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The Development of English Vowel Perception in Monolingual and Bilingual Infants: Neurophysiological Correlates

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Abstract

The goal of this paper was to examine intrinsic and extrinsic factors contributing to the development of speech perception in monolingual and bilingual infants and toddlers. A substantial number of behavioral studies have characterized when infants show changes in behavior towards speech sounds in relation to amount of experience with these sounds. However, these studies cannot explain to what extent the developmental timeline is influenced by experience with the language versus constraints imposed by cortical maturation. Studies using electrophysiological measures to examine the development of auditory and speech processing have shown great differences in infant and adult electrophysiological correlates of processing. Many of these differences are a function of immature cortex in the infant. In this paper, we examined the maturation of infant and child event-related-potential (ERP) electrophysiological components in processing an English vowel contrast and explored to what extent these components are influenced by intrinsic (e.g., sex) versus extrinsic factors, such as language experience (monolingual vs. bilingual). Our findings demonstrate differences in the pattern of ERP responses related to age and sex, as well as language experience. These differences make it clear that general maturational factors need to be taken into consideration in examining the effect of language experience on the neurodevelopment of speech perception.

Keywords

bilingual; development; electrophysiology; infants; MMN; speech perception; vowels

1. Introduction

Considerable research has demonstrated changes in how infants perceive speech during the first year of life (Jusczyk, 1997; Werker & Curtin, 2005). Many of these changes are the result of exposure to the speech patterns of the ambient language, and begin even before birth (e.g., Moon, Cooper & Fifer, 1993; Nazzi, Bertoncini, & Mehler, 1998). Around six months of age, infants' vowel discrimination is influenced by the distribution of vowel phones in the native language, and by ten months of age, infants show ambient-language influences on consonant discrimination (e.g., Kuhl, Williams, Lacerda, Stevens, & Lindblom, 1992; Werker & Tees 1984, Werker & Curtin, 2005). During the second half of the first year of life, infants are also beginning to learn the phonotactic properties of the ambient language (e.g., Jusczyk, et al., 1994).

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Speech perception abilities, however, are not mature at 12 months of age. Young children continue to learn to make use of more subtle cues (e.g., Nittrouer and Miller 1997a, b; Nittrouer et al. 2000). For example, Sundara, Polka, and Genesee (2006) demonstrated that English-learning four year olds were significantly better at discriminating the /d versusð/ contrast than 10- to 12-months-olds, but significantly poorer than monolingual English adults. Recent studies have also shown that young toddlers (12–17 months of age) do not make use of some phonological distinctions in more difficult word identification tasks (Stager and Werker, 1997; Werker & Stager, 2000), even though they are able to discriminate them in other, presumably simpler tasks (e.g., Baily and Plunkett, 2002; see, Curtin, Byers-Heinlein and Werker; this issue). These studies indicate that the time-course of speech perception development extends beyond age four. In addition, the finding that task demands modulate infants' performance suggests that native language (L1) speech perception is attention-dependent, at least until 18 months of age. As will be discussed below, adult L1 speech perception is highly automatic, but it is unclear when in development this automaticity is achieved.

1.1. The development of automatic selective perception

Jusczyk (1997) includes in his model of speech perception the claim that children learn to automatically attend to the relevant acoustic-phonetic features of the input. This notion of L1 speech perception being automated has been more fully addressed in Strange's Automatic Selective Perception (ASP) model (Strange & Shafer, 2008; Strange, this issue). In this model L1 learners establish selective perceptual routines (SPRs) that weight the relevant acoustic-phonetic information of the native language to allow for fast and efficient perception of native-language phonemes. The robustness and automatic nature of L1 SPRs allow for recovery of the phonemic information even under adverse conditions (e.g., background noise, divided attention). What has not been addressed in this model is the time-course of development of these SPRs. However, poor performance on some speech perception tasks (specifically, those which require more resources) by infants under the age of 18 months, suggests that these SPRs are not fully automated until at least 18 months of age. One goal of this paper is to examine evidence for automaticity of SPRs in children using electrophysiological measures.

1.2. Monolingual versus bilingual speech perception development

Two possible reasons exist for the extended time period needed for speech perception skills to fully develop. One is that a certain amount of experience with a language is necessary to achieve adult-like levels of speech perception. The alternative, but not mutually-exclusive, reason is that the brain structures supporting speech perception are immature and need to fully develop.

A number of studies have shown a relationship between vocabulary size, age and phonological abilities. In general, older toddlers with larger vocabularies demonstrate better performance on tasks requiring use of increasingly detailed phonetic representations compared to younger toddlers with smaller vocabularies (e.g., Fernald, Swingly, & Pinto, 2001; Werker, Fennell, Corcoran, & Stager, 2002). Some studies suggest that the need to differentiate more words as vocabulary size increases puts pressure on the child to more finely encode phonological distinctions (Charles-Luce & Luce, 1995; Metsala, 1999) and some have demonstrated a clear relationship between phonological abilities and vocabulary size (e.g., Mills Prat, Zangl, Stager, Neville, & Werker, 2004; Conboy & Mills, 2006). However, it is difficult from these studies to disentangle the contributions of language experience and general maturation to phonological development because maturation could constrain word learning, as well as phonological abilities.

Examination of speech perception development in the context of bilingual input can serve as an interesting test of the contribution of extrinsic (input) versus intrinsic (maturational) factors to the time course of development. Studies of adult bilinguals clearly show that the amount of experience with the language affects speech perception of the L2 measured both at the behavioral level (e.g., Pallier, Bosch, & Sebastian-Galles, 1997; Baker, Trofimovich, Mack, & Flege, 2002; Flege & MacKay, 2004; Nishi, Strange, Akahane-Yamada, Kubo, & Trent-Brown, 2008; Levy & Strange, 2008), and neurophysiological level (e.g., Zhang, Kuhl, Imada, Iverson, Pruitt, et al., 2009; Zevin, Maurer, Datta, Rosania & McCandliss; submitted). Even studies with bilingual adults who learned the L2 before age five years (e.g., Yeni-Komshian, Flege, & Liu, 2000; Pallier, Bosch & Sebastian-Galles, 1997; Peltola, Tuomainen, Koskinen, & Aaltonen, 2007) or have learned the two languages simultaneously from birth (Dupoux, Peperkamp & Sebastian-Galles, 2010) show differences from monolinguals for some speech processing tasks.

The factors that contribute to speech perception differences between adult monolinguals and bilinguals, whether they have learned the L2 early or late in life, are not easily identified because the learning experience and amount of use of the two languages is difficult to ascertain across the adult's lifespan. Studies of bilingual development are crucial to gain a better understanding of how and why bilingual speech perception differs from the monolingual case. An additional issue is that L2 learners often show poor speech perception similar to children with language impairment (see Shafer, et al., 2005). This similarity can cause difficulty in determining which bilingual children have genuine speech and language deficits, caused by intrinsic factors, versus which children merely need more experience with the L2 (an extrinsic factor).

Some studies that have examined speech perception development in bilingually exposed infants using behavioral methods have demonstrated similar patterns to monolinguals (e.g., Bosch & Sebastián-Gallés, 2001; Sundara, Polka & Molnar, 2008; Byers-Heinlein, Burns, & Werker, 2010; Werker & Curtin, this issue). Phonological and lexical abilities in a given language have been shown to be related to vocabulary size of that language (e.g., Marchman, Fernald, & Hurtado, 2009). Other studies, however, have shown differences. For example, Spanish-Catalan exposed infants stop discriminating the Catalan e/ɛ contrasts, similar to monolingually-exposed Spanish infants, but at a later age (12 months) show behavioral discrimination of this contrast. Monolingual Catalan exposure leads to a typical pattern of maintaining the e/ɛ contrast throughout (Bosch & Sebastián-Gallés, 2003). Conboy and Mills (2006) also showed different patterns of development for monolingual and Spanish-English bilingual children. Using ERPs to examine neural correlates of known and unknown words, they found a relationship between the size of the conceptual vocabulary and ERP responses. They also found differences in hemispheric involvement in processing words from the dominant and nondominant languages. These different findings regarding bilingual development may be related to phonetic-distributional and lexical factors in the two languages (Curtin, et al., this issue; Sundara & Scutellaro this issue). Languages showing more distinct phonologies (in terms of prosody and segments) may be easier to separate earlier in development.

In summary, the amount and nature of experience with speech sounds in the ambient environment influence the time-course of development. Different patterns found in bilingual compared to monolingual development are likely to result from the relative amount of experience with the two languages and to the relationship between the phonologies of the L1 and L2.

1.3. Influence of cortical maturation on speech perception

The nature of the input is clearly different for monolingually-and bilingually-exposed infants, but the mechanisms underlying language acquisition are identical, as pointed out by Curtin, et al. (this issue). Maturation of brain mechanisms supporting speech perception will be driven by intrinsic (genetic) factors and not by the language-specific nature of the ambient environment. Sensory systems do require some input to allow for normal organization and maturation (e.g., absence of auditory input in the case of congenital deafness, interferes with normal maturation, see Knudson, 2004), but there is no evidence that the language-specific nature of the input influences development of general brain mechanisms of speech perception. The development of speech perception in a bilingual context provides an opportunity to examine the relative contributions of general brain maturation and language-specific experience to this process. To fully evaluate these contributions it is necessary to examine what is currently understood regarding maturation of auditory cortex that will be involved in speech perception.

In general, maturation of neocortex proceeds from primary regions (involved primarily in receiving sensory input and sending motor output), to secondary regions (involved in higher-level sensory and motor processing) to tertiary/association regions (involved in integration of information across many levels, modalities and cortical regions (e.g., Huttenlocher & Dabholkar, 1997; see Shafer & Garrido-Nag, 2007). In terms of the auditory modality, auditory processing at the cortical level is quite immature in newborns because the neural structures are immature (Moore & Linthicum, 2007). Immature cortical regions can be characterized in terms of fewer neurons, sparser dendritic branching, fewer axon collaterals and incomplete myelination of axons that leads to slower and attenuated transfer of information.

