SPECIAL ISSUE ARTICLE

Speech discrimination in 11-month-old bilingual and monolingual infants: a magnetoencephalography study

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Abstract

Language experience shapes infants' abilities to process speech sounds, with universal phonetic discrimination abilities narrowing in the second half of the first year. Brain measures reveal a corresponding change in neural discrimination as the infant brain becomes selectively sensitive to its native language(s). Whether and how bilingual experience alters the transition to native language specific phonetic discrimination is important both theoretically and from a practical standpoint. Using whole head magnetoencephalography (MEG), we examined brain responses to Spanish and English syllables in Spanish-English bilingual and English monolingual 11-month-old infants. Monolingual infants showed sensitivity to English, while bilingual infants were sensitive to both languages. Neural responses indicate that the dual sensitivity of the bilingual brain is achieved by a slower transition from acoustic to phonetic sound analysis, an adaptive and advantageous response to increased variability in language input. Bilingual neural responses extend into the prefrontal and orbitofrontal cortex, which may be related to their previously described bilingual advantage in executive function skills. A video abstract of this article can be viewed at: https:// youtu.be/TAYhj-gekqw

Research highlights

- Using whole head magnetoencephalography (MEG), we compared 11-month-old monolingual and bilingual infants to examine how the experience of bilingualism changes the course of developmental speech perception.
- Monolingual infants showed evidence of neural sensitivity to one language, while bilingual infants were sensitive to two languages.
- Compared to monolingual infants, bilingual infants showed a slower transition from acoustic to phonetic sound analysis, an adaptive brain response to increased variability in language input.
- Bilingual infants' brain responses extended into prefrontal and orbitofrontal cortex, brain areas known to be involved in executive functioning.

Introduction

From cooing and babbling to the production of words and sentences, children learn their native language(s) within the first three years of life. Because neither adults nor computers can accomplish this task as effectively, understanding the process by which the infant brain encodes language presents one of the key questions in neuroscience. Recent research indicates that infants learn rapidly from exposure to language, combining pattern detection and computational abilities with unique social skills (Saffran, Aslin & Newport, 1996; Kuhl, Tsao & Liu, 2003). A key element in this process is the child's language experience: Studies consistently show that quality and quantity of language input are strongly associated with the rate of subsequent language growth (Hart & Risley, 1995; Ramírez-Esparza, García-Sierra & Kuhl, 2014; Ramírez-Esparza, Garcia-Sierra, & Kuhl,

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2016), real time language processing (Weisleder & Fernald, 2013), and brain measures in language relevant areas (Noble, Houston, Kan & Sowell, 2012).

To date, the literature on language acquisition has focused predominantly on children acquiring a single language. However, a growing number of children worldwide grow up bilingually, clearly indicating that the infant brain is capable of encoding not only one, but multiple languages simultaneously. The existing research suggests that, in general, the same learning mechanisms that are used to prepare the monolingual infant to attend to a single language are also used to prepare the bilingual infant to attend to two languages, without confusing them (Werker, Byers-Heinlein & Fennell, 2009). Studies with infants prenatally exposed to two languages from different rhythmic classes show that they begin to discriminate their two languages from birth (Byers-Heinlein, Burns & Werker, 2010). Like monolingual babies, bilingual babies use auditory and visual cues to discriminate their two languages (Weikum, Vouloumanos, Navarra, Soto-Faraco, Sebastián-Gallés *et al.*, 2007).

Much less clear is whether and how dual language exposure affects phonetic learning towards the end of the first year of life. Phonetic learning has been termed a 'pathway to language' because it reliably predicts many subsequent stages in language acquisition, such as lexical and grammatical growth (Kuhl, Conboy, Coffey-Corina, Padden, Rivera-Gaxiola *et al.*, 2008). A central phenomenon in phonetic learning is the transition from universal to native language specific phonetic discrimination: Until about 6 months of age, infants are capable of discriminating among many, if not all, the phonetic units of the world's languages. By 12 months of age, a perceptual narrowing process is well under way: Infants' sensitivity to native speech sounds increases, and their sensitivity to non-native (foreign language) speech sounds decreases (Kuhl, Stevens, Hayashi, Deguchi, Kiritani *et al.*, 2006; Tsao, Liu & Kuhl, 2004; Werker & Tees, 1984). While the loss of non-native sound discrimination abilities between 6 and 12 months of age is not complete, and is somewhat dependent on the exact contrasts and the relationship between the native and non-native languages under investigation (Best & McRoberts, 2003; Werker & Curtin, 2005; Kuhl *et al.*, 2008), studies consistently show a steep decline in the discrimination of non-native speech sounds by the child's first birthday.

Whether and how this critical transition is affected by dual language exposure is still a matter of debate. Some studies suggest that bilingual infants follow a different developmental trajectory, while others claim that the same general pattern is followed. Bosch and Sebastián-Gallés (2003a) tested Spanish and Catalan monolingual and bilingual 4-, 8-, and 12-month-old infants on a vowel contrast that is phonemic in Catalan but not in Spanish. All groups discriminated the contrast at 4 months of age. However, only Catalan monolingual infants were successful at 8 months of age. By 12 months, the bilingual group was successful as well. The same U-shaped developmental pattern was later shown for consonants (Bosch & Sebastián-Gallés, 2003b), as well as for vowels that are contrastive in both languages (Sebastián-Gallés & Bosch, 2009). Together, these studies suggest that differences may exist between monolingual and bilingual development of speech perception. The proposed explanation is that tracking statistical regularities across two languages affects the ability to discriminate acoustically similar phonetic categories.

Other studies have not replicated this pattern. For example, Sundara, Polka, and Molnar (2008) show that 10–12-month-old French-English bilingual babies are able to behaviorally discriminate French and English consonants and vowels, while age-matched French monolinguals are unable to do so. Along similar lines, Spanish-English 4- and 8-month-olds can discriminate acoustically similar vowel contrasts that are phonemic in one but not the other language (Sundara & Scutellaro, 2011). A study by Burns, Yoshida, Hill and Werker (2007) tested English- and French-relevant voice-onset-time (VOT) consonant discrimination in 6–8-, 10–12-, and 14–20-month-old English monolingual and French-English bilingual infants. While bilingual infants of all three age groups were able to discriminate contrasts in both languages, only the youngest group of monolinguals discriminated both contrasts.

