings show that the strength of bilingual infants' neural responses to the phonetic units in their two languages is associated with the relative amount of language input they receive in the two languages at home. Finally, we show a predictive relationship between infants' early neural responses to the phonetic units of their two languages and their later word development in both languages, as well as a predictive relationship between early exposure to their two languages and later word development.

In summary, our results support the view that bilingual and monolingual infants may differ in the trajectory they follow in the development of speech perception—bilingual infants may remain "open" longer to language experience than monolingual infants, neurally committing to the languages they hear at a later point in time. We show that bilingual infants' neural commitment is affected by differences in exposure to their two native languages, and that early exposure to language in the home is linked to concurrent neural discriminatory responses and to subsequent word production.

This report summarizes results from the first stage of data analysis in a larger cross-sectional longitudinal study of the development of speech and language processing in bilingual children. This study is, to our knowledge, the first investigation to employ neural measures of phonetic discrimination in bilingual infants while concurrently assessing language input and utilizing a longitudinal design to link early phonetic discrimination and language input to subsequent bilingual word development.

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References

Albareda-Castellot, B., Pons, F., & Sebastián-Gallés, N. (2011). The acquisition of phonetic categories in bilingual infants: New data from an anticipatory eye movement paradigm. *Developmental Science*, *14*, 395–401.

Alho, K., Sainio, K., Sajaniemi, N., Reinikainen, K., & Näätänen, R. (1990). Event-related brain potential of human newborns to pitch change of an acoustic stimulus. *Electroencephalography and Clinical Neurophysiology*, *77*, 151–155.

Best, C. T., & McRoberts, G. W. (2003). Infant perception of non-native consonant contrasts that adults assimilate in different ways. *Language and Speech*, *46*, 183–216.

Bosch, L., & Ramon-Casas, M. (2011). Variability in vowel production by bilingual speakers: Can input properties hinder the early stabilization of contrastive categories?. *Journal of Phonetics*, *39*, 514–526.

Bosch, L., & Sebastian-Galles, N. (2001). Evidence of early language discrimination abilities in infants from bilingual environments. *Infancy*, *2*, 29–49.

Bosch, L., & Sebastián-Gallés, N. (2003a). Simultaneous bilingualism and the perception of a language-specific vowel contrast in the first year of life. *Language and Speech*, *46*, 217–243.

Bosch, L., & Sebastián-Gallés, N. (2003b, August). *Language experience and perception of voicing contrast in fricatives: Infant and adult data*. Paper presented at the 15th International Congress of Phonetics, Barcelona, Spain.

Burns, T. C., Yoshida, K. A., Hill, K., & Werker, J. F. (2007). The development of phonetic representation in bilingual and monolingual infants. *Applied Psycholinguistics*, *28*, 455–474.

Cardillo, G. C. (2010). *Predicting the predictors: Individual differences in longitudinal relationships between infant phonetic perception, toddler vocabulary, and preschooler language and phonological awareness*. Doctoral dissertation, University of Washington.

Cardillo-Lebedeva, G. C., & Kuhl, P. K. (2009, October). *Individual differences in infant speech perception predict language and pre-reading skills through age 5 years*. Paper presented at the Annual Meeting of the Society for Developmental & Behavioral Pediatrics, Portland, OR.

Čeponienė, R., Hukki, J., Cheour, M., Haapanen, M. L., Koskinen, M., & Alho, K., et al. (2000). Dysfunction of the auditory cortex persists in infants with certain cleft types. *Developmental Medicine and Child Neurology*, *42*, 258–265.

Cheour, M., Čeponienė, R., Hukki, J., Haapanen, M. L., Näätänen, R., & Alho, K. (1999). Brain dysfunction in neonates with cleft palate revealed by the mismatch negativity. *Clinical Neurophysiology*, *110*, 324–328.

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

Conboy, B. T. (2002). Patterns of language processing and growth in early English–Spanish bilingualism. Doctoral dissertation, University of California San Diego and San Diego State University. *Dissertation Abstracts International, Section B: The Sciences and Engineering, 63* (UMI no. 5193).

Conboy, B. T., & Mills, D. L. (2006). Two languages, one developing brain: Event-related potentials to words in bilingual toddlers. *Developmental Science*, *9*, F1–F12.

Conboy, B., Rivera-Gaxiola, M., Klarman, L., Aksoylu, E., & Kuhl, P. K. (2005). Associations between native and nonnative speech sound discrimination and language development at the end of the first year. In A. Brugos, M. R. Clark-Cotton, & S. Ha (Eds.), *Supplement to the proceedings of the 29th Boston University conference on language development*.

Conboy, B. T., Sommerville, J. A., & Kuhl, P. K. (2008). Cognitive control factors in speech perception at 11 months. *Developmental Psychology*, *44*, 1505–1512.