Of particular relevance to this study, neural structures (assemblies) in cortical auditory areas receiving input from the periphery are still quite immature in newborns, and intense sounds with large spectral differences are necessary to drive encoding and discrimination. By six months of age, these neural assemblies receiving input have matured to a sufficient degree to support discrimination and learning of more fine-grained speech information, although they do not reach more adult-like levels of processing until five years of age (Ponton, et al., 2002). Neural assemblies that make connections across auditory areas and into association regions show even later maturation, reaching adult-like levels after puberty (Ponton, et al. 2002).

Maturation of these neural structures certainly places limits on the time course of speech perception development. For example, differences in brain maturation for female and male infants influence processing of speech versus nonspeech information (e.g., Shucard, Shucard, Campos, & Salamy, 1982). Several studies have suggested that delayed maturation could contribute to speech perception deficits in children with specific language impairment (e.g., McArthur & Bishop, 2005; Shafer, et al., 2007). Disentangling the contribution of maturational constraints (which are intrinsic, genetically-specified) from input factors will be important for constructing a more complete model of speech perception development and for understanding speech deficits.

1.4 Maturation of mismatch responses used in testing speech perception

Electrophysiological potentials recorded from the scalp (the electroencephalogram or EEG) are summations of underlying inhibitory and excitatory post-synaptic potentials generated by tens of thousands of neurons firing. Event-related potentials (ERPs) are time-locked portions of the EEG activity to a particular stimulus or event (Vaughan & Kurtzberg, 1992). However, neural activity in response to multiple stimuli and processes that are irrelevant to

the stimulus or event of interest is reflected in electrical potentials recorded at the scalp. Thus, averaging a large number of trials is generally undertaken in ERP studies because activity unrelated to the stimulus of interest will not be time-locked and will cancel out with increasing number of trials. ERPs allow examination of the timing of processing with resolution in the millisecond range, in some cases. They provide less information regarding the location of the source of the response because the potentials recorded at the scalp are summations of processing that results from an unknown number of sources. However, neurobiological evidence (e.g., from animal research, or structural maturation studies) can often provide good evidence for identifying likely sources of some ERP components (e.g., Vaughan & Kurtzberg, 1992; Moore & Linthicum, 2007). Of particular importance, the fine-grained temporal information provided by ERPs allows examination of changes in speed of information processing across development (e.g., Shafer, et al., 2000; Ponton, et al., 2002).

The principal ERP measure that has been used for studying speech perception has been the mismatch negativity (MMN) component. In adults, the MMN appears as a negative deflection to the ERP waveform at fronto-central scalp sites with inversion in polarity at inferior-posterior sites, generally found between 100 and 300 ms following the acoustic change of interest. The major sources of the processes indexed by MMN are in the auditory cortex (Näätänen, Paavilainen, Rinne & Alho, 2007). MMN is hypothesized to index change detection from a sound representation constructed to a repeated stimulus or pattern (Näätänen, et al., 2007; Sussman, 2007). Most importantly, the MMN can reveal whether representations in auditory cortex are sufficiently robust to allow for automatic, preattentive discrimination. When a stimulus change is sufficiently large, it leads to an orienting response, which is indexed by a positive response (P3a) following the MMN. MMN has been characterized as being attention-independent because it is operational without attention (e.g., in sleep), or with attention (e.g., counting the deviants; see Sussman, 2007).

A number of studies have shown that MMN is sensitive to the phonemic status of speech sounds in a listener's language (e.g., Näätänen, et al., 1997; Winkler, et al., 1999; Shafer, Schwartz & Kurtzberg, 2004). Larger amplitude MMNs are elicited from listeners for whom two speech sounds are categorized as different phonemes compared to listeners for whom the speech sounds fall into the same phonemic category. Hisagi and colleagues, however, have demonstrated that focusing attention on a non-native contrast can result in increased MMN amplitude to the level observed for native listeners (Hisagi, Shafer, Strange & Sussman, 2010). This finding is consistent with the claim that L1 speech perception is highly automatic, but that focused attention can allow for good performance for non-native speech perception (Strange, this issue).

Studies of children older than four years of age reveal similar negativity to the adult MMN, but at later latencies (e.g., Shafer, Morr, Kreuzer & Kurtzberg, 2000; Shafer, Morr Datta, Kurtzberg & Schwartz, 2005; Lovio Pakarinen, Huotilainen, Alku, Silvennoinen, Näätänen, 2009; Shafer, Yu & Datta, 2010). In contrast, only some studies of children under the age of four find a negativity that might index similar processes to the adult MMN (e.g., Cheour, Shestakova, Alku, Ceponiene, & Näätänen, 2002; Kushnerenko; Ceponiene, Bolan, Fellman & Näätänen, 2002). Other studies have observed a positive mismatch response (pMMR) at frontal-central sites to changes in pitch (e.g., Morr, Shafer, Kreuzer & Kurtzberg, 2002) and changes in phonemes (e.g., Dehaene-Lambertz & Dehaene, 1994; Leppänen et al., 2002; Friederici et al., 2002; Friedrich et al., 2004), and in some cases, the pMMR is found in addition to a negative MMR (nMMR) (e.g., Friederici et al., 2002; Leppänen, Richardson, Pikho, Eklund, Guttorm, et al., 2002; Morr, et al., 2002; Kushnerenko, Winkler, Horváth, Näätänen, Pavlov, et al., 2007). The term MMR is used to indicate the difference between ERPs to a standard and deviant stimulus, and "p" and "n" indicate the polarity of the MMR. Few studies have examined toddlers, but these studies also suggest difference from older

children, with no clear negativity being observed consistently before four years of age (e.g., Morr, et al., 2002).

One explanation for the inconsistency in observing an nMMR, which may be the precursor of the adult MMN, across the first few years of life is that the large pMMR masks the nMMR (e.g., Morr, et al., 2002; Kushnerenko, et al., 2002). Thus, understanding the functional significance of the pMMR is important. Children's ERP responses evoked to an auditory stimulus show a large frontal central positivity (P1, or P100) that declines in amplitude and latency with increasing age (e.g., Ponton, et al., 2002). The pMMR is an increase in positivity around the P1 latency of the ERP to the deviant compared to that of the standard stimulus. The accumulation of evidence regarding this pMMR indicate that it is likely to reflect a fairly primitive level of encoding and discrimination in terms of recovery-from refractoriness of neural populations receiving afferent input from the thalamus and which contribute to the P1 component (Kushnerenko, et al., 2007; Shafer, et al., 2010). Evidence supporting this interpretation comes from a number of findings, including that the pMMR can be obtained during sleep (e.g., Friedrich, Weber, Friederici, 2004; Kushnerenko, et al., 2007). This pMMR decreases in amplitude with increasing age and is generally absent by age eight years (Datta, Shafer, Schwartz, Morr & Kurtzberg, 2010; Shafer, et al., 2010), except to very fine-discriminations (Ahmed, Clarke, & Adams, 2008). The failure to observe a pMMR in older children and adult is likely to be due to the increased specificity of neural populations firing to particular acoustic information, leading to a very small-amplitude response that is masked by other mature components (e.g., N1b and the MMN, see Shafer, et al., in 2010).

The maturational time course of the processes indexed by the (adult) MMN remains somewhat unclear. One reason for some confusion about the development of the MMN is that the discriminative mechanism itself (indexed by MMN) is often confused with the information that is being discriminated. Specifically, the brain can be sufficiently mature to support the processes indexed by MMN, but representations themselves can be insufficient to allow for pre-attentive, automatic discrimination. Accumulating evidence from infant studies suggests that an early negativity, preceding a pMMR, is observed without attention only to large spectral changes (Morr, et al., 2002; Kushnerenko, et al., 2007). This early nMMR may be a precursor of the MMN or to the adult N1b, which matures quite late (and reflects recovery from refractoriness of a different population than that indexed by P1; e.g., Ponton, et al., 2002). A recent, well-controlled study suggests that smaller changes in frequency or changes in intensity reveal only a pMMR in sleeping newborns (Kushnerenko et al., 2007). In this study, which used different standards and deviants across different conditions, the only case showing negativity, rather than a pMMR was to a frequency deviant in the context of a broad-band white noise standard stimulus. The authors convincingly argue that the large (P1) positivity to the white noise standard is the result of the spectral richness of the noise inducing activity in a large range of afferent (input-receiving) neural populations. The lesser spectral richness of a harmonic tone, in contrast, elicits a smaller positive (P1) response due to activation of a smaller set of neural assemblies and it is this pattern that leads to greater negativity of the deviant, rather than the processes indexed by the adult MMN. The important point here is that nMMRs are not consistently found to fine-grained spectral differences in awake infants and are absent in sleeping newborns (at least, in the most comprehensive study by Kushnerenko, et al., 2007). In addition, the research by Moore and colleagues (e.g., Moore & Linthicum, 2007) suggests that the neural regions (cortical layers) that are the likely sources of the adult MMN are not sufficiently mature before three months of age to be considered to be the source of infant MMRs for perinatal infants.

Several studies have shown a late nMMR (peaking after 400ms) in infants (e.g., Kurtzberg, Hilpert, Kreuzer, & Vaughan, 1984; Leppanen, Pihko, et al., 1999; Leppanen, et al., 2002), more often found to stimuli differing in duration (e.g., voice-onset-time of /da/ vs. /ta/, geminate /t/ in /ata/ vs /atta/. This late nMMR could be the precursor of the adult MMN, but its very late latency compared to the adult MMN indicates immaturity.