Taken together, the results of studies on bilingual sound discrimination in infancy have so far been mixed, perhaps due to differences in methodologies and the characteristics of languages under investigation. Further insights into this question can be gained by the use of neuroimaging or brain recordings. The transition from universal to native language specific phonetic discrimination is typically measured with the mismatch response (MMR; Näätänen, Lehtokoski, Lennes, Cheour, Huotilainen *et al.*, 1997), which consists of two distinct components. The early component, typically occurring between 100 and ~260 ms post stimulus, signals a less mature, acoustic level of neural encoding and discrimination. The late component, with a typical latency of ~260–460 ms post stimulus, signals a more mature,

phonetic level of analysis (Friedrich, Herold & Friederici, 2009; Rivera-Gaxiola, Silva-Pereyra & Kuhl, 2005; Shafer, Yu & Datta, 2010, 2011).[1] As infants transition from universal to native language specific phonetic discrimination, the late MMR component shows a selective increase to native language sounds. At the same time, the early MMR component in response to native and non-native sounds decreases, reflecting the decline in universal discrimination ability (Kuhl et al., 2008). This pattern of results has been replicated in a number of electroencephalography (EEG) studies with monolingual infants (Rivera-Gaxiola, Garcia-Sierra, Lara-Ayala, Cadena, Jackson-Maldonado et al., 2012; Rivera-Gaxiola et al., 2005; Kuhl et al., 2008). The transition from universal to native language specific phonetic discrimination, with the accompanying increase in the late MMR and decrease in the early MMR component, typically occurs by 11 months of age. Since most of this research has been conducted with EEG, which lacks spatial resolution, the areas of the infant brain involved in this process are still under investigation. Two recent MEG studies suggest the involvement of bilateral temporal, fronto-temporal, and motor areas (Imada, Garcia-Sierra, Lara-Ayala, Cadena, Jackson-Maldonado et al., 2006; Kuhl, Ramírez, Bosseler, Lin & Imada, 2014).

Very few brain studies of speech discrimination have so far been conducted with bilingual infants. Shafer et al. (2011) recorded EEGs associated with English vowel contrasts in monolingual English and bilingual Spanish-English 3- to 36-month-olds. In monolinguals, the early MMR component decreased in amplitude with increasing age and language experience, as has previously been shown in other studies. Bilingual infants showed a different pattern of results, with a large late MMR, which the authors interpreted as indexing increased attentional demands experienced by bilingual infants. Petitto, Berens, Kovelman, Dubins, Jasinska et al. (2012) used functional Near Infrared Spectroscopy (fNIRS) with 4–6- and 10–12-month-old bilingual and monolingual infants as they processed native language sounds, non-native language sounds, and non-linguistic tones. Whole-brain analyses revealed that all infants showed greater activations to language stimuli relative to non-linguistic tones; however, there were no significant

differences between native and non-native language conditions, or between activations in the right and left hemisphere in either the monolingual or the bilingual group. Region of Interest (ROI) analyses in the left inferior frontal cortex showed that there were no differences between the younger (4–6-month-old) bilingual and monolingual group. However, an important difference emerged between the two older groups: While 10–12-month-old bilingual infants showed neural sensitivity to native and non-native phonetic contrasts, their monolingual peers exhibited sensitivity to native phonetic contrasts only. The authors conclude that monolingual and bilingual babies follow the same overarching developmental trajectory; however, the bilingual babies have a residual capacity to neurally discriminate foreign language contrasts at a time when monolingual infants can no longer do so.

This finding suggests that bilingual infants may remain in the universal phonetic discrimination phase for a longer period of time compared to monolingual infants, in agreement with the results of an EEG study by Garcia-Sierra, Rivera-Gaxiola, Percaccio, Conboy, Romo et al. (2011). The study used a double oddball paradigm with Spanish and English sounds to show that 6–9-month-old Spanish-English bilingual infants do not neurally discriminate either one of the languages, and exhibit predominantly positive (less mature) rather than negative (more mature) MMR responses. While no monolingual infants participated in the study, other studies using the same stimuli and paradigm show that monolingual 6–8-month-old infants typically exhibit neural discrimination of native and non-native contrasts (Rivera-Gaxiola et al., 2005; Rivera-Gaxiola, Silva-Pereyra, Klarman, Garcia-Sierra, Lara-Ayala et al., 2007). Importantly, the 10–12-month-old bilingual infants in the Garcia-Sierra study showed discrimination of both languages, as evidenced by a negative MMR in response to both contrasts. Consequently, Garcia-Sierra et al. (2011) argue that, while these data do not indicate a developmental delay by bilingual infants, they do suggest an extended universal sound discrimination phase.

Together, behavioral and brain studies suggest that bilingual and monolingual speech perception are similar in many ways; however, important differences have also been observed. One plausible hypothesis is that the transition from universal to native language specific phonetic discrimination occurs later in development in bilingual compared to monolingual infants (Kuhl, 2004; Kuhl & Rivera-Gaxiola, 2008; Garcia-Sierra et al., 2011). Bilingual infants split their time between two languages. If the amount of time required to transition from universal to language specific listening depends on language input and variability, bilingual infants may stay

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[1] In the EEG literature, these two components are known as the pMMR and nMMR, where p and n stand for positive and negative, and refer to the polarity of the EEG response. MEG measures the magnetic flux passing through a sensor surface, and its polarity depends on the direction of the magnetic field relative to this sensor area. The two components are thus defined by specific time windows, rather than by polarity.

in the universal listening stage for a longer period of time compared to monolingual infants, simply because it takes more time for sufficient data (speech) to be experienced. If this prediction is correct, one should be able to observe reliable differences in neural processing between monolingual and bilingual infants by their first birthday.

To test this hypothesis, the present study used, for the first time in bilingual infant research, whole head magnetoencephalography (MEG), which presents an important advantage over previous EEG or fNIRS studies. MEG and EEG both indicate the summed response of the neuronal postsynaptic electric current; however, MEG is more sensitive to neuromagnetic signals perpendicular to the cortical surface. While EEG and MEG both provide excellent temporal resolution (unlike hemodynamic techniques such as fNIRS or fMRI), MEG also offers excellent spatial resolution because the magnetic signal is left nearly intact by the conductivity gradients as it travels through the brain and skull tissue (Dale & Halgren, 2001). On the other hand, the EEG signal distribution is very sensitive to fine details of the conductivity boundaries in the head.

Using MEG technology, we directly compared the locus and timing of neural activity between eight Spanish-English bilingual and eight English monolingual 11-month-olds. Using a double oddball paradigm, we calculated the MMR for English and Spanish and compared them at the within- and the between-group levels in two time windows (100–260 ms and 260–460 ms) identified in a number of previous studies (for example, Cheour, Ceponiene, Lehtokoski, Luuk, Allik *et al.*, 1998; Conboy & Kuhl, 2011; for review see Näätänen, Paavilainen, Rinne & Alho, 2007). Because this is an initial MEG investigation with bilingual infants, statistical analyses were conducted across the entire brain surface, without any a priori hypotheses about localization differences between the two groups. This design allowed us to test three specific predictions: First, we predicted that monolingual infants would show a stronger English than Spanish MMR in the late window, replicating previous EEG work (Rivera-Gaxiola *et al.*, 2005; Rivera-Gaxiola *et al.*, 2007; Rivera-Gaxiola *et al.*, 2012; Kuhl *et al.*, 2008). Based on previous infant MEG research on speech perception (Imada *et al.*, 2006; Kuhl *et al.*, 2014), we predicted that we would observe this effect in bilateral fronto-temporal and motor areas, but also expected to see the involvement of other brain regions. We hypothesized that the bilingual group would exhibit no differences between Spanish and English in the late time window, indicating their equal phonetic sensitivity to both languages. Second, we predicted that bilingual, but not monolingual, infants would show a

stronger early MMR in response to English compared to Spanish. The English contrast is acoustically more salient. However, in infants who have already transitioned from universal to native language specific speech discrimination (as we hypothesized to be the case for the monolingual group), this component typically decreases by 11 months of age. Because of the acoustic nature of the early response, we predicted that this effect would map to brain areas related to auditory processing (i.e. temporal cortex). Third, at the between-group level, we predicted stronger brain responses to Spanish sounds in the bilingual compared to the monolingual group, reflecting the fact that Spanish is a native language for bilinguals, but not monolinguals. We had no specific predictions as to the location of this effect.