David, A., & Wei, L. (2008). Individual differences in the lexical development of French-English bilingual children. *The International Journal of Bilingual Education and Bilingualism*, *11*, 598–618.

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

De Houwer, A. (2007). Parental language input patterns and children's bilingual use. *Applied Psycholinguistics*, *28*, 411–424.

De Houwer, A. (2009). *Bilingual first language acquisition*. Bristol, UK: Multilingual Matters.

Fenson, L., Bates, E., Dale, P., Goodman, J., Reznick, J. S., & Thal, D. (2000). Measuring variability in early child language: Don't shoot the messenger. *Child Development*, *71*, 323–328.

Fenson, L., Dale, P., Reznick, J., Bates, E., Thal, D., & Pethick, S. (1994). Variability in early communicative development [Monograph]. *Monographs of the Society for Research in Child Development, 59* (Serial no. 242).

Fenson, L., Marchman, V. A., Thal, D., Dale, P. S., Reznick, J. S., & Bates, E. (2007). *MacArthur Communicative Development Inventories: User's guide and technical manual* (2nd ed.). Baltimore, MD: Brooks Publishing Co.

Friederici, A. D., Friedrich, M., & Christophe, A. (2007). Brain responses in 4-month-old infants are already language specific. *Current Biology*, *17*, 1208–1211.

Friederici, A. D., Friedrich, M., & Weber, C. (2002). Neural manifestation of cognitive and precognitive mismatch detection in early infancy. *Neuroreport*, *13*, 1251–1254.

Friedrich, M., Herold, B., & Friederici, A. D. (2009). ERP correlates of processing native and non-native language word stress in infants with different language outcomes. *Cortex*, *45*, 662–676.

Friedrich, M., Weber, C., & Friederici, A. D. (2004). Electrophysiological evidence for delayed mismatch response in infants at-risk for specific language impairment. *Psychophysiology*, 772–782.

Garcia-Sierra, A., Diehl, R. L., & Champlin, C. (2009). Testing the double phonemic boundary in bilinguals. *Speech Communication*, *51*, 369–378.

Garcia-Sierra, A., Ramirez-Esparza, N., & Kuhl, K. P. (2010). Speech discrimination of English, Spanish, and Mandarin consonants in monolingual and bilingual infants: An event related potentials experiment. *Journal of the Acoustical Society of America*, *128*, 2351.

He, C., Hotson, L., & Trainor, L. J. (2007). Mismatch responses to pitch changes in early infancy. *Journal of Cognitive Neuroscience*, *19*, 878–892.

Jackson-Maldonado, D., Thal, D. J., Fenson, L., Marchman, V. A., Newton, T., & Conboy, B. (2003). *MacArthur inventarios del desarrollo de habilidades comunicativas: User's guide and technical manual*. Baltimore, MD: Brookes Publishing Co.

Kuhl, P. K. (2004). Early language acquisition: Cracking the speech code. *Nature Reviews Neuroscience*, *5*, 831–843.

Kuhl, P. K. (2010). Brain mechanisms in early language acquisition. *Neuron*, *67*, 713–727.

Kuhl, P. K., Conboy, B. T., Coffey-Corina, S., Padden, D., Rivera-Gaxiola, M., & Nelson, T. (2008). Phonetic learning as a pathway to language: New data and native language magnet theory expanded (NLM-e). *Philosophical Transactions of the Royal Society B-Biological Sciences*, *363*, 979–1000.

Kuhl, P. K., Conboy, B. T., Padden, D., Nelson, T., & Pruitt, J. (2005). Early speech perception and later language development: Implications for the "critical period.". *Language Learning & Development*, *1*, 237–264.

Kuhl, P. K., Stevens, E., Hayashi, A., Deguchi, T., Kiritani, S., & Iverson, P. (2006). Infants show a facilitation effect for native language phonetic perception between 6 and 12 months. *Developmental Science*, *9*, F13–F21.

Luck, J. S. (2005). *An introduction to the event-related potential technique*. Cambridge, MA. The MIT Press.

McCarthy, G., & Wood, C. C. (1985). Scalp distributions of event-related potentials: An ambiguity associated with analysis of variance models. *Electroencephalography and Clinical Neurophysiology*, *62*, 203–208.

Mattock, K., Polka, L., Rvachew, S., & Krehm, M. (2010). The first steps in word learning are easier when the shoes fit: Comparing monolingual and bilingual infants. *Developmental Science*, *13*, 229–243.

Morr, M. L., Shafer, V. L., Kreuzer, J. A., & Kurtzberg, D. (2002). Maturation of mismatch negativity in typically developing infants and preschool children. *Ear and Hearing*, *23*, 118–136.

Näätänen, R. (1990). The role of attention in auditory information processing as revealed by event-related potentials and other brain measures of cognitive function. *Behavioral and Brain Sciences*, *13*, 201–288.