In summary, an nMMR that could index the same processes as the adult MMN is not consistently observed to more fine-grained auditory contrasts until four years of age. The inconsistent presence of the nMMR under age four suggests that the representations of many contrasts are insufficiently robust to allow for pre-attentive, automatic discrimination in infants and toddlers. The presence of an nMMR to a more subtle contrast in an infant may indicate attention to the contrast. Evidence from structural brain maturation suggest that the neural structures involved in the discriminative processes indexed by MMN are unlikely to be functional much before six months of age, because they are insufficiently mature. Thus, at younger ages (newborn up to four or five months of age) discrimination must be supported by other neural assemblies (Moore & Lithecum, 2007). Even after the discriminative processes indexed by MMN become functional, continued structural development of neural assemblies occurs, leading to faster, more efficient discrimination.

1.5. The Present Study

One goal of the current study was to examine the relationship between language input and brain development during the first few years of life to determine which changes in speech perception are more related to general maturational changes (including sex differences) and which are more related to the environment. The vowel contrast /e/ versus /ɪ/ was selected because previous studies from our laboratory have shown this contrast to be challenging for both children with specific language impairment (SLI; Shafer, et al., 2005; Datta, et al., 2010) and for late learners of English with Spanish as a first language. The Spanish language contrasts five vowels (/i, e, a, o, u/) and /e/ can occur as an allophone of /e/, but English /ɪ/ does not occur at all (Hammond, 2001). In a study with late learners of English with Spanish as a first language, using the short, 50-ms versions of the vowels (from Shafer, et al., 2005), we found that late bilinguals were poor at identifying the nine stimuli, particularly for the stimuli labeled as /ɪ/ by monolinguals.¹ In the present study, the longer 250-ms versions of these vowels were selected for use because these were more natural when presented in isolation, and the contrast was more likely to be salient for the youngest infants.

Children listened to the vowel stimuli in the classic “passive” task in which a video was shown with the sound muted. It is impossible to verbally direct children under the age of three to attend to the video and ignore the auditory stimuli (as is done with older children and adults). Thus, the goal of this study was to determine whether there was evidence of automaticity of speech processing and to make inferences concerning how the children are allocating attention based on the ERP responses. In the case that speech perception of the vowel contrast is automatic, then attention to or away from the speech sounds will not affect discrimination, as indexed by MMN (Hisagi, et al., 2010). Our results from four- to seven-year old children suggested automaticity of processing this vowel contrast for monolinguals

¹Nine of 13 monolingual adults, 9 of 13 early bilingual adults but only 4 of 12 late bilinguals adults identified Stim 3 as /ɪ/ at better than chance levels (> 75%) after participating in a passive MMN paradigm using these stimuli. For Stim 9, 10/13 monolinguals, 11/13 early bilinguals, 9/12 late bilinguals, identified the stimulus as /e/ at better than chance levels (> 67%; note that both the monolinguals and early bilinguals showed 8 participants each at 100%, and the late bilinguals showed 5 at 100% for Stim 9) (Garrido, Hisagi, Datta & Shafer, in preparation). Note that these stimuli were presented free field, allowing for some background noise, rather than over ear inserts, as in Shafer, et al. (2005), which accounts for somewhat worse categorization performance by the adults in this study compared to adults and children in the previous study.

by four years of age because the majority of this age group showed robust negativity consistent with the MMN peaking between 300 and 400 ms (Shafer, et al., 2010).

We predicted that age would determine latency and amplitude of the P1 ERP component for both monolingual and bilingual groups of children because maturational factors should most heavily influence the processes indexed by this obligatory component. We expected to see emergence of the MMN/nMMR to the English vowel contrasts (ɪ vs. ε) selected for this study with increasing age, but also with increasing experience with English. We predicted that the younger infants and toddlers would show pMMR to this vowel contrast because they would have insufficiently detailed representations to support automatic, preattentive discrimination. With increasing age, we expected to see an increasing number of children showing the nMMR between 300 and 400 ms (presumably the emerging MMN) because more children will have developed robust representations. The children from the bilingual group were expected to lag behind those from the monolingual group in showing nMMRs, because some of them may have insufficient experience with English to have developed robust representations. We also predicted that females would show a different time-course of development than males, because other studies have found more rapid maturation of brain regions involved in language for female infants (e.g., Shucard, et al., 1982).

2.0 Method

2.1. Participants

To date 52 infants from monolingual English-speaking households (infant monolinguals or IM group) and 58 infants from English-Spanish bilingual environments (infant bilingual or IB group) have been recruited to participate in the study. Eleven infants from the IM and nine infants from the IB group either did not complete ERP testing or had noisy electrophysiological data. Fifteen of the infants from the IM group and thirteen of the infants from the IB group have been tested at more than one age in the data set presented in this paper. Altogether 140 test sessions are presented here. The breakdown of ages and number of males and females in each group are shown in Table 1. Participants were recruited from the greater New York area, which includes a diverse Hispanic population. Parents of bilingual participants completed questionnaires concerning language-background (LBQ) and developmental history. Caretakers judged the amount of English versus Spanish the child heard in different environments (e.g., home, playground) or from different people (e.g., father, mother, nanny) on a 7-point scale, with 1 as mostly English and 7 as mostly Spanish, and 4 as equal exposure. The bilingual children range from those who come from a Spanish dominant household and who produced first words in Spanish, to those who have one or both parents choose to use English most of the time and whose first words were in English. In all but three cases, one or both parents are bilingual Spanish-English speakers, typically of Hispanic origin. In the three cases, the children were exposed to Spanish in daycare. The last three columns of Table 1 show the number of bilingual children in each age group receiving exposure to more English than Spanish (LBQ scores < 3), more Spanish than English (LBQ scores > 5) or balanced exposure to Spanish and English (LBQ scores between 3 and 5) in the home and community. Approximately half of the children in the bilingual group were receiving balanced exposure to Spanish and English, one third was receiving more English than Spanish and one fifth more Spanish than English. The majority of infants come from families with middle- to upper-class socioeconomic status (SES) according to the Hollingshead Two-Factor Index of Social Position (Myers & Bean, 1968). Samples of the participants' speech (and parent's speech) were also collected to allow identification of regional language variety (for Spanish or English) (not reported here). Hearing was screened for all participants. For children under 30 months old, Transient Evoked Otoacoustic Emissions (TPOAE) was used. Most children passed the hearing screening, but a few did not complete the hearing screening due to noncompliance.

2.2. Stimuli and Procedures

The stimuli were two exemplars selected from a nine-step continuum of phonetically similar vowels, categorized as /ɪ/ as in *bit* to /ɛ/ as in *bet*. The continuum was made from re-synthesized versions of a natural token (female voice) using the Analysis by Synthesis Lab, version 3.2 (see Shafer, et al., 2007; 2010; Datta, et al., 2010 for details). The speech sounds were edited to 250 ms in duration with a rise and fall time of 5 ms. F_0 was maintained at 190 Hz. The third (F3) and the fourth (F4) formants were also kept constant at 2174 Hz and 3175 Hz, respectively. The nine exemplars were made by increasing F1 and decreasing F2 in equal steps from /ɪ/ to /ɛ/. The two tokens (Stim 3 and Stim 9) selected for the ERP studies had mean center frequencies of F1 at 500 and 650, and F2 at 2160 and 1980 Hz respectively. Stim 3 was consistently identified as [ɪ] and Stim 9 as [ɛ] by children with typical language development (TLD) (Datta, et al., 2010) and by monolingual American English-speaking adults in a pilot study. The stimuli were presented free field over two loudspeakers (approximately 1 m from child) at 86.5 dB SPL in trains of 10 at a rate of one stimulus per 600 ms. The intertrain interval was 1500 ms. Two deviant stimuli were presented in each train of 10 for an overall probability of 20%. The deviants could occur in the 4th and 8th, 5th and 10th or 6th and 10th positions. Stim 9 [ɛ] was presented as the standard and Stim 3 [ɪ] as the deviant. The children listened to up to 200 of these trains (resulting in 400 deviant trials) (see Shafer, et al., 2010).

Infants and toddlers sat on the caretaker's lap inside a sound shielded booth, with a children's video chosen either by the caretaker or the child playing silently through the monitor in front of the child. One research assistant stayed inside the booth and entertained the child with quiet toys, in the case that the child lost interest in the video (inferred by child looking away). Each ERP session lasted 28 to 40 minutes with breaks. All sessions were videotaped, with a DVD camera placed under the monitor and focused on the child's face.

2.3. ERP Recording

Participants under four years of age used a 63-channel Geodesic net (without eye electrodes, sites 63 and 64; see Figure 1). The net electrodes make contact with the scalp via sponges soaked in a saline solution. For all studies, the EEG was amplified with a bandpass of 0.1 to 30 Hz using Geodesic Amplifiers. A Geodesic software system (NetStation version 4.1) in continuous mode was used to acquire the data at a sampling rate of 250 Hz per channel for later off-line processing. The continuous EEG was processed off-line, using a lowpass filter of 20 Hz, and segmented into epochs with an analysis time of 800 ms post-stimulus and a 100 ms pre-stimulus baseline. The data were then baseline corrected and examined for artifact using Netstation software. Epochs with excessive artifact (greater than $\pm 140 \mu V$) on more than 5 channels were excluded from the average. Bad channels (on more than 20 % of the trials) were replaced by a spline interpolation algorithm from surrounding channels. ERP averages were calculated for each stimulus type (standard, deviant) and baseline corrected using the 100-ms pre-stimulus activity. Subtraction waveforms were created by subtracting the standard waveform from the deviant waveform for each participant. ERP averages were re-referenced to an average-reference. The number of trials after averaging ranged from 75 to 392 for the deviant and 250 to 860 for the standard, with over 90% of the children having more than 100 trials for the deviant stimulus.