Methods

Participants

Sixteen bilingual and 17 monolingual 11-month-old infants participated in the study. Participants were recruited through the University of Washington Subject Pool or flyers handed out at public libraries and community centers. For the bilingual infants, criteria for participation included regular exposure to English and Spanish through interactions with native speaker(s) from birth. For the monolingual group, participation criteria included no regular exposure to languages other than English. Language exposure was initially assessed over the phone. Parents were asked to assess the approximate amount of time their child spends listening to English, Spanish, and any other languages. For the bilingual group, families were invited to the laboratory only if the parents confirmed that their child hears a comparable amount of English and Spanish on a day-to-day basis, and is not exposed to any other languages. For the monolingual group, only infants whose parents confirmed no significant exposure to languages other than English were invited to participate. If the MEG procedure was successful, parents of bilingual and monolingual children were asked to fill out a language background questionnaire (details below).

The infants had no reported hearing or neurological problems, no history of ear infections, were born full-term (between 39 and 42 weeks gestational age), and had typical birth weight (between 6 and 10 lbs). Data from seven bilingual and five monolingual infants were rejected due to fussiness resulting in excessive noise (see Averaging and Rejection below). Four additional monolingual infants and one additional bilingual infant were excluded due to technical difficulties. The mean age

and standard deviation after rejection was as follows: 350 ± 24 days for eight bilingual infants (five girls), 347 ± 19 days for eight monolingual infants (four girls). Written informed consent in accordance with the Human Subjects Division at the University of Washington was obtained from the parents.

Socioeconomic status (SES)

The bilingual and the monolingual groups were matched on SES as measured by the Hollingshead scale (Hollingshead, 1975), the most widely used index of SES. Based on parental education, occupation, and marital status, the Hollingshead scale generates a number between 10 and 66. In the bilingual group, the SES scores ranged between 28 and 66 with a mean and standard deviation of 50.8 ± 15.2. In the monolingual group, the SES scores ranged between 25 to 61 with a mean and standard deviation of 48.8 ± 14.4. This means that the bilingual and monolingual participants came from fairly diverse SES backgrounds. While the average bilingual and monolingual SES scores are fairly high, some children were from families of high SES and some were from families of lower SES in both groups.

Language exposure assessment

If the MEG procedure was successful, parents were asked to fill out a language background questionnaire which included questions about exposure to English and other languages that infants received from each of the parents, siblings, extended family members, other adults living in the home, daycare providers, and radio or television. Six out of eight bilingual children who were included in the analyses heard English from one native-speaking parent and Spanish from the other native-speaking parent. Children's exposure to each language was about equal, with total exposure to Spanish ranging from 40% of the time to 65% of the time. One bilingual child had parents who spoke only English, but had a native Spanish-speaking nanny who had been watching him from birth, for 10–12 hours Monday–Friday. One bilingual child had parents who spoke only Spanish, but was enrolled full-time in an English-only daycare from the time she was 6 weeks old. None of the monolingual infants had any significant exposure to languages other than English.

Stimuli

Rivera-Gaxiola et al. (2005) created three consonant-vowel syllables that were used in a double oddball paradigm. The paradigm uses a phonetic unit common to English and Spanish as a standard sound, and two deviant sounds, one exclusive to English, and one exclusive to Spanish. The standard sound was a voiceless alveolar unaspirated stop, which is perceived as /da/ in English and as /ta/ in Spanish. The English deviant was a voiceless aspirated alveolar stop (/t^ha/). The Spanish deviant was a prevoiced alveolar stop (/da/). The stimuli were naturally produced by a female Spanish/English bilingual speaker. Their duration was 230 ms.

Experimental design

A double oddball paradigm was used. The standard sound was presented on 80% of the trials. Deviants appeared in a pseudo-random fashion (no more than three standards in a row could be presented) and were each presented on 10% of the trials. The stimulus onset asynchrony (SOA) was 1200 ms, consistent with previous infant studies using the same paradigm (Rivera-Gaxiola et al., 2005; Bosseler, Taulu, Pihko, Mäkelä, Imada et al., 2013; Kuhl et al., 2014).

Experimental procedure

To prepare the infants for testing, a lightweight nylon cap containing five head position estimation (HPI) coils was placed on the infants' heads. The locations of the HPI coils with respect to the head as well as additional points to determine the head surface were digitized with the Polhemus Fastrack digitizer (Colchester, VT, USA). The number of additional points varied but was typically in the range of 50–150. During recordings, HPI coils were activated continuously to generate alternating magnetic fields at frequencies between 80 and 321 Hz, and were used to track the infants' head positions during the recordings. Infants were placed in a custom-made adjustable chair that made it easy to adjust their height under the MEG sensor array for an optimal position for MEG recording (Figure 1). During recordings, an assistant waved toys silently in front of the infants to entertain them. A silent video played in the background throughout the 18-minute session. There were variable amounts of head movement throughout the recording sessions. The head position-tracking algorithm followed by mathematical head position standardization allowed us to compensate for movement and to reject epochs with excessive movement (see Averaging and Rejection below).

MEG measurement

MEG was recorded using a 306-channel Elekta Neuromag® system at the University of Washington's Institute

Figure 1 *Infant in MEG during measurement. A custom-made adjustable chair was used in order to adjust to the infant's height, placing the infant's head under the MEG sensor array for an optimal position during the recording.*

for Learning & Brain Sciences (I-LABS). The system contains 102 magnetometers and 204 gradiometers. The magnetometers measure the magnetic flux through their superconducting pickup loops while the gradiometers measure the spatial difference of the flux through two oppositely wound pickup loops, located side by side. The MEG sensors are not referenced and the convention is to plot the positive flux up and negative flux down. MEG signals were continuously recorded with analog band-pass filtering (0.03–650 Hz) and sampled at 2 KHz.

Preprocessing

MEG data were preprocessed using in-house Matlab software and MaxFilter (Elekta-Oy). All data were downsampled to 500 Hz, preprocessed using temporal signal space separation (tSSS) and head movement compensation transformed to the mean head position to minimize reconstruction error (Taulu, Kajola & Simola, 2004; Taulu & Hari, 2009). It was inevitable that there was some movement by the infant subject, the parent, or the assistant inside the magnetically shielded room, potentially causing movement-related magnetic interference. This rendered the application of tSSS very important for the study. For group-averaged waveform analyses, all subjects were transformed to mean head position of each group (bilinguals and monolinguals). Automatic cardiac artifact suppression with signal space projection (SSP) was applied, and further band-pass filtering (1–40 Hz).

