AN INVESTIGATION OF EARLY PHONETIC PROCESSING IN MONOLINGUAL AND BILINGUAL INFANTS USING NEW FUNCTIONAL NEAR-INFRARED SPECTROSCOPY (FNIRS).

By

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A thesis submitted in conformity with the requirements for the degree of Master’s of Arts

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PHONETIC DISCRIMINATION IN THE FIRST AND SECOND HALF-YEAR OF LIFE: AN INVESTIGATION OF MONOLINGUAL AND BILINGUAL INFANTS USING EVENT-RELATED FUNCTIONAL NEAR-INFRARED SPECTROSCOPY (FNIRS)

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Abstract

How do infants learn the sounds of their native language? Do they need to use general-auditory or language-specific mechanisms to make sense of the distributional nature of their phonetic input? To answer this question, this study investigated the neural correlates of phonetic discrimination in monolingual and bilingual infants (2-6 and 10-14 months) and adults using a new lens afforded by functional Near-Infrared Spectroscopy (fNIRS) neuroimaging. All participants heard syllables phonetically contrastive in their native English and Hindi (non-native) in an oddball paradigm while being imaged with fNIRS. Age comparisons of infant brain activation in multiple sites revealed that left Broca’s area showed a developmental decline in response to native-language experience only. Bilateral STG showed robust recruitment at both ages in response to both stimulus languages. These findings were robust across monolinguals and bilinguals. Together, the results suggest that all infants use neural tissue predisposed for linguistic-phonetic processing in early life.
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As infants, we begin life able to hear linguistic distinctions between sounds (called phonetic contrasts) in any of the world’s languages (e.g. Werker & Tees, 1984; Kuhl et al., 2006; Polka & Werker, 1994; Best, McRoberts & Silver-Isenstadt, 1995; Best, McRoberts & Sithole, 1988; Burns, Yoshida, Hill & Werker, 2007; Eimas, Siqueland, Jusczyk & Vigorito, 1971; Baker, Golinkoff & Petitto, 2006). The fact that infants lose this universal capacity after nearly one year of age and become sensitive to phonetic distinctions only in their native-language has led to much controversy over the biological basis of this capacity. On the one hand, evidence that infants perceive distinct phonetic sounds that cross category (phoneme) boundaries (such as from /ba/ to /pa/) but cannot perceive linguistic/phonetic sounds that fall within phoneme boundaries has led some to suggest that infants are born with brain mechanisms uniquely dedicated to processing language. On the other hand, evidence that the same capacity can be shown to occur in primates has led others to suggest that the biological basis is auditory. On the whole, research studying phonetic discrimination in infants has been done using behavioural methods. Using these methods on monolingual and bilingual infants, evidence has been furnished in support of both a general-auditory and a language-specific account of phonetic discrimination. In order to resolve this controversy we conducted neuroimaging studies examining the brains of young and older monolingual and bilingual infants as they listened to language sounds contrastive in their native and non-native language using functional Near-Infrared Spectroscopy (fNIRS), a state-of-the-art imaging system like functional Magnetic Resonance Imaging (fMRI), but one that tolerates movement and can be used with very young infants. Through this, we hoped to discover first time evidence of the neural tissue that allows native-language phonetic development in early infancy.
Over the course of several decades, researchers have come to emphasize the importance of domain-general auditory learning in the development of an infant’s native-language phonetic categories (Kuhl et al., 2008; Sundara, Polka & Molnar, 2008; Maye, Weiss & Aslin, 2008; Fennell, Heinlein & Werker, 2007; Werker et al., 2007; Sebastián-Gallés & Bosch, in press). After early studies suggesting that infants are born with neural mechanisms enabling linguistic-phonetic discrimination (Eimas et al., 1971; Eimas, 1975), studies were run showing that the same capacity could also be found in Macaque monkeys (Kuhl & Padden, 1983; Kuhl & Padden, 1982). Kuhl and Padden (1983) took this result to mean that the early infant capacity for discriminating between phonetic units was probably based on broad auditory guidelines constraining audition in humans and animals, and not due to speech-specific mechanisms found only in humans. Later research showed these auditory constraints to be modified by language experience, with infants showing evidence of having established native-language vowel phonology as early as 6 months of age (Kuhl, Williams, Lacerda, Stevens & Lindblom, 1992). With the establishment of native-language vowel phonology, infants were shown to fail at the discrimination of non-native vowel contrasts (e.g. Polka & Werker, 1994). Having established their native-language consonant phonology, infants around 10-14 months were shown to fail at the discrimination of non-native consonant contrasts (e.g. Werker & Tees, 1984).