2.4. Analysis

The standard deviation across sites was calculated for each ERP condition (standard, deviant and deviant minus standard). This variance measure (termed global field power, GFP) reveals time periods of maximum response to the stimulus of interest. Children's auditory evoked potentials are dominated by the large fronto-central positivity (P1) that inverts in polarity at inferior posterior sites (see Figures 4 and 5 below). The latency and amplitude of

P1 (also called P100) is easily identified from the GFP analysis and was identified from the standard waveform for each participant. Pearson's (r) correlations between age and peak amplitude and age and peak latency were computed. Infants show both positive and negative MMRs to the change stimulus. The presence of these, as well as their latencies and topographies all change dramatically with age. Thus, to address whether bilingual exposure results in difference in discrimination of these vowel sounds, we compared topographies of the MMRs (specifically, deviant minus standard). The Pearson's (r) correlations were calculated for consecutive 40-ms intervals from 80 to 400 ms comparing pairs of topographical maps. The grand means for two language-exposure groups were compared within an age-group. The grand mean topographies were also compared for adjacent age groups (e.g., three months versus six months) to determine whether infants of the same age or infants of the same language exposure group were more alike. To determine statistical differences in the MMR responses, t -tests were performed to identify sites showing significant differences from zero between 200 and 400 ms and, in a second comparison, significant differences between the IM and IB groups. Ten frontocentral sites were selected for this comparison, including left sites 13 (F3), and 17 (C3), midline sites 4 (Fz) and 65 (Cz) and right sites 62 (F4) and 54 (C4) that showed significant findings in other investigations of speech perception in children (e.g., Shafer, et al., 2005 e.g., Shafer, et al., in press). Four additional sites (two left, 9 and 16 and two right 58 and 57) near these we also included to allow us to better determine which sites showed the most robust responses. Pearson's (r) correlations were calculated to examine relationships between ERP measures at the left frontal site (9) and right frontal site (57) and age.

3. Results

3.1. Maturation of the obligatory P1

The analyses in this section focused on whether the age of language group influenced the amplitude or latency of the P1 component, which indexes detection and encoding of acoustic-phonetic information. As expected, a large fronto-central positivity (P1) peaking between 100 and 300 ms dominated the waveforms of infants and children. Figure 2 displays the grand mean GFPs for each age and language group. Using GFP to select the latency of the P1 was superior to focusing on one site because no bias was introduced by site selection. The peak latency was negatively correlated with age ($r = -0.68$, $p < 0.0001$, $df = 140$; confidence intervals -0.76 to -0.58), shifting from approximately 210 ms at 3 months of age to 150 ms at 36 months of age. There were no significant differences in the latency of the peak between the monolingual and bilingual groups. Figure 3, top graph displays the P1 latencies for each participant in each group plotted against age. Linear curve fits for the two language groups show nearly identical lines (IM y -intercept = 214, $SD = 4.9$, slope = -0.067 , $SD = 0.008$; IB y -intercept = 212, $SD = 5.3$, slope = -0.063 , $SD = 0.009$). No correlation of peak amplitude with age was found ($r = 0.03$, $p = 0.74$). However, the 6-month-old IM group showed significantly greater amplitude than the same-age IB group ($df = 31$, $p = 0.01$; ML mean = 3.83, $SD = 1.40$; BL mean = 2.76, $SD = 0.87$). This difference, however, is driven by the female infants ($df = 15$; $p = 0.002$) and not the males ($df = 14$, $p = 0.76$). The remaining age groups showed almost identical peak amplitudes (seen Figure 2).

Comparisons of topography were also undertaken because it is possible for the GFP measures to show similar peaks and amplitudes in the face of differing contribution from left and right hemisphere or anterior and posterior sites. To make use of information from all sites, we calculated Pearson's (r) for six successive 40-ms time intervals between 80 and 280 ms following stimulus onset. Pearson's (r) is related to the Global Dissimilarity Index (GDI) that has been used in a number of recent papers using ERP methods by the equation $GDI = 2(1 - 2r)$. We chose to report the correlation coefficient (r) rather the GDI because interpretation of (r) is familiar to most researchers across fields. The results of these

comparisons between IM and IB groups using the standard-stimulus grand means of each age group revealed high similarity, with correlations ranging from 0.84 for the 3-month olds to between 0.94 and 0.98 for the other groups (see Table 2). The highest correlations for an age group were found near the P1 peak. Correlations across age groups were also high (above 0.70) for the 240–280 ms time interval. For the three younger age groups, the highest (r) was between the language groups that were the same age (see Table 3). For the three older groups, the highest correlation was not always between the same age IM and IB groups (see Table 3). However, these groups (18-, 24-, 36-months) showed correlations with each other greater than 0.94 for all pair-wise comparisons of the 160–200 ms interval.

In summary, these analyses demonstrated that age strongly influenced the latency and the topography of the P1 peak. The 18- to 36-month old groups all had highly similar topographies for the P1 peak. One language group difference was found, but only for female 6-month-old infants, with the IM group showing larger amplitude GFP to the vowels than the female infants from the IB group.

3.2. MMR responses

The analyses in this section focused on whether children in the difference age and language groups demonstrated discrimination of the vowel contrasts and whether discrimination was reflected in a pMMR and/or nMMR response. One challenge in multi-channel ERP research is to determine which sites and time intervals are relevant for statistical analysis. Guidance can come from the prior literature for selecting sites and times of interest, but the current developmental research in infants and toddlers is too sparse to rely solely on this literature. Global field power can help select time periods of interest, but it is less useful for selecting component latencies than for the P1 analysis because the MMRs are relatively smaller in amplitude (compared to P1) and do not result in well-defined GFP peaks. Figure 2 (right graphs) reveals that the IM groups exhibit a somewhat robust peak around 260 ms. The IB 3- and 6- month old groups also show peaks near this latency. However, the GFP calculation for individual participants often showed multiple peaks or no clear peak that could be selected as representing the peak latency of the MMR responses. We also predicted that the infant MMRs would shift earlier in latency with age and that the negative MMR should become apparent with increasing age. The GFP measure does not allow evaluation of whether the response topography shifts from superior site positivity to superior site negativity. Thus, selecting peak latencies to represent maturation of the positive and negative MMR responses requires topographical information. This brings us to the question of which of the 63 electrode sites should be selected for this analysis?

3.2.1 Descriptive topography of MMRs—Figures 4 and 5 display butterfly plots of twelve sites for each age group and language group that are expected to show MMRs, based on previous research. These MMR waveforms are calculated by subtracting the ERPs to standard from that of the deviant for each site. The butterfly plots overlay multiple sites chosen to reveal where these sites are showing differing polarity. For example, for most of the age groups, the superior frontal sites (red and orange shades) show positivities peaking between 200 and 240 ms and the inferior posterior sites (black) show negativities in this time frame. The MMR response is easier to identify in these plots as points where the superior frontal and posterior inferior sites are showing inverse polarity. What we observe in these figures is that the superior anterior positivity is clearly identifiable for the monolingual (IM) groups in all but the 12-month olds. For the bilingual (IB) infants this is true only for the three-, six-, and 36-month old groups. Closer examination of the figures shows superior positivity for the IB 12-, 18- and 24- month olds, but that it is substantially smaller than for their monolingual counterparts.

A second observation is that the 36-month old infants from the IM group show a superior site negativity following the pMMR with a first peak around 340 ms. This negativity, which we will call the nMMR, appears to be greater over right- compared to left sites when it is measured relative to the right and left mastoids, respectively. This topography was found for 4- to 5-year old monolingual children (Shafer, et al., in press), as shown in Figure 6. The 24-month olds also show robust nMMR across right superior sites and at F3 beginning around 340 ms and continuing beyond 700 ms. For the younger IM groups, C4 is becoming more negative relative to the other superior sites.

For the IB groups, the infants in the three youngest groups show similar pattern for the developing nMMR to the IM infants. The 12-month-old IB group is somewhat similar to the same-age IM group, showing negativity at the right central site, C4. The 6-month-old IB group appears to be similar to the same-age IM group in the later time frame of the negativity, except that the right mastoid does not show inversion (i.e., positive amplitude). The three-month-olds from both the IM and IB groups are different from the older age-groups, in that the left central site (C3) is the most negative.

The three older IB age groups show different patterns than their IM comparison groups. The 36-month olds from the IB group show superior negativity following the pMMR, but primarily at the left central site, C3, and it is not until a later time frame that negativity is found over most superior sites. The 18-, and 24-month olds from the IB group show some superior-site negativity following the pMMR, but at a different site compared to the other IB groups and compared to their IM same-age group. The IB 24-month olds show prominent late negativity (later than 300 ms) at F4, whereas the 18-month olds show it at F3.

3.2.2 t-tests for early MMRs—We performed *t*-tests on FZ(4), CZ(65), F3(13), F4(62), C3(17) and C4(54), which have shown significant MMRs in previous studies and on an additional four sites (left frontal site 9 and 16 and right frontal 57 and 58), allowing for fine-grained coverage of the frontocentral regions. The GFP and butterfly plots along with finding from Shafer et al., (2010) suggest focusing on two 40-ms time intervals between 200 and 280 ms. These early time intervals are expected to show a pMMR, rather than an nMMR because four-year old monolingual English-speaking children showed a pMMR in this time interval (Shafer, et al., 2010). Table 4 presents the results of *t*-tests for the 200 to 280 ms intervals in the first column. Sites that showed significant differences from zero ($p < 0.05$) for the subtraction waveforms are listed. We were particularly interested in sites showing significance for four or more groups because the probability of finding this by chance (with $p < 0.05$ for *t*-tests) when testing 10 sites is 0.02. The probability of three groups showing significance by chance is 0.17, and for five groups is 0.002. At the left frontocentral sites, significance for five groups was found at site 9. Sites 13 (F3) and 16 showed significance for three groups (see Table 4). Only the 3-month-old IM group failed to show significance at one of these left frontal sites. Of the IB infants, Only the 6- and 36-month-old infants showed significance at left frontocentral sites, at site 13 (F3) for both groups and at site 9 for the 36-month-old group.

At right frontocentral sites, significant differences for four groups were found for site 62(F4), and for three groups for sites 54(C4), 57 and 58. All of the IM groups, except the 12-month-olds showed significance for at least one of these four sites (see Table 4). For the IB groups, the three-month olds showed significance at site 54, the 12-month olds at site 57, and the 36 month olds at site 58 and site 62. The 6-, 18- and 24-month olds showed no differences over right sites. Three of the IM groups also showed significant differences at the midline site 4(FZ). These were the 6-, 26 and 36-month old groups.