Averaging and rejection

Data were epoched with respect to the onset of each stimulus (−100–700 ms) and averaged by condition (English deviant, Spanish deviant, standard before English deviant, and standard before Spanish deviant) for each bilingual and monolingual subject. Data were baseline corrected (−100–0 ms). Epochs were rejected when the infant's head position could not be located with the MaxFilter software, or when peak-to-peak amplitude was over 3 pT/cm (gradiometers) and 4 pT (magnetometers). The number of epochs was equalized across conditions by random uniform sampling to match the condition with the minimum number of epochs, and subjects with fewer than 75 epochs were rejected. Grand group averages were created by averaging all bilingual epoched data and all monolingual epoched data. The averaged sensor-level signals were inspected by comparing the waveforms after the stimulus onset to the baseline. The noise level of the evoked response was quantified by calculating the standard deviation of the MEG signal in the pre-stimulus baseline period. This procedure was performed separately for each MEG channel and the signal-to-noise ratio was determined by comparing the peak amplitude value of the post-stimulus response to the baseline standard deviation, i.e. the estimated noise level. Only subjects that had evoked response amplitudes at least twice as large as two times the standard deviation value of the baseline were included in the analysis to ensure reliable analysis.

Anatomical and forward modeling

A template source space made of both cortical surfaces (~20,484 source points with a median edge of 3 mm) and subcortical volumes (~6007 source points with a grid spacing of 5 mm) was constructed from the Freesurfer segmentation of an MRI of one 14-month-old subject. Forward modeling was done using the Boundary Element Method (BEM). The source space and the BEM surface were aligned and warped to optimally fit each subject's digitized head points using the head model's scalp surface. All modeling was done with in-house Matlab software, the Neuroelectromagnetic Source Analysis (NSA) Toolbox, and Freesurfer (Destrieux, Fischl, Dale & Halgren, 2010).

Source analysis

Source analysis was done with the sLORETA inverse algorithm (Pascual-Marqui, 2002) without dipole orientation constraints using gradiometers and magnetometers. The sLORETA activity estimate is similar to the minimum-L2-norm solution, except that it is normalized using the resolution matrix to achieve zero localization bias (i.e. the maximum of each estimated point-spread

function is located at the true location of each modeled dipole). The noise covariance was computed from the pre-stimulus time period ($-100–0$ ms) of all accepted trials. The SNR was assumed to be 3, and the noise regularization parameter was set to SNR^{-2} (i.e. 1/9). A global scaling of sLORETA values was performed on each subject based on the pre-stimulus period of all conditions. All statistical analyses focused on the English and Spanish MMR. The MMR at each source point and time point was calculated by taking the L2-norm (i.e. the square root of the sum of the squares) of the vector difference between the deviant and corresponding standard three-dimensional sLORETA activity vectors (i.e. in the x, y, and z directions). These were defined as the English MMR (native for both groups) and the Spanish MMR (native for the bilingual group, non-native for the monolingual group).

Statistical analyses

Group-level inferences at the cortical source level were conducted with spatiotemporal threshold-free cluster enhancement (TFCE), an extension of TFCE (Smith & Nichols, 2009) that uses spatiotemporal instead of spatial connectivity. Here, we used height and extent exponents of 2 and integrated from an alpha value of 1, for two separate time windows. Previous EEG studies have shown that the MMR in infants and young children consists of two distinct components signaling different neural processes. A recent analysis of each 20 ms interval between 100 ms and 600 ms post stimulus suggests that the early component extends up to 260 ms in young children (Shafer *et al.*, 2010). Other studies suggest that the late component typically spans the 250–450 ms time window (see Cheour *et al.*, 1998; Conboy & Kuhl, 2011; Shafer *et al.*, 2010). Based on these findings, the time windows of 100–260 and 260–460 were selected for statistical analyses of the early and late component, respectively.

TFCE involves a sequence of steps. First, the mean and variance multivariate time series are computed across subjects. These are then used to compute the *t*-value multivariate time series, which is then spatiotemporally enhanced resulting in the TFCE time series. Our TFCE approach enhances spatiotemporally connected sources (i.e. source regions that are locally connected in both space and time). Like cluster-level inference, TFCE increases the sensitivity of finding the true signal of spatiotemporally extended sources, but avoids having to select an arbitrary primary cluster-inducing threshold, thereby allowing inference to be made at the voxel level and single time sample level, albeit after the spatiotemporal enhancement. These voxelwise values represent the amount of cluster-like local spatial and temporal support.

Family-wise error rate (FWER) control was performed with permutation tests using the empirical permutation distribution of the maximum spatiotemporal TFCE statistic. This is equivalent to the procedure performed for spatial TFCE in fMRI research using the maximum spatial TFCE statistic, or for cluster-level inference using the maximum mass or cluster size statistic. For one-sample paired permutation tests, the sign of each subject's source activity difference was randomly assigned (i.e. a 2^N permutation sample space, where N is the number of subjects), whereas for two-sample permutation tests, the group labels were randomly assigned (i.e. 4000 Monte Carlo samples were taken from the $N!$ permutation sample space). FWER corrected *p*-values were obtained using inverse percentiles from the null permutation distribution of the maximum TFCE statistic.

Region of Interest (ROI) analysis

A bilateral prefrontal and orbitofrontal ROI was obtained by letting a seed vertex iteratively grow based on the mesh connectivity of the high-resolution template cortical surfaces in the left and right cortical surfaces separately. The areas selected for ROI analyses were carefully chosen to include brain regions known to be involved in executive function skills (Goldman-Rakic, 1996; Fuster, Bodner & Kroger, 2000). These areas have previously been shown to be active during language switching and selection in bilingual adults (Buchweitz & Prat, 2013; Price, Green & von Studnitz, 1999; Stocco & Prat, 2014; Hernandez, Dapretto, Mazziotta & Bookheimer, 2001). The scaled sLORETA activity of each subject was averaged across all source points belonging to the ROI. An ROI two-sample *t*-test was computed at each time sample within the two time windows of analyses (100–260 ms and 260–460 ms) to examine the between-group differences in neural activation for the Spanish and the English MMR. False discovery rate (FDR) control (*q*-value<0.05) was used to correct for multiple hypotheses testing across time in the two temporal windows separately (Genovese, Lazar & Nichols, 2002).