Following from the above studies, contemporary researchers working within this auditory-general model have come to suggest that the specific mechanism underlying phonetic learning in infants is one that tracks statistical regularities in the infant’s incoming distributional speech input (Maye, Werker & Gerken, 2002; Maye, Weiss & Aslin, 2008). According to the statistical learning account, infants have to gather sufficient phonetic information from parental language input in order to construct phonetic categories that serve to aid word learning. These
phonetic categories are thought to be distributions containing the many variants of each native-language phonetic unit culled from his or her language environment (Werker et al., 2007). It is only when the distributions representing native-language phonetic units have stabilized that the infant is said to be in a mode of native-language phonetic perception. Once achieved, infants then become less sensitive to phonetic distinctions in the languages to which they had not been exposed.

In the above accounts of statistical learning, predictions were not made about the progression of brain activity throughout infancy, rather they were made about behaviour. By contrast, other researchers such as Kuhl, Conboy, Padden, Nelson and Pruitt (2005) use behavioural study of phonetic discrimination to form predictions about the brain. They hypothesized that infants showing evidence of being more sensitive to non-native phonetic distinctions are proceeding slower in their language development than infants who are less so. Furthermore, they hypothesized that these infants have neural circuitry that is less ‘committed’ to the statistical properties of the phonetic units in their native-language. They found that infants who were better at non-native language phonetic discrimination at seven months of age showed worse progress on lexical and grammatical measures at 18 and 24 months of age. Following from these results, the authors suggested that infants must progress towards a state where they must be responsive, on both brain and behaviour levels, to their native-language exclusively if they are to develop to a deeper level of native-language processing. Other studies have found that later language ability is indeed predictable from early electrical measures of brain activity during phonetic discrimination. They had indeed found that infants, whose electrical brain response showed relatively high sensitivity to native-language contrasts, and lower sensitivity to non-native language contrasts, had better language ability up to 30 months of age (Imada et al., 2006;
Rivera-Gaxiola, Pereyra & Kuhl, 2005; Rivera-Gaxiola, Klarman, Garcia-Sierra & Kuhl, 2005). Taken alone, the results of these studies impute high value on to inductive statistical learning of distributional phonetic input as the cornerstone of later language development. However, as will be discussed below, infants deductively parse their language input with mechanisms other than just statistical learning.

In contrast to the above statistical learning account, is the pattern recognition account. Several lines of inquiry into language acquisition have pointed to the possibility that phonetic development for human infants is guided primarily by a sensitivity to highly specific rhythmic-temporal patterns in the input, initially corresponding in size and duration to phonetic-syllabic units, but expanding over the first year of life (c.f. Petitto & Marentette, 1991). It is this mechanism, hypothesized to be unique to language processing and distinct from other auditory processing, which permits infants to find salient, attend to, and segment core phonetic units (and their categorical groupings) from the constantly varying linguistic stream around them (Petitto, 1997; Baker, Idsardi, Golinkoff, & Petitto, 2005; Baker, Michnick-Golinkoff, & Petitto, 2006; Petitto, 2007; for corroborating accounts see Tallal, 1993; Benasich & Tallal, 2002; Benasich, Thomas, Choudhury & Leppänen, 2001; Marcus, 2000; Marcus, Vijayan, Bandi Rao & Vishton, 1999; Gomez & Gerken, 1999; Zatorre & Belin, 2001).

Early support for this pattern recognition account came from research showing that, like hearing infants, deaf infants recreate the unique temporal and hierarchical groupings and rhythmical characteristics of natural language structure by babbling. Unlike hearing infants, they engage in what was called ‘manual babbling’ (Petitto & Marentette, 1991). This provided important evidence that phonetic development in infancy could progress through means in addition to the exclusive reliance on statistical regularities in auditory speech input.
Furthermore, it was shown that young hearing infants, who had never been exposed to sign language, can nonetheless categorically discriminate soundless phonetic units according to sign-phonetic/phonemic boundaries, while older hearing infants could not. Though sign-phonetic units are soundless, the hearing infants showed the identical developmental attenuation trajectory as found in the speech literature (Baker, Golinkoff, and Petitto, 2006). These studies shifted the focus away from the strictly auditory understanding of phonetic development, and towards one that understood the infant as starting phonetic development with important language-learning mechanisms already in place.

The same mechanism that contributes to infant understanding of the language input on the syllable level may also contribute to understanding it on a grammatical level. Importantly, if the learning of grammar rules is subserved by statistical learning, then infants should need repeated experience with the grammatical ordering of particular words (Marcus, 2000). However, neonatal infants have been shown to rapidly recognize short, immediately repetitive, patterns of syllables representing artificial grammars as early as soon after birth (Gervain, Macagno, Cogoi, Pena & Mehler, 2008). Later on, at the age of seven and 12 month old, infants can learn abstract arbitrary grammar rules from short exposure to nonsense syllable sentences (Marcus et al., 1999; Gomez & Gerken, 1999). These older infant studies both used test stimuli that were related only in grammar to the habituation stimuli, suggesting to the authors that infants were able to quickly detect the relevant grammatical rules, and did not simply track statistical regularities of the auditory speech input, as would be argued by Saffran, Johnson, Aslin and Newport (1999).