The first two columns of Table 5 shows the *t*-test comparisons between the same-age IM and IB groups for the 200–240 ms and 240–280 ms intervals. Only the left fronto-central site 9 and site 13 show significant group differences. The six- and 12-month old IM groups show significantly greater positivity than their IB counterparts. The 36-month olds exhibited a reverse pattern, with the IM group now tending to show greater negativity than the IB group ($p = 0.06$). Figures 4 and 5 show that for site 9 (thick red trace) the 18- and 24-month old IM groups continue to show positivity, but of less amplitude than the younger IM groups, and greater positive amplitude than the older groups.

In summary, the response to the deviant stimulus was significantly more positive than the response to the standard at a cluster of left (9, 13 and 16) and right (57, 58, and 62) frontocentral sites for the younger IM groups, and more negative for the oldest, 36-month-old, IM group. The IB groups, however, showed a different pattern, with 3- and 6-month olds showing greater positivity, but 12-, 18- and 24-month olds showing more negativity to the deviant compared to the standard. The 6-month-old IB group showed positivity at F3 (site 13) but not at the more superior, site 9. All but the 3- and 24-month old groups showed significant differences between the IM and IB same-age groups over left frontocentral sites 9 or 13, with the IM group showing greater positivity, for all but the 36-month old group, which shows the reverse pattern of greater negativity than the IB group.

3.2.3. *t*-tests for later MMRs—In four- to five-year-old IM children a significant nMMR (presumably MMN) is present following the pMMR, peaking between 300 and 400 ms (Shafer, et al., 2010). Our figures reveal that the 24- and 36-month-old groups are showing evidence of some negativity in this time-frame. To determine whether significant differences from zero were present and whether nMMR is emerging, we performed *t*-tests on the 320–360 ms and 360–400 ms time intervals on the same 10 frontocentral sites used in the analyses with the earlier intervals.

Similar to the earlier intervals, the left superior site 9 shows significance for five of the 12 groups ($p = 0.02$). For the IM age groups up to 18-months of age the response is positive (see Table 4, Figures 4 and 5). For the 24- and 36-month old IM groups, the amplitude has fallen to zero or below zero, respectively. In contrast to the IM groups, all of the IB age groups, except the three-month olds show slightly negative amplitudes or amplitudes close to zero, with 18-month olds showing significant negativity in this time-frame.

Over the right superior region, significant findings for five of the groups are seen at site 57 (between F4 and C4). Both three-month old IM and IB groups and the 18-month-old IM group show significant positivity at site 57. The 24- and 36-month old IM groups and the 6-, 12- and 24-month-old IB groups, however, tended to show negativity at site 57, with it reaching significance for the IB 12-month olds, and IM 18- and 24-month-olds (see Figures 4 and 5, above). No other right or midline site showed significance for more than one group (see Table 4).

For the comparisons between age groups, site 9 continues to show group differences. As can be observed in Figures 4 and 5, the IM 6-, 12-, 18-, and 24-month olds show greater positivity of the MMRs than the same-age IB groups in these later time-intervals. The 36-month old IM group showed greater negativity of the MMRs than their IB counterparts. These differences, however, are significant only for the 6-, 12- and 18-month olds at site 9 (see Table 5).

At the right sites, a significant difference between groups was only observed at site 54 (C4) for the 24-month olds, with the IM group showing greater negativity than the IB group.

In summary, in the later time-intervals, the left sites continue to show some positivity (pMMR) for all but the oldest IM groups. The right sites, however, no longer show large positivities, and the older children begin to show a clear negative deflection (nMMR) from the zero baseline. The principal difference between the groups is greater negativity at the left and right superior sites for IB groups up to 24 months of age. However, at 36 months of age, the IM and not the IB group shows well-defined negativity (nMMR) at fronto-central sites. topography of this nMMR is quite similar to that found in older 4- to 5- year old monolingual children (shown in Figure 6; see Shafer, et al., 2010).

3.3. Topography of the MMRs

The figures and *t*-tests suggest that the IM and IB groups are different in timing of the pMMR and nMMR and in topography of these responses. Differences in topography would suggest different neural sources contributing to the response. To quantify these apparent differences in topography we calculated Pearson's correlation coefficient (*r*) using all 63 sites between all pairs of IM and IB age groups for successive 40-ms intervals. Table 6 presents Pearson's *r* between the IM and IB grand means for each age group. As can be seen, the six-month old groups show significant correlations ($r > 0.25$) from 240 to 320 ms, the 12-month olds from 120 to 240 ms, the 18-month olds from 120–160 ms, and the 24- and 36-month old groups from 200 to 320 ms. The 6-month- and 18-month-old groups also show significant negative correlations in the 360–400 ms interval. The 3-month olds showed no significant correlation of topography. The highest correlation value for each age group for the MMR responses ranged from 0.37 to 0.52. In contrast, values for the P1 comparisons (above) were much higher, ranging from 0.82 to 0.98. These lower (*r*) values indicate that factors other than age are contributing to the variance of these topographies.

We also examined whether each infant group resembled the adjacent age group in topography within a language group. For the IM groups, all groups showed significant positive correlations with the adjacent age group in the 240–320 ms time range (see Table 7). In contrast, for the IB group only the three- compared to six-month old showed significant positive correlations for both intervals between 240–320 ms, and 18- compared to 24-month old infants and 24- compared to 36-month olds for the 240–280 ms interval. For the other IB group comparisons there were significant negative correlations for some time intervals, but no significant positive correlations.

It was possible that the IB group looked like younger IM infants, so we also compared topographies between an IB age group and the next youngest IM group. This analysis indicated that the IB six-month olds showed some similarity to the younger IM three-month olds, and the IB 36 month olds were actually more similar to the IM 24-month olds ($r = 0.56$) for the 240–280 ms range than to the IB 24 month olds ($r = 0.31$). The IB 36 month olds showed a negative correlation with the IM 24 month olds in the later time intervals, 320–400 ms, where the nMMR is first observed.

Overall, these topographical comparisons reveal the most similarity across language groups in the pMMR time range. The IB groups showed less similarity to adjacent ages with the same language experience than for the IM groups. This finding suggests greater variability across the IB compared to the IM groups. The next set of analyses will allow for examination of variability.

3.4. Distribution of MMR latencies and amplitudes

Previous studies have shown that the latency of the MMN in children is negatively correlated with age (Shafer, et al., 2000; Shafer, et al., in 2010). In these investigations with older children (four- to 10-years of age), and a study using a large frequency difference with

infants (Morr, et al., 2002) it was possible to select a peak for the MMN responses using a single site, such as FZ (Shafer, et al., 2000; Morr, et al., 2002) or C4 (Shafer, et al., in 2010). This approach is problematic for the current data sets because the MMRs are largest at different sites for different age groups. Rather than selecting a peak latency from one site, we used the set of sites displayed in Figures 4 and 5 to identify the latency of the largest positive peak (among F3, F4, C3, C4, and Fz) and used inversion at one or more of the inferior sites to help identify this peak. We found that a single peak could easily be selected for the pMMR for the majority of children. However, selecting a peak latency for the later MMN-like negativity observed in the older infants was difficult because many of the infants showed gradual onset of the negativity at one or more sites, with multiple negative-going deflections that could be selected. For this reason we focused on the pMMR for this analysis.

Figure 3 (bottom graph) displays the peak latency of the pMMR for each individual plotted against age. The IM infants are shown as filled circles and the IB infants as unfilled squares. The IM infants demonstrated a significant negative correlation with age ($r = -0.31$, 95% confidence interval (CI) = -0.50 to -0.08 , $p = 0.009$). The curve fit shows that the latency of the pMMR gradually shifts earlier for the IM group, by approximately 1.4 ms per month (y intercept = 254 ms $\pm$ 10.4 SD, slope = -0.046 ± 0.017 SD). The IB group, in contrast, is showing no change in pMMR latency (y-intercept 236 ms $\pm$ 10.1 SD, slope = -0.003 ± 0.017 SD) ($r = -0.02$, 95% CI = -0.26 to 0.22 , $p = 0.86$).

One possible reason for the shift in pMMR latency in the IM group is that there is a gradual increase in negativity in the later time interval cutting into the later portion of the pMMR. In this case, the amplitude of the pMMR would decrease with age to a greater extent in later time intervals. Figure 7 shows amplitude at left superior site 9 plotted against age for the two groups in four time intervals between 200 and 400 ms. Recall that a number of IM and IB groups showed differences at this site. What stands out in this plot is that, for the younger infants, the distribution is shifted positive for the IM infants and negative for the IB groups. With increasing age, the amplitude becomes more negative for the IM infants across all four, time intervals. The later two time intervals show significant negative correlation with age for the IM infants, as shown in Table 9. The amplitude decreased about 0.7 μ V per year. In contrast, for the IB group, a cluster of infants under 600 days (under 20 months) show very negative amplitudes and most of the IB toddlers between 20 and 30 months show negativity, unlike their same-age IM peers. Most of the oldest IB infants, however, show positivity between 200 and 320 ms. When fitting a line to the IB data, the slope is close to zero. Essentially, the younger IB infants tend to show positivity (but with a cluster showing very negative responses), the intermediate groups show negativity and the older children show positivity.

At right superior sites the IM and IB infants show similar amplitude distributions. As can be observed in Figure 8, the curve fits show similar y-intercepts and nearly identical slopes (all rounding to -0.001) for the two groups. The correlation with age was not significant for any group with the IM group showing (r) values of -0.15 and -0.18 and the IB group of -0.21 and -0.15 , respectively, for the two time intervals. The younger infants have a much larger range of values with close to half of each group showing positivity and half showing negativity at site 57. With increasing age more infants show negativity. A larger number of older infants will be needed to determine whether this pattern is significant.