Näätänen, R. (1992). *Attention and brain function*. Hillsdale, NJ: Lawrence Erlbaum Associates, Publishers.

Näätänen, R., Lehtokoski, A., Lennes, M., Cheour, M., Huotilainen, M., & Iivonen, A., et al. (1997). Language-specific phoneme representations revealed by electric and magnetic brain responses. *Nature*, *385*, 432–434.

Pang, E. W., Edmonds, G. E., Desjardins, 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.

Pearson, B. Z., Fernandez, S. C., Lewedeg, V., & Oller, D. K. (1997). The relation of input factors to lexical learning by bilingual infants. *Applied Psycholinguistics*, *18*, 41–58.

Ramirez-Esparza, N., Garcia-Sierra, A., & Kuhl, K. P. (2010). Naturalistic social communication and speech development in monolingual and bilingual infants. *Journal of the Acoustical Society of America*, *128*, 2459.

Ramon-Casas, M., Swingley, D., Sebastián-Gallés, N., & Bosch, L. (2009). Vowel categorization during word recognition in bilingual toddlers. *Cognitive Psychology*, *59*, 96–121.

Rivera-Gaxiola, M., Klarman, L., Garcia-Sierra, A., & Kuhl, P. K. (2005). Neural patterns to speech and vocabulary growth in American infants. *Neuroreport*, *16*, 495–498.

Rivera-Gaxiola, M., Silva-Pereyra, J., Klarman, L., Garcia-Sierra, A., Lara-Ayala, L., & Cadena-Salazar, C., et al. (2007). Principal component analyses and scalp distribution of the auditory P150-250 and N250-550 to speech contrasts in Mexican and American infants. *Developmental Neuropsychology*, *31*, 363–378.

Rivera-Gaxiola, M., Silva-Pereyra, J., & Kuhl, P. K. (2005). Brain potentials to native and non-native speech contrasts in 7- and 11-month-old American infants. *Developmental Science*, *8*, 162–172.

Shafer, L. V., Yu, H. Y., & Datta, H. (2011). The development of Englsih vowel perception in monolingual and bilingual infants: Neurophysiological correlates. *Journal of Phonetics*, *39*, 527–545.

Sebastián-Gallés, N., & Bosch, L. (2002). Building phonotactic knowledge in bilinguals: Role of early exposure. *Journal of Experimental Psychology: Human, Perception and Performance*, *28*, 974–989.

Sebastián-Gallés, N., & Bosch, L. (2009). Developmental shift in the discrimination of vowel contrasts in bilingual infants: Is the distributional account all there is to it? *Developmental Science*, *12*, 874–887.

Sundara, M., Polka, L., & Genesee, F. (2006). Language-experience facilitates discrimination of /d-ð/ in monolingual and bilingual acquisition of English. *Cognition*, *100*, 369–388.

Sundara, M., Polka, L., & Molnar, M. (2008). Development of coronal stop perception: Bilingual infants keep pace with their monolingual peers. *Cognition*, *108*, 232–242.

Sundara, M., & Scutellaro, A. (2011). Rhythmic distance between languages affects the development of speech perception in bilingual infants. *Journal of Phonetics*, *39*, 505–513.

Trainor, L., McFadden, M., Hodgson, L., Darragh, L., Barlow, J., & Matsos, L., et al. (2003). Changes in auditory cortex and the development of mismatch negativity between 2 and 6 months of age. *International Journal of Psychophysiology*, *51*, 5–15.

Tsao, F.-M., Liu, H.-M., & Kuhl, P. K. (2004). Speech perception in infancy predicts language development in the second year of life: A longitudinal study. *Child Development*, *75*, 1067–1084.

Tsao, F.-M., Liu, H.-M., & Kuhl, P. K. (2006). Perception of native and non-native affricate-fricative contrasts: Cross language tests on adults and infants. *Journal of the Acoustical Society of America*, *120*, 2285–2294.

U.S. Bureau of the Census (2009). *Income, poverty, and health insurance coverage in the United States*. Washington, DC: U.S. Bureau of the Census.

Velleman, S. L., & Vihman, M. M. (2002). Whole-word phonology and templates: Trap, bootstrap, or some of each?. *Language Speech and Hearing Services in Schools*, *33*, 9–23.

Vihman, M. M., Thierry, G., Lum, J., Keren-Portnoy, T., & Martin, P. (2007). Onset of word form recognition in English, Welsh, and English-Welsh bilingual infants. *Applied Psycholinguistics*, *28*, 475–493.

Werker, J. F., & Byers-Heinlein, K. (2008). Bilingualism in infancy: First steps in perception and comprehension. *Trends in Cognitive Sciences*, *12*, 144–151.

Werker, J. F., & Curtin, S. (2005). PRIMIR: A developmental framework of infant speech processing. *Language Learning and Development*, *1*, 197–234.

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