Results

Waveforms

Averaged waveforms for each group of eight infants, transformed to the mean head position of all accepted subjects, are shown in Figure 2. An example gradiometer pair from the right hemisphere temporal region is shown for each group. Standard and deviant sounds evoked
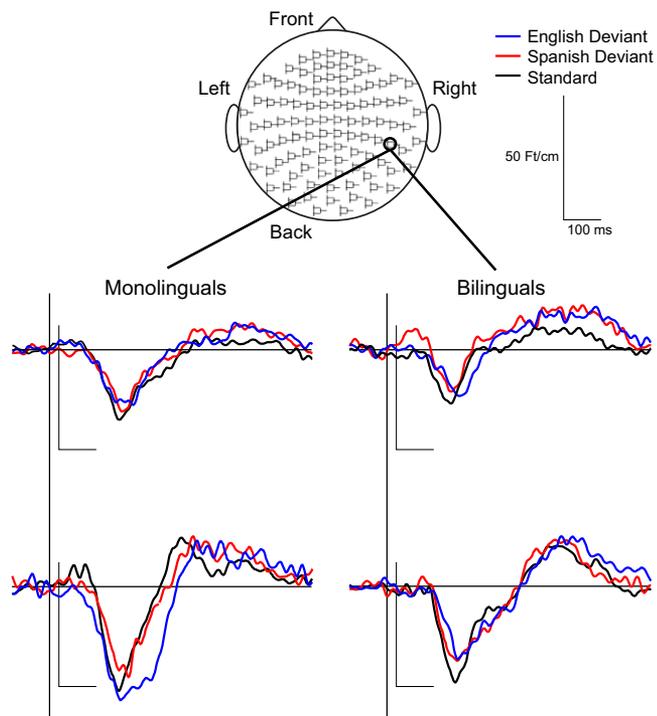
Figure 2 *Grand averaged responses (mean across all subjects included in analyses) in Monolinguals (left) and Bilinguals (right) from one example gradiometer pair over the right temporal area. Each gradiometer consists of two oppositely wound pickup loops and measures the spatial difference of the magnetic flux across these loops. The gradiometer reading is converted to a unit corresponding to the spatial gradient of the magnetic field (in femto Tesla) over the baseline (in centimeters) direction of the gradiometer, resulting in units of fT/cm. A pair of gradiometers is presented to show the difference of magnetic flux in two orthogonal directions. Responses to the English deviant (/t^ha/) and the Spanish deviant (/da/) are shown in blue and red, respectively. Responses to the predeviant standard (perceived as /da/ in English and as /ta/ in Spanish) are shown in black.*

magnetic fields in both hemispheres. The responses in monolinguals and bilinguals consisted of a biphasic waveform, in agreement with previous electroencephalography (EEG) studies with monolingual and bilingual infants that used the same stimuli (Conboy & Kuhl, 2011; Garcia-Sierra *et al.*, 2011; Rivera-Gaxiola *et al.*, 2005).

Threshold free cluster enhancement

Statistical analyses using spatiotemporal TFCE were conducted in two time windows (an early window of 100–260 ms post stimulus and a late, window of 260–460 ms post stimulus), at the within- and between-group levels. All reported *p*-values are the minimum

corrected *p*-values for all source points across either the early or the late window.

Within group analyses

Within each group, we examined the differences in neural activation for the Spanish and the English MMR.

Monolinguals. In the early time window, the difference between the English MMR and the Spanish MMR was not significant ($p = .15$). In the late time window, the English MMR was significantly larger than the Spanish MMR ($p = .004$). This pattern of results replicates previous EEG studies (Kuhl *et al.*, 2008; Rivera-Gaxiola *et al.*, 2005), and indicates phonetic sensitivity to English and a lack of phonetic sensitivity to Spanish. As shown in Figure 3, the differences between the Spanish and the English MMR were widespread over the right hemisphere superior and medial temporal gyrus, superior temporal sulcus, inferior frontal gyrus, ventromedial prefrontal cortex, orbitofrontal cortex, dorsolateral prefrontal cortex, and the sensori-motor speech area. Left frontal and orbitofrontal areas were also involved, but to a lesser extent.

Bilinguals. The bilingual group showed the opposite pattern of results. In the early time window, the English MMR was significantly larger than the Spanish MMR ($p = .04$). As shown in Figure 4, this effect mapped predominantly to the left superior and middle temporal gyrus, the left superior temporal sulcus, the left sensori-motor speech area, and the parahippocampal gyrus. In the late time window the differences between the English and the Spanish MMR were not significant ($p = .29$).

Between-group analyses

We examined the differences between monolingual and bilingual infants in neural activation separately for the English MMR and for the Spanish MMR.

English MMR. The two groups did not differ in their neural activation for the English MMR in the early ($p = .81$) or in the late ($p = .63$) time window. These results indicate that the two groups are equally sensitive to English.

Spanish MMR. In the early time window, the bilingual group showed a stronger neural response compared to the monolingual group ($p = .04$). In the late time window, the difference between the two groups was marginally significant ($p = .08$), again in the direction of
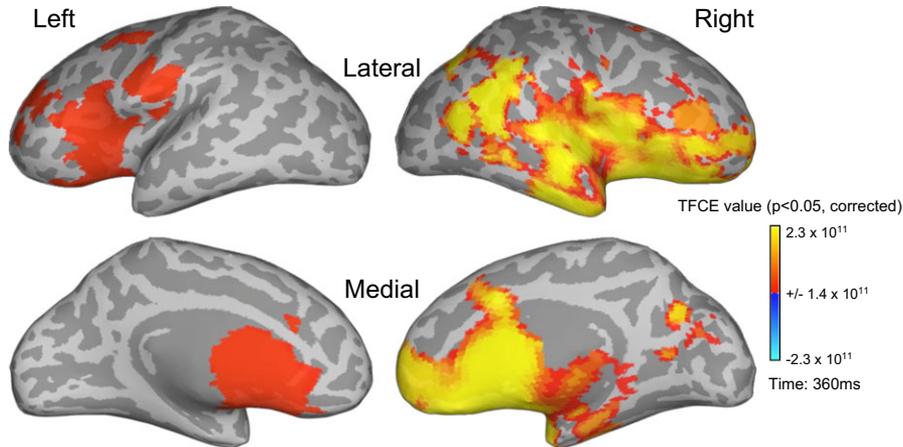
Figure 3 *English (native) MMR vs. Spanish (non-native) MMR in the monolingual group at 360 ms post stimulus. Positive TFCE values (areas shown in yellow and red) indicate locations where the English MMR was significantly stronger than the Spanish MMR. Negative TFCE values (blue color) indicate locations where the Spanish MMR is significantly stronger than the English MMR (not observed). A movie of this effect across the entire time window is included in supporting materials.*
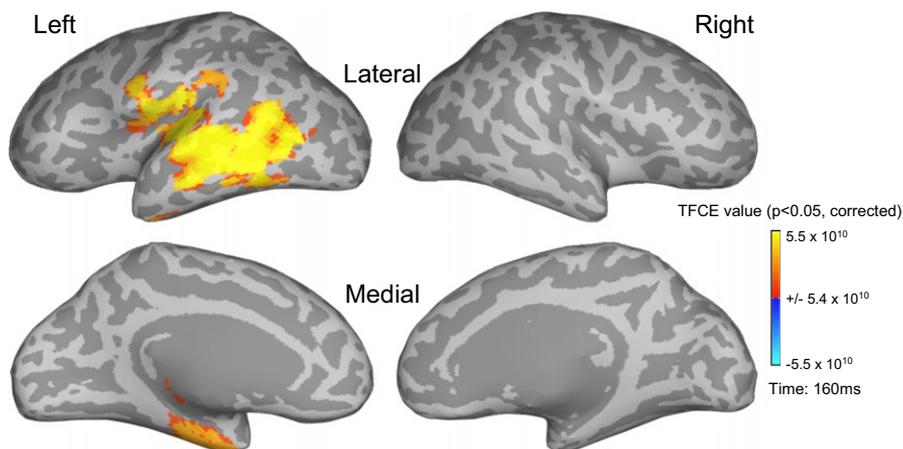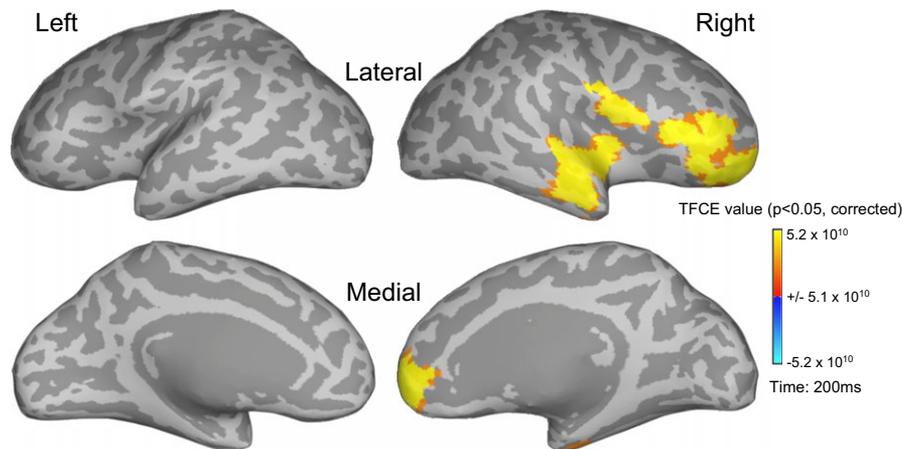