In summary, these correlations with age reveal that the IM infants show a gradual shift in peak latency of the pMMR and increasing negativity with age for the later time intervals. The IB infants do not show correlations with age. Rather, they tend to show increased negativity for the toddlers between 12- and 24-months of age, but positivities at the earlier

ages and at 36 months. In addition, a substantial number of IB 6-month olds show large negativities at the left superior frontal sites, represented best by site 9.

3.5. Sex differences

It is possible that some of the differences found between the IM and IB groups are related to sex, since a number of studies have shown considerable sex differences in ERPs at these ages (e.g., Shucard and Shucard, 1990; Shucard, Shucard, Cummins & Campos, 1981; Shucard, et al., 1982; Shafer, Shucard & Jaeger, 1999) and our analysis of the P1 peak showed a difference in amplitude for six-month-old female infants. The following analyses examine to what extent sex accounts for differences in the MMR response. Figure 9 displays the amplitude at site 9 for time intervals 240–280 and 360–400 ms for the female and male infants separately. We fitted lines to the IM and IB males and females separately for these intervals. The male infants show much less of a difference in the y-intercepts and slopes of these lines compared to the female IM and IB infants (see Table 9). These graphs reveal that many of the female IB infants less than 400 days have very large negativities extending from 200 to 400 ms. The older IB females exhibit less negative amplitudes compared to the younger females. For the older infants, language group differences are less apparent, with the lines converging. However, we currently have only three girls in the 3-year-old IM group. We will need more females to determine whether the 3-year old IB and IM groups are different.

We also examined the language background and socioeconomic (SES) status for the younger IB infants to rule out these as factors leading to the highly negative response. The infants with the most negative responses at superior sites came from a variety of backgrounds. Several received mostly English at home and Spanish at daycare, some heard both Spanish and English at home and several heard Spanish from a nanny or grandmother, rather than a parent. In all cases, these infants were exposed to American English in one situation (e.g., home or daycare), or by at least one person (e.g., father). The SES of the children with these highly negative responses also varied, with some from mid- to upper-SES backgrounds and some from lower SES. The one factor that was consistently present for the infants with the most negative responses was being female.

In summary, for infants younger than 14 months of age, clear sex differences are observed. In particular, approximately half of the girls from the IB group showed large negativities from 200 to 400 ms. The male infants in the two groups show more similar distributions, although the distribution is shifted negative in the later time interval for the younger male IB infants compared to IM infants.

4.0 Discussion

These preliminary results show differences in MMR responses to an American-English vowel contrast between infants in the two language-exposure situations, but also reveal that developmental age and sex play a role in the nature of these responses. Infants in the monolingual (IM) group exhibited predicted patterns of response. The youngest IM infants showed a robust positive discriminative response (pMMR) at superior sites and this pMMR decreased in amplitude and latency with increasing age, similar to findings with tone contrasts (Morr, et al., 2002). Many of the IM infants over 30-months of age showed negativity (nMMR) at some superior sites, particularly in the later time-intervals. This negativity often followed a pMMR, and is likely to be the emerging MMN consistently observed in children older than four years of age and in adults (Shafer, et al., 2000; Näätänen, et al., 2007; Lovio, et al., 2009; Shafer, et al., 2010).

In contrast, the infants from bilingual (IB) backgrounds showed a very different distribution for the pMMR and emerging nMMR. Many IB infants between 6- and 29-months of age showed more negative responses at superior site between 200 and 400 ms compared to the IM infants. For infants under 14-months of age, this nMMR was particularly large for IB females. Most of the IB toddlers between 14- and 29-months of age, whether male or female, also showed increased negativity of the MMRs at superior sites, relative to the IM group. The older IB infants (30–46 months) showed similar patterns to the IM group, but the emerging nMMR, which is likely to be the precursor of MMN, seems to onset at a later latency for a number of the IB compared to the IM three-year olds. Below we will discuss these patterns in relationship to our knowledge of brain development and the maturation of infant obligatory and MMR components.

4.1. Maturation of speech perception: P1 obligatory component

Our findings support the claim that the neural sources of the P1 are fairly mature during the first year and that language experience has little effect on stimulus encoding properties at this early level of processing. The P1 obligatory component, which indexes detection and encoding of acoustic information (e.g., Ponton, et al., 2002), shifted earlier in latency at a rate of approximately 2 ms per month. The two language-exposure groups showed highly similar topographies for P1 across all age groups. They also showed nearly identical rates of change of latencies for this P1 peak. These changes in latency are probably related to continued myelination that allows for faster conduction rates of electrical signals, and are found into adolescence (Ponton, et al., 2002; Sussman, Steinschneider, Gumenyuk, Grushko, Lawson, 2008). The cortical sources of this P1 component are likely to be in Layer 4 and deep Layer 3 (where thalamocortical pathways terminate), layers which mature rapidly from six- to twelve months of age (Ponton, et al., 2002; Moore & Linthicum, 2007). The only language group difference was in the amplitude of the P1 for the six-month old females. The IB infants showed less positivity than the same-age female IM infants. We suggest that the smaller amplitude of the P1 for six-month old girls is related to an attentional component, the Nd. This will be discussed further in a later section.

4.2 Development of speech perception as indexed by pMMR

All the infant and toddler groups showed a prominent positivity (pMMR) peaking between 200 and 300 ms and largest at superior sites. The topography of this pMMR, however, changed with age. In particular, the three-month-olds show robust pMMR at right frontal and central sites. In older children (6 months to 6-years of age), the left sites show greater positivity of the MMR, than the right (see Shafer, et al., 2010). The latency and amplitude of this pMMR also shifted earlier and became less positive with age, although we suggest that these changes may be partially a function of the emergence of the MMN between 300 and 400 ms.

Our data suggest continuity in the development of the pMMR, with it showing gradual changes in amplitude and latency for the IM group from three-months to six-years of age. All of the evidence taken together indicates that the pMMR indexes detection and encoding of the acoustic properties of a stimulus in terms of afferent (input) connections into primary auditory cortex. Specifically, the pMMR reflects greater recovery from refractoriness of the neural populations firing to the deviant compared to the standard vowel (Shafer, et al., in 2010). Repetition of a stimulus leads to reduced firing in a neural population receiving (afferent) input, with greater reduction at shorter ISIs. The ISI between deviant vowels is greater than that for standard vowels, and allows for greater recovery, and thus larger amplitude P1 responses. The presence of the pMMR, however, does not necessarily indicate perception of the stimulus difference. This hypothesis, that pMMR is recovery from refractoriness of P1, is consistent with our understanding of infant brain development. We

know cortical layers indexed by P1 are sufficiently mature during the first year of life, and thus can support discrimination. The finding of a pMMR in sleeping infants, and that spectrally-rich stimuli have a larger P1 than less rich stimuli, also supports this explanation (Kushnerenko, et al., 2007).

4.3 Development of speech perception as indexed by nMMR/MMN

In our data, the first clear signs of an nMMR occurred around six-months of age. With increasing age, a larger proportion of infants showed negativity, particular at right superior sites and in the later time intervals between 300 and 400 ms. The gradual shift in latency and decline in amplitude of the pMMR with increasing age may, in part, be a by-product of the increasing amplitude of this nMMR. This nMMR could be a precursor of the adult MMN and will be termed nMMR/MMN in the remainder of the discussion. The studies by He and colleagues are consistent with this suggestion (He, Hotson & Trainor, 2009; 2007). They observed a pMMR in both two and four-month old infants to frequency changes (of 1/12 octave and 1/2 octave). However, only the four-month-old groups showed clear nMMRs. A few studies of newborn infants have shown an nMMR to speech contrasts and suggested that this negativity was a precursor of the adult MMN (e.g., Cheour, et al., 2002). However, this possibility is unlikely because the cortical layers supporting the adult MMN are not sufficiently mature in newborns to be the source of this response (Moore and Linthicum, 2007). It is more likely that perinatal MMRs, whether positive or negative, are generated by a marginal layer of neurons present at birth, but which declines with increasing age (Moore & Linthicum, 2007).

The nMMR/MMN emerging between four and six months of age is likely to have cortical sources initially limited to deep layer 3 and layer 4 because these mature rapidly between six and 12 months of age. With increasing age other cortical layers mature (Layer 2, shallow Layer 3 and Layer 5) and will contribute to the discriminative processes indexed by MMN (see Steinschneider, Fishman & Arezzo, 2008). As these areas mature, the nMMR/MMN in response to a particular contrast will shift earlier in time, as has been found up to age ten years (e.g., Shafer, et al., 2000; 2010) and preattentive discrimination will be observed to increasingly more difficult contrasts (e.g., Gomes, et al., 1999).

The finding of sex differences in whether an nMMR/MMN was present in young infants revealed the role of intrinsic, maturation factors in influencing speech perception development. Studies have shown earlier maturation of brain regions for female compared to male infants during the first year of life (e.g., Shucard & Shucard, 1990) and better discrimination, as reflected by MMRs for females compared to male one-month old infants in relationship to testosterone levels (Friederici, Pannekamp, Partsch, Ulmen, Oehler, Schmutzler & Hesse, 2008). This earlier maturation could account for more female than male infants showing large negativities during this first year. However, the finding that not all female infants showed an nMMR/MMN and that language group influenced its presence indicated that cortical maturation is not the only factor determining the presence of an nMMR/MMN response. In the next section we will argue that the presence of an nMMR/MMN at both left and right superior sites in the younger age groups indexes increased attention to the stimulus change.

4.3. Automaticity and attention in speech processing

A number of studies of various phonetic contrasts have shown that in the typical passive task, where attention is directed to a video, non-native listeners show smaller MMN amplitudes than native listeners (e.g., Shafer, Schwartz & Kurtzberg, 2004; Sharma & Dorman, 2000; Cheour et al., 1998; Rivera-Gaxiola et al., 2005; for review Näätänen, et al., 2007). Hisagi and colleagues (2010) found that directed attention to a non-native (Japanese)

vowel duration contrast led to more American-English adult listeners showing robust MMNs than when attention was directed away (to a visual oddball task). This finding supports the predictions of the ASP model that listeners are less automatic at processing non-native speech contrasts and that directing additional attentional resources to the task can improve discrimination (Strange, this issue). Children compared to adults also appear to need more attentional resources for relatively difficult discriminations. For example, Gomes and colleagues (1999) showed that MMN was not elicited to a tone contrast when stimuli were presented with a long ISI of 3 s in eight- to 10-year-old children without directed attention, whereas adults showed comparably robust MMNs with and without attention.

In speech perception studies, MMN serves to reveal the distinctiveness of two representations in auditory sensory cortex at a pre-attentive level (Hisagi, et al., 2010). Salient objects or sounds are hypothesized to be explicitly represented in sensory cortex (Koch, 2004). In the case that a sound pattern is not explicitly represented in auditory cortex, attention would be needed to facilitate discrimination (e.g., Münte, Altenmüller, & Jäncke, 2002; Restuccia, et al., 2005). Crick and Koch (1990) also point out that overlearning can lead to explicit representations in sensory areas. Thus, we argue that overlearning of the speech patterns of a native language leads to explicit representation in auditory cortex, and that these representations are the basis for the native-language SPRs proposed by Strange (this issue). This notion of overlearning native-language SPRs is also consistent with Kuhl's notion of neural commitment to native-language speech categories (Kuhl, et al., 2008). These explicit representations allow for robust pre-attentive discrimination, and thus, robust MMNs.

Behavioral research showing categorical perception in newborn infants indicates that they must have some rudimentary form of explicit representation of phonetic categories (Jusczyk, 1997). However, newborns will not have explicit representations of their native language phonetic categories, because experience is required to formulate these. It is likely that attention is required to set up these native-language categories. Thus, the presence of nMMR/MMN found for most 4- to 5-year olds in Shafer et al. (2010) indicates that by this age, explicit, highly-salient representations of the phoneme categories for [ɪ] and [e] are available to native English-speaking children, and discrimination is highly automatic. We also have evidence that the representations of this vowel contrast are robust in eight- to 10-year-old children with typical language development from two studies where we found robust MMNs with or without attention to the auditory modality (Shafer, et al., 2005; Datta, et al., 2010). Lack of automaticity would be inferred from finding a number of children not showing an MMN in the passive task. Since the passive task does not rigorously control for attention, it allows some children to choose to attend to the speech sounds, whereas others will ignore these sounds.

The more variable presence of nMMR/MMN in infants between six- and 47-months of age that we observed in the current data set indicates lack of robust representations and may reflect variability in whether the infants were attending to the sound contrast or not. In a recent study from our lab, we found that directing infants' attention to a contrast change for 6- to 8-month old infants leads to elicitation of an nMMR rather than pMMR for tone or speech contrasts (Garrido-Nag & Shafer, in prep.). This is an important finding because it shows that for the same infant, the pMMR can dominate under one condition, and an nMMR under another condition.

Under the attention explanation, the different distribution of nMM/MMN versus pMMR responses for IM and IB infants could be explained in the following way. For the IM infants, their task is simpler in that they only have to deal with the phonetic inventory of English, and thus, they were less interested in the vowel sounds we presented, or lost interest in them

more quickly. In contrast many of the IB children, in particular females, have recognized that they are dealing with more than one phonetic inventory, and thus are allocating additional attentional resources to processing the vowel stimuli. The finding that IB female six-month olds showed smaller GFP amplitudes at the P1 latency to the standard stimulus ERPs also suggests increased allocation of attentional resources to the stimuli. In a different paper with 8- to 10-year old children using these same stimuli, we found that directing attention to the stimuli led to an Nd component, indicating attention, and seen as smaller GFP (Shafer, et al., 2007).

The claim that more infants from the IB than IM group are paying attention to the vowel sounds is consistent with Werker and colleagues' suggestion that infants exposed to two or more languages need to track statistics separately for the languages for successful learning, and that this would require comparing and contrasting the languages (Curtin, Byers-Heinlein, and Werker's, this issue). It is highly likely that this additional task for infants from bilingual environments could lead to increased attention to the speech stimuli.

The older IB children (30–46 months) more closely resembled the IM children, possibly because they had set up their inventories by this age and no longer found the vowel sounds particularly interesting. Overall, a greater proportion of the older children showed increased negativity at right superior sites, which was probably the MMN. This presumed MMN at these later ages may indicate that the phonetic representations of these vowels are explicitly represented in auditory cortex for these children, and thus discrimination now occurs automatically. Support for our hypothesis, that attention is required for discrimination of this vowel contrast at younger ages, will be obtained if we find in our longitudinal study that particular infants showing nMMRs at six or 12 months of age, show pMMRs at older ages (e.g., 18 or 24-months of age). In contrast, early automaticity for the contrast will be supported if, once an infant shows nMMR, then at all subsequent ages, she/he continues to show nMMR.

4.4. Relationship between the nMMR and language experience

Our results revealed that language-specific information in the input influences MMR responses in infants. In particular, the 6-month old female infants from bilingual backgrounds appear to be sensitive to the presence of two languages in the input. Some behavioral results are consistent with this finding, showing that bilingually-exposed infants maintain phonemic contrasts for both languages (e.g., Sundara, Polka & Molnar, 2008; Byers-Heinlein, Burns, & Werker, 2010). However, other studies suggest that bilingually-exposed infants may initially have difficulty determining the phonetic inventories of the two languages and actually stop showing discrimination of a contrast found only in one of the languages, whereas monolingually-exposed infants will maintain it; then later, toward 12 months of age these bilingual children will demonstrate discrimination of the contrast (e.g., Bosch & Sebastián-Gallés, 2001). One explanation for this pattern of findings is that in cases where the infant cannot track the statistical properties of the two languages independently, the infant may fail to show discrimination of a contrast that occurs in only one of the languages (Curtin, et al., this issue). Similar suprasegmental and segmental properties may lead to greater difficulty in doing this because the infant may “tag” a phone as the incorrect language and this could lead to the appearance of greater acoustic variability for a phonetic category. In the case of our study, English and Spanish differ in rhythmic properties (stress-timing vs. syllable-timing), and should be relatively easy to track separately, as shown by Sundara and Scutallaro (this issue).

It will be interesting to see whether presence of an nMMR at early ages (under two years) is predictive of later language ability, particularly for bilingual children. Other research has observed smaller or absent MMN in grade-school children with language impairment (LI)

(e.g., Uwer, et al., 2002; Shafer, et al. 2005, Bradlow, Kraus, Nicol, McGee, Cunningham, & Carrell, 1999) and suggests a relationship between infant MMR measures and later language impairment (e.g., Friedrich, Herold, & Friederici, 2009; Choudhury & Benasich, 2010; Kuhl et al., 2008). It is unknown to what extent experiential factors rather than some biological limitation on perception or maturation leads to poor discrimination. It is possible that less attention to speech (leading to less experience) could underlie the pattern of findings observed in all of these studies (Shafer, et al., 2005). Examining a bilingually-exposed population can help address this question because the amount of English experience, in the absence of a language deficit, can be observed for influences on the development of speech representations.

5.0 Conclusion

These preliminary data indicate that ERP MMR responses can serve as useful indicators of speech and language development in both monolingual and bilingual contexts. We will need more children in the 24- and 36-month-old age groups to determine which variables show the strongest relationship with the ERP measures and with language scores. Our current analyses suggest that the nMMR/MMN will provide the important information regarding whether the nature of the input is sufficient for constructing robust speech representations (extrinsic factors). In contrast, the P1 and the pMMR could indicate whether a child has a more general maturational delay (P1) or poor auditory acuity (pMMR) that can then lead to poor speech representations (intrinsic factors). It is also possible that poor attention to speech at certain stages of development could lead to poor development of representations.

We argued that the nature of the MMR (positive versus negative) can reveal how infants are allocating attention to processing speech at different ages, and can provide information on whether native-language speech perception has become automatized. We have also shown that making use of a number of analysis tools (GFP, topography correlations) provides a rich picture of the neurodevelopment of speech perception. These cross-sectional results will serve as a basis for examining the relationship between ERP measures, preschool language measures, and amount of language use (Spanish versus English) in our longitudinal cohort.

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64 Channel Geodesic Sensor Net Map
Electrical Geodesics, Inc.

Figure 1.

Relative scalp locations of electrodes using the Geodesic net. Site 51 and 26 fall on the mastoid bone behind the ear and site 10 at the nasion, which is the indentation where the nose meets the forehead. Infant nets do not include sites 63 and 64 (electrodes under the eyes).

Figure 2.

Grand mean GFPs for each age and language group. GFP to the standard stimulus is shown on the left and to the subtraction stimulus (deviant minus standard) on the right. The left-most dotted vertical line indicates the vowel sound onset. For the left graphs, the second vertical line is drawn through the 36-month old peak, and third through the 3-month old peak, illustrating a shift in latency with age. For the right graphs, the second vertical line is drawn through the most prominent peak for the 6-month olds and reveals a small peak for other age groups at this latency of approximately 260 ms. The third vertical line is drawn through a second small peak at approximately 340 ms for the 36-month olds.

Figure 3.

Top graph. Peak latency of the P1 (or P100), calculated from GFP, for each participant in the IM and IB groups plotted against age. Curve fits show nearly identical shifts in latency with age for the two groups. The bottom graph displays the latency of the most prominent positive peak selected from superior-frontal sites for each participant in each age group plotted against age. The curve fit for the IM group shows a negative slope, revealing a shift to earlier latency with increasing age. In contrast the slope for the IB group is close to zero, indicating no change in latency across age.

Figure 4.