Figure 4 *English MMR vs. Spanish MMR in the bilingual group at 160 ms post stimulus. Positive TFCE values (areas shown in yellow and orange) indicate locations where the English MMR was significantly stronger than the Spanish MMR. Negative TFCE values (blue color) indicate locations where the Spanish MMR is significantly stronger than the English MMR (not observed). A movie of this effect across the entire time window is included in supporting materials.*

bilinguals having a stronger response compared to the monolinguals. These results indicate that the bilingual group is more sensitive to Spanish than the monolingual group. As shown in Figure 5, the above-described significant between-group differences mapped onto the right anterior superior and middle temporal gyrus, inferior frontal cortex, sensori-motor speech area, frontal pole, dorsolateral and ventrolateral prefrontal cortex and orbitofrontal cortex. Because prefrontal and orbito-frontal areas are strongly implicated in executive function skills that are known to be enhanced in bilinguals, we further explored this result with a follow-up between-group analysis in a bilateral prefrontal region of interest (ROI).

Region of Interest (ROI) analysis

In a bilateral prefrontal ROI, we examined between-group differences in neural activation for the English and the Spanish MMR in the early and late time windows. For the English MMR, no significant between-group differences were observed. For the Spanish MMR, the bilingual group again showed significantly stronger neural activity than the monolingual group ($q < 0.05$).

Figure 5 *Bilingual vs. monolingual responses to Spanish MMR at 200 ms post stimulus. Positive TFCE values (areas shown in yellow and orange) indicate locations where bilinguals exhibited significantly stronger Spanish MMR responses than the monolinguals. Negative TFCE values (blue color) indicate locations where the monolinguals exhibited significantly stronger Spanish MMR responses than the bilinguals (not observed). A movie of this effect across the entire time window is included in supporting materials.*

As indicated in Figure 6, significant differences were found in both time windows.

Discussion

Speech perception begins as a universal process, wherein infants initially discriminate all phonetic contrasts in the world's languages, and then, through social interaction and consistent exposure to speech, become specialized in perceiving the sounds of native language (Best & McRoberts, 2003; Kuhl *et al.*, 2008; Werker & Hensch, 2015; Werker & Tees, 1984). Using whole head MEG, the present study compared the neural underpinnings of phonetic narrowing in Spanish-English bilingual and English monolingual 11-month-olds. In a double oddball paradigm, differences between the English and the Spanish MMR were examined at the within- and between-group levels in an early and a late time window. The participating infants were 11 months old. At this age, monolingual infants are known to have already transitioned from universal to native language specific phonetic processing (Rivera-Gaxiola *et al.*, 2005; Rivera-Gaxiola *et al.*, 2012; Kuhl *et al.*, 2008; Imada *et al.*, 2006; Kuhl *et al.*, 2014; Best, McRoberts, & Goodell, 2001; Polka, & Werker, 1994). Using a novel method, we sought to replicate this finding, and examined whether and how the bilingual infants may differ from their monolingual peers. The monolingual group was hypothesized to show neural evidence of phonetic narrowing and selective sensitivity to English in the late analysis window. The bilingual group, on the other hand, was

hypothesized to show equal sensitivity to both languages in the late analysis window, and increased sensitivity to English, the more salient contrast, in the early analysis window.

The MEG results support our hypotheses. In the late, but not in the early, window the monolingual group showed a significantly stronger English than Spanish MMR. This is in agreement with results of previous EEG studies, which show that between 6 and 11 months of age, as infants transition from universal to native language specific speech discrimination, the late (phonetic) MMR shows a selective increase to native language sounds, while the early (acoustic) MMR component decreases. This transition has been termed 'native language neural commitment' (NLNC; Kuhl, 2004), and has been replicated in English- and Spanish-learning monolingual children between 6 and 11 months of age (Rivera-Gaxiola *et al.*, 2005; Rivera-Gaxiola *et al.*, 2012; Kuhl *et al.*, 2014). The NLNC model argues that, between 6 and 11 months of age, learning of the acoustic and statistical regularities of ambient speech alters the responsiveness of the infant brain. Specifically, as infants experience a sufficient amount of native language input, processing becomes automatic, as indexed by a decrease in lower-level (acoustic) sound analyses and an increase in higher-level (phonetic) sound analysis. Our current results advance previous EEG findings by identifying the brain areas involved in this critical transition. Our findings suggest the involvement of a wide range of bilateral brain areas, with a significant right hemisphere bias. A number of studies with adult participants indicate that both hemispheres participate in
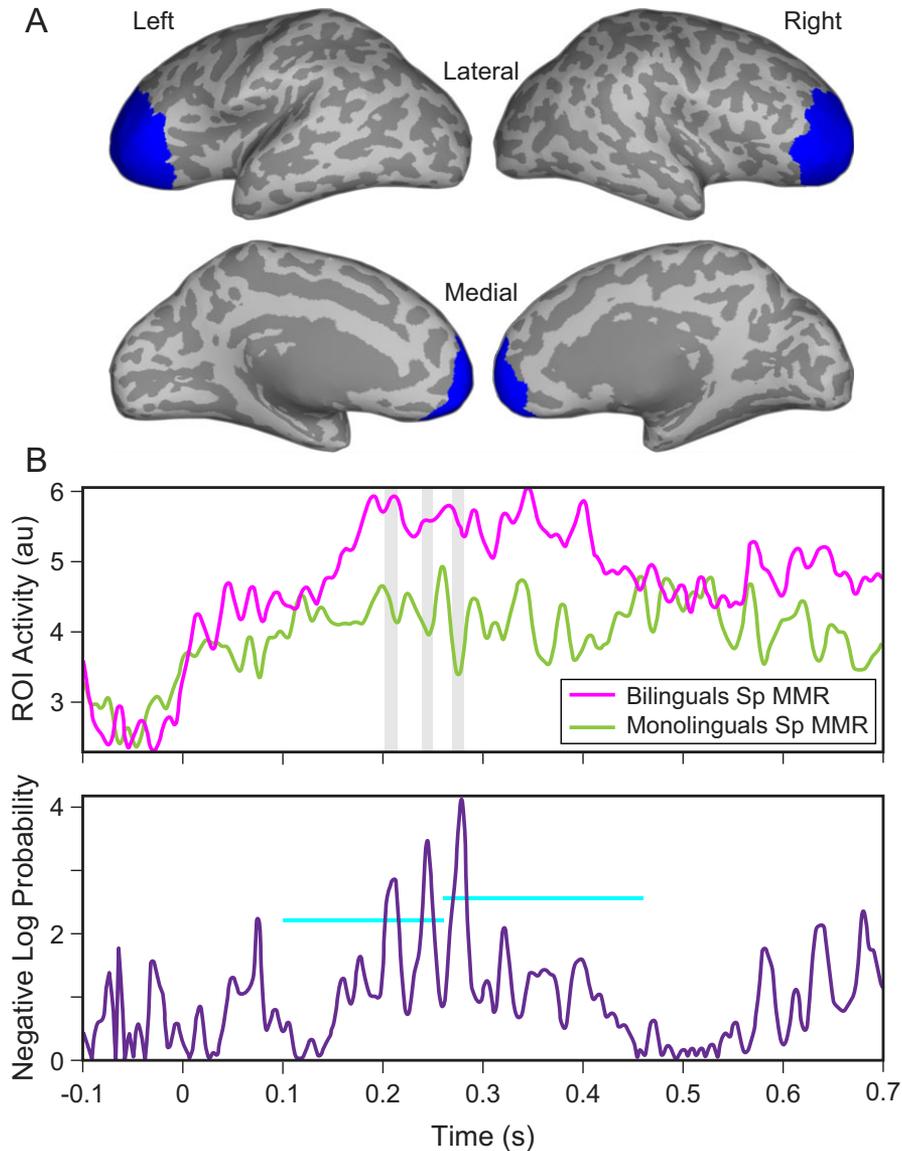
Figure 6   *A: Brain areas selected for ROI analysis are shown in blue. B (top panel): Mean ROI activity waveforms for the Spanish MMR are shown for the bilingual (pink) and monolingual (green) groups. Bilinguals showed significantly greater activity at three time ranges, shown as shaded grey bands behind the waveforms. Two significant time ranges occurred in the acoustic window, and one in the phonetic window. B (bottom panel): Negative log p-value waveforms. Blue lines indicate the two temporal windows used for separate FDR control and the two significance thresholds obtained for the two windows at q < 0.05.*

speech perception (Kuuluvainen, Nevalainen, Sorokin, Mittag, Partanen *et al*., 2014; Shtyrov, Kujala, Palva, Ilmoniemi & Näätänen, 2000; Shtyrov, Pihko & Pulvermüller, 2005), and it has been proposed that a semantically meaningful lexical context may be a prerequisite for left-lateralized activity in response to consonant or syllable changes (Shtyrov *et al*., 2000; Shtyrov *et al*., 2005). In our paradigm, syllables were presented in a stream, without any context. Furthermore, young preverbal infants do not yet have a large

and reliable lexicon to help them contextualize sounds in a stream of syllables, which could further explain the observed right hemisphere bias. Previous EEG research suggests that the left hemisphere specialization for speech emerges slowly over development, as the size and efficiency of the lexicon increases (Mills, Plunkett, Prat & Schafer, 2005). The rightward asymmetry that we observed could also arise as a result of infants' increased sensitivity to prosodic features of speech. To this end, infant-directed speech, which consists of exaggerated

prosodic contours, is known to be tightly coupled to advanced development of speech in the first years of life (Ramírez-Esparza *et al*., 2014). Future longitudinal and cross-sectional studies should explore when and how the neural processing of phonemes becomes more left lateralized over development.

In contrast to the monolingual group, the bilingual group showed no differences between the English and the Spanish MMR in the late MMR window. In the early window, however, they showed a stronger English compared to Spanish MMR. These results indicate that the bilingual infants neurally discriminate between the two languages, but only at the acoustic level, as signaled by the early MMR component. An equally strong late MMR response to Spanish and English can be interpreted as signaling equal phonetic sensitivity to both languages, as one would predict based on infants' dual language exposure. A stronger early MMR to English likely reflects the fact that the English contrast is perceptually more salient as it involves aspiration (Garcia-Sierra *et al*., 2011). As previously suggested, the early MMR component reflects a less specialized, universal acoustic detection process that plays a prominent role in the early stages of speech discrimination, but then decreases over time as processing becomes more automatic (Shafer *et al*., 2010; Rivera-Gaxiola *et al*., 2005). Confirming its lower-level, acoustic nature, the observed differences mapped onto left hemisphere superior temporal cortex, the seat of auditory processing. The involvement of these areas in speech processing has previously been observed in infants and adults (Kuhl *et al*., 2014; Price, Wise, Warburton, Moore, Howard *et al*., 1996). Note that although the English voicing contrast is highly salient, no differences in the acoustic MMR were observed in the monolingual group. We interpret these results as confirming our previous finding that the monolingual, but not the bilingual, infants have transitioned from lower-level (acoustic) to higher-level (phonetic) discrimination.

The transition to native language specific listening at the end of the first year of life is known to predict subsequent milestones in language acquisition. For example, monolingual infants who show a strong late (phonetic) MMR response to native language sounds at 11 months of age exhibit rapid advances in the acquisition of words and sentences (Kuhl *et al*., 2008). By contrast, an enhanced or prolonged acoustic MMR component has been associated with poorer language skills at 2 or 3 years of age (Friedrich *et al*., 2009; Weber, Hahne, Friedrich & Friederici, 2004). The current results suggest that an extended acoustic sound analysis may also be part of the typical developmental trajectory in bilingual infants. However, we emphasize that this does not mean that bilingual language acquisition is 'delayed' or 'deviant' in any way. Instead, we propose that remaining in the universal listening stage indicates a highly adaptive brain response, and a distinct advantage in a situation when two languages are being mapped simultaneously.