Butterfly plots for the three younger age groups comparing the IM (left) and IB (right) groups. Superior sites 13 (F3), 17 (C3), 62 (F4), 54 (C4), 4 (FZ), 65 (CZ), 9 and 57 are expected to show the same polarity and inferior sites 26 (LM) and 52 (RM) the opposite polarity for a mature MMN and the pMMR. This pattern holds for the 6-month olds and the 3-month olds, except for RM. The 12-month-olds show a different patterns with the IM group showing superior site positivity for most left and midline sites (solid lines), but negativity for some right sites (broken lines) and for LM. The IB group, in contrast, shows superior site negativity, except for C3, and inferior site positivity.

Figure 5.

Butterfly plots for the three older age groups comparing the IM (left) and IB (right) groups. Superior sites 13 (F3), 17 (C3), 62 (F4), 54 (C4), 4 (FZ), 65 (CZ), 9 and 57 are expected to show the same polarity and inferior sites 26 (LM) and 52 (RM) the opposite polarity for a mature MMN and the pMMR. This pattern generally holds for both IM and IB groups around the pMMR peak. The IB group shows less difference in amplitude between the superior and inferior sites at the pMMR latency and differences in which sites show negativity versus positivity in later intervals compared to the same age IM group.

Figure 6.

Top. Butterfly plots for 4- to 5-year old monolingual-American English children to the vowel contrast. Sites 13 (F3), 17 (C3), 62 (F4), 54 (C4), FZ (4) and 9 are expected to show the same polarity and LM (26) and RM (51) show opposite polarity. These older children exhibit a pMMR peaking around 229 ms over left sites, followed by a nMMR peaking around 337 ms over right sites. The bottom topography maps illustrate the relative distribution of positivity and negativity over the scalp at these two times with red showing positivity and blue showing negativity.

Figure 7. Amplitudes for each infant for four 40-ms time intervals at left superior site 9 plotted against age. The ovals highlight clusters of IM and IB infants that show little overlap.

Figure 8. Amplitudes for each infant for two 40-ms time intervals at right superior site 57 plotted against age. Linear curve fits are shown for each group (IM and IB).

Figure 9.

Amplitudes for female and male infants plotted against age. Curve fits for females (top) and males (bottom) for the 240–280 and 360–400 ms time intervals. Only the female infants show obvious differences between language exposure groups in the y-intercept and slope of the response.

Table 1

Total number of infants and number of female and male infants in each age and language group. The last three columns indicate how many children in each bilingual age group receive more English, more Spanish, or balanced exposure. IM = infant monolinguals and IB = infant bilinguals.

Group	N	female	male	More English	More Spanish	Balanced
3 mo IM	8	5	2	NA		
3 mo IB	10	2	7	3	1	6
6 mo IM	16	10	6	NA		
6 mo IB	17	7	11	4	4	9
12 mo IM	14	7	7	NA		
12 mo IB	12	7	5	4	3	5
18 mo IM	12	5	10	NA		
18 mo IB	7	3	6	2	0	5
24 mo IM	13	7	3	NA		
24 mo IB	10	4	4	4	1	5
36 mo IM	10	3	7	NA		
36 mo IB	11	4	7	6	2	3
Total	140	64	75	23	11	33

Table 2

Correlations between Monolingual and Bilingual ERP topographies to the standard stimulus from 40 to 280 ms. The bolded values indicate the interval with the highest r .

Group	40–80 ms	80–120 ms	120–160 ms	160–200 ms	200–240 ms	240–280 ms
3 months	0.11	0.18	0.09	0.59	0.82	0.84
6 months	0.62	0.75	0.82	0.96	0.97	0.95
12 months	0.22	0.26	0.83	0.94	0.92	0.65
18 months	0.36	0.04	0.94	0.98	0.96	0.53
24 months	0.38	0.25	0.92	0.96	0.88	0.68
36 months	0.63	0.79	0.97	0.98	0.93	0.53

Table 3

Pairs showing the highest (r) for the P1 GFP peak interval (different interval for some ages, see Table 2)

Group	r	Comparison group
3 mo IM	0.84	3 mo IB
3 mo IB	0.84	3 mo IM
6 mo IM	0.96	6 mo IB
6 mo IB	0.97	6 mo IB
12 mo IM	0.94	12 mo IB, 24 mo IM
12 mo IB	0.94	12 mo IM
18 mo IM	0.98	18 mo IB, 24 mo IM, 36 mo IB
18 mo IB	0.99	36 mo IM
24 mo IM	0.98	18 mo IM
24 mo IB	0.96	24 mo IM
36 mo IM	0.99	18 mo IB
36 mo IB	0.98	36 mo IM, 18 mo IM, 18 mo IM

Table 4

Significant sites by age and language group between 200 and 280 and 320 and 400 ms. Bolded sites $p \leq 0.01$, unbolded sites $p < 0.05$.

Group	200–280 ms	320–400 ms
3 mo IM	54	4,9,57
3 mo IB	54	57
6 mo IM	4,9,13,16,62	9,16
6 mo IB	13	
12 mo IM	9,17,25	9
12 mo IB	57	57
18 mo IM	9, 13, 16 , 57	9, 13 ,16,57
18 mo IB		9
24 mo IM	4, 9,16,58,62,65	54,57
24 mo IB		
36 mo IM	54, 58 ,62	16
36 mo IB	4,9 ,13, 58, 62	

Table 5

Sites showing significant differences between the IM and IB groups for each age for the four time intervals (bold p < 0.01; unbolded sites p < 0.05).

Group	200–240 ms	240–280 ms	320–260 ms	360–400 ms
3 mo				
6 mo	9	9	9	9
12 mo	9	9	9	9
18 mo	-	13	9,13,57	9,13
24 mo	-	-	-	54
36 mo	9(p=0.06)	-	-	-

Table 6

Correlations (r) between Monolingual and Bilingual ERP topographies of the subtraction waves from 120 to 400 ms. ($r > 0.26$ are significant (confidence interval 0.01 to 0.48)).

Group	120–160 ms	160–200 ms	200–240 ms	240–280 ms	280–320 ms	320–360 ms	360–400 ms
3 months	–0.14	–0.22	–0.12	0.12	0.17	0.04	–0.15
6 months	–0.01	0.02	0.19	0.52	0.46	0.15	<u>–0.26</u>
12 months	0.44	0.31	0.37	0.20	–0.02	0.02	–0.08
18 months	0.44	0.25	0.15	0.20	–0.03	–0.04	<u>–0.31</u>
24 months	–0.17	0.05	0.39	0.47	0.41	0.22	0.22
36 months	0.14	–0.02	0.01	0.45	0.33	0.16	0.21

Table 7

Correlations of ERP topographies of the subtraction waves from 120 to 400 ms for adjacent age groups. The column heading reflects interval onset.

Group	120-160 ms	160-200 ms	200-240 ms	240-280 ms	280-320 ms	320-360 ms	360-400 ms
Mono 3 vs. 6 mo	0.31	0.15	0.13	0.26	0.33	0.23	0.23
IM 6 vs. 12 mo	-0.16	-0.11	-0.02	0.47	0.53	0.39	0.33
IM 12 vs. 18 mo	-0.08	<u>-0.15</u>	0.14	0.32	0.39	0.31	0.01
IM 18 vs. 24 mo	-0.28	<u>-0.25</u>	0.18	0.36	0.46	0.11	-0.10
IM 24 vs. 36 mo	-0.06	-0.26	-0.18	0.42	0.34	0.12	0.17
IB 3 vs. 6 mo	0.34	0.01	0.23	0.46	0.35	0.06	-0.20
IB 6 vs. 12 mo	<u>-0.38</u>	-0.04	-0.14	-0.24	-0.04	0.05	0.15
IB 12 vs. 18 mo	<u>-0.41</u>	<u>-0.30</u>	-0.14	-0.12	-0.06	0.10	-0.19
IB 18 vs. 24 mo	0.08	-0.05	0.11	0.28	0.09	0.19	0.19
IB 24 vs. 36 mo	-0.13	<u>-0.36</u>	0.00	0.31	0.01	<u>-0.32</u>	-0.17

Table 8

Correlations of ERP topographies of the subtraction waves from 120 to 400 ms for each bilinagual group and the immediately younger monolingual group.

Group	120-160 ms	160-200 ms	200-240 ms	240-280 ms	280-320 ms	320-360 ms	360-400 ms
IB 6 vs. IM 3	-0.10	0.01	0.22	0.33	0.25	0.09	0.05
IB 12 vs. IM 6	0.07	0.01	0.00	-0.17	-0.09	-0.22	-0.07
IB 18 vs. IM 12	-0.08	<u>-0.44</u>	-0.03	0.21	0.06	0.11	0.13
IB 24 vs. IM 18	0.15	0.07	0.15	0.25	0.18	-0.08	-0.20
IB 36 vs. IM 24	0.11	-0.07	0.13	0.56	0.25	<u>-0.33</u>	<u>-0.26</u>

Table 9

Correlation coefficient (r), p value, y-intercept and slope for the IM and IB infants across four time intervals. Significant p values are bolded.

Time and Group	r	p	y intercept	slope
IM 200–240	−0.17	0.15	1.17	−0.001
IM 240–280	−0.14	0.24	1.56	−0.001
IM 320–360	−0.30	0.01	1.92	−0.002
IM 360–400	−0.27	0.02	1.41	−0.002
IB 200–240	0.17	0.16	−0.39	0.000
IB 240–280	0.12	0.32	−0.10	0.001
IB 320–360	−0.01	0.96	−0.21	0.000
IB 360–400	0.01	0.94	−0.55	0.000
IM girls 240	−0.12	0.48	1.69	−0.001
IB girls 240	0.31	0.11	−2.00	0.002
IM boys 240	−0.14	0.41	1.36	−0.001
IB boys 240	0.01	0.93	0.94	0.000
IM girls 360	−0.28	0.08	1.63	−0.002
IB girls 360	0.18	0.37	−2.07	0.001
IM boys 360	−0.24	0.17	1.13	−0.001
IB boys 360	−0.14	0.38	0.30	−0.001