The results of the present study, like previous EEG work from our laboratory (Garcia-Sierra *et al*., 2011), suggest that the neural encoding of two languages takes a longer time compared to the encoding of a single language. Given the continuity in language development, an extended acoustic sound analysis phase that we observed in the bilingual group may be related to the well-documented gap between bilingual and monolingual children on measures of lexical and grammatical growth (Oller & Eilers, 2002; Mahon & Crutchley, 2006; Portocarrero, Burright & Donovick, 2007). However, it is important to emphasize that bilingual infants and children only lag behind their monolingual peers when a single language is considered; on measures that combine both languages, bilinguals perform equally to or better than age-matched monolingual peers (Pearson, Fernández & Oller, 1993; Hoff, Core, Place, Rumiche, Señor *et al*., 2012). The neural differences between bilingual and monolingual infants that we observed here, although significant and non-trivial, should also be interpreted in light of the fact that the bilingual group is simultaneously encoding an additional repertoire of phonemes. With this important distinction in mind, the observed similarities between the two groups are perhaps even more impressive than the differences. For example, we found no significant between-group differences in either acoustic or phonetic discrimination of English. Thus, despite still showing evidence of acoustic discrimination between English and Spanish, the bilingual group, when directly compared to the monolingual group, does not lag behind on the neural encoding of English. Most crucially, the bilingual group is simultaneously also encoding the sounds of Spanish. In a direct between-group comparison, the bilingual group showed a stronger Spanish MMR in the acoustic window, and a marginally stronger Spanish MMR in the phonetic window, suggesting that they are well on their way to encoding the phonetic categories for Spanish sounds. Together, these results suggest that the encoding of two languages does take a longer time compared to the encoding of a single language; however, it does not take twice as long.

Most importantly, our results support the notion that, besides the obvious benefit of acquiring another language, exposure to two languages in infancy may be related to other cognitive advantages. Specifically, we found evidence that bilingual, but not monolingual,

brain responses extend into prefrontal and orbitofrontal cortex, areas known to be involved in executive functioning. Enhancements in executive function skills have been consistently shown in bilinguals throughout the lifespan. For example, 7- and 12-month-old infants from bilingual families have been shown to be more flexible learners of speech structures (Kovacs & Mehler, 2009a, 2009b). Bilingual toddlers exhibit a prolonged period of flexibility in their interpretation of potential word forms (Graf Estes & Hay, 2015). In bilingual children, advantages have been shown on metalinguistic tasks (Cromdal, 1999), switching tasks (Bialystok & Martin, 2004), Stroop tasks (Martin-Rhee & Bialystok, 2008), and theory of mind tasks (Goetz, 2003). Bilingual adults consistently outperform monolinguals on conflict resolution and Stroop tasks (Bialystok, Craik & Luk, 2008). While it is important to acknowledge that some studies have failed to find such enhancements (for example, Paap & Greenberg, 2013), the bulk of research is consistent with the idea that simultaneous exposure to two languages results in advancements in executive function skills in children and adults, and translates into protective effects against cognitive decline with aging (Bialystok, Craik & Freedman, 2007; for review see Bialystok, 2011).

Enhancements in executive functioning in bilinguals are thought to arise as a result of a constant need to resolve conflict at the linguistic level, which then boosts the ability to resolve non-linguistic conflict (Bialystok, 2009). Neuroimaging evidence with adult participants shows that prefrontal and orbitofrontal regions are activated when bilinguals are selecting or switching languages (Hernandez *et al.*, 2001; Price *et al.*, 1999; Stocco & Prat, 2014). Anatomical studies indicate a series of connections between prefrontal cortex, anterior cingulate, and orbitofrontal cortex, all of which are known to be involved in language processing in bilinguals (Botvinick, Braver, Barch, Carter & Cohen, 2001; Bunge, Hazeltine, Scanlon, Rosen & Gabrieli, 2002). The organization of these networks is such that the constant need to manage attention between the two languages enhances bilingual executive control (Abutalebi & Green, 2007). The bilingual infants studied here, when directly compared to monolingual infants, showed significantly stronger Spanish MMRs in a region of interest that was selected to include areas known to be involved in executive functioning: namely, the bilateral prefrontal and orbitofrontal cortex. These responses may be related to language switching and selection, as has previously been shown in bilingual adults (Hernandez *et al.*, 2001; Price *et al.*, 1999; Stocco & Prat, 2014). Interestingly, between-group differences in areas related to executive functioning were observed despite the fact that the task involved merely listening to a stream of syllables from both languages, at an age when infants are just beginning to produce their first words. Interestingly, executive function processes are among the later cognitive skills to emerge in development, which is typically attributed to the protracted development of the prefrontal lobes (Casey, Tottenham, Liston & Durston, 2005). The current results suggest, however, that simultaneous exposure to two languages and the constant need to resolve linguistic conflict in infancy might boost the activity of these brain areas during a time in development when other activities that strengthen executive function skills may not yet be frequently practiced.

Taken together, the results of the present study indicate that, by 11 months of age, the infant brain shows neural sensitivity to the language or languages present in the environment: the monolingual brain is committed to one language, and the bilingual brain shows sensitivity to two. The results suggest that the dual sensitivity of the bilingual brain may be achieved by a slower transition from acoustic to phonetic sound analysis. It is important to acknowledge that the current results are based on a single time point in development. It is, of course, possible and likely that the differences between bilingual and monolingual speech processing change over time, and longitudinal studies are critical to assess how monolingual and bilingual children continue their language-learning trajectory. Another variable that requires further study is the role of SES on bilingual language acquisition. In the present study, the monolingual and the bilingual groups were carefully matched on SES, allowing us to make between-group comparisons. While participating children came from families of varying SES backgrounds, the average SES was fairly high, unlike in some other studies with bilingual infants (for example, Garcia-Sierra *et al.*, 2011). Future brain and behavioral studies should examine the interaction between SES and bilingualism in greater detail. The results of the present study suggest that splitting the time between two languages in early infancy results in an adaptive and advantageous neural response to a greater variability in language input. While remaining in a state of heightened neural plasticity may cause slower growth of each of the languages, it also leads to a heightened sensitivity of the prefrontal cortex in responding to speech sounds, which may be related to more efficient cognitive resources for performing executive function tasks. Thus, the experience of bilingualism appears to alter not only the scope of language acquisition and use, but also a broader scope of cognitive processing from a very young age onward.

Acknowledgements

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Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article:

Video S1. Monolinguals: English MMR vs. Spanish MMR between 260 and 460 ms post stimulus. Areas shown in yellow and red indicate locations where the English MMR was significantly stronger than the Spanish MMR.

Video S2. Bilinguals: English MMR vs. Spanish MMR between 100 and 260 ms post stimulus. Areas shown in yellow and red indicate locations where the English MMR was significantly stronger than the Spanish MMR.

Video S3. Spanish MMR in bilinguals vs. monolinguals between 100 and 260 ms post stimulus. Areas shown in yellow and red indicate locations where bilinguals exhibited significantly stronger Spanish MMR responses than the monolinguals.