While pointing to important mechanisms underlying language development, the above studies build plausible accounts for both the auditory-general and language-specific biological
basis for phonetic discrimination. Furthermore, all of the above studies are based on the study of monolingual infants. For a fuller account of the extent of the human infant’s ability to learn language, the case of bilingual infants must be turned to.

*Phonetic Development in Bilinguals*

If phonetic learning in infancy is so important to language performance later on, then what does this mean for infants who are born into bilingual circumstances? Studies on bilingualism and phonetic learning in infancy are sparse and controversial. On the one hand, evidence has been found that bilingual phonetic learning keeps up with its monolingual counterpart (Burns, Yoshida, Hill & Werker, 2007; Bosch & Sebastián-Gallés, 2001; Sundara, et al., 2008; Norton, Baker & Petitto, 2003; see also Petitto, Katerelos, et al., (2001) showing that bilinguals attain classic language milestones in each of their languages on the same time table and on the overall identical time table as monolingual children). On the other hand, evidence has been provided that bilingual phonetic learning lags behind its monolingual counterpart (Bosch & Sebastián-Gallés, 2003; Werker & Fennell, 2004; Sundara & Polka, 2006). According to Kuhl (2007), delays in bilingual phonetic learning could be attributable to them taking longer than monolinguals to stabilize the distributions representing native-language phonetic units in each of their languages.

*Beyond Behavioural Studies: New Advances from Neuroimaging*

Behavioural studies on phonetic discrimination in infants do not provide clarity as to whether it arises from general auditory or linguistic processes because infants could in fact be discriminating based on the general perceptual features of phonetic contrasts yet appear to be linguistically discriminating (Baker, Golinkoff and Petitto, 2006). For this reason, neuroimaging studies can help identify what specific brain processes are engaged during phonetic
discrimination. It promises exciting possibilities to determine the nature and development of phonetic learning in infants.

Several decades of neuroimaging results of phonetic processing in adults have shown the left Superior Temporal Gyrus (STG) to be the brain area that responds involuntarily to phonetic distinctions that are phonemic in the subjects’ native language (Celsis et al., 1998; Joanisse et al., 2007; Zevin & McCandliss, 2005; Hutchison, Blumstein & Myers, 2008; Burton, Small & Blumstein, 2000; Petitto et al., 2000). It has also shown in adults that the left Inferior Frontal Gyrus (IFG), a brain area considered to subserve morphosyntactic processing (e.g. Kovelman, Baker & Petitto, 2008) is also involved in speech discrimination (Burton et al., 2000; Golestani & Zatorre, 2004; Blumstein, Myers & Rissman, 2005; Strand, Forssberg, Klinberg & Norrelgen, 2008; Meister, Wilson, Deblieck, Wu & Iacoboni, 2007; Iacoboni, 2008).

Numerous studies of infants using functional Near-Infrared Spectroscopy (fNIRS) have localized sensitivity to speech perception and phonetic distinctions in brain sites within the left temporal area at large (Minagawa-Kawai et al., 2007; Pena et al., 2003; Gervain et al., 2008) and more specifically in the left STG (Dehaene-Lambertz, Dehaene & Hertz-Pannier, 2002; Petitto, 2008; Petitto, Baker, Baird, Kovelman & Norton, 2004). The processing of prosodic information in infants has been localized in the right temporal and temporoparietal areas, also similar to what has been found in the adult literature (Fumitaka, Watanabe, Nakano & Taga, 2007). One study of infants using MEG found significant left Superior Temporal area activation in response to phonetic change as early as five days after birth (Imada et al., 2006). In infants at six and twelve months of age Imada and colleagues also found significant Broca’s area activation time-yoked to the response in the Superior Temporal area. The authors suggested that this Broca’s area activation arrives in tandem with the onset of canonical babbling (cf. Petitto & Marentette, 1991;
Petitto, 1997; Petitto, 2000; Petitto, Zatorre, Gauna, Nikelski, Dostie & Evans, 2000; Holowka & Petitto, 2002; Petitto, Holowka, Sergio, Levy & Ostry, 2004). These studies have revealed remarkable neural organization for language processing so early in life.

As of yet, no studies have been published to date on the neural correlates of phonetic development in infants learning two languages from birth. This is especially surprising given the strong predictions that are made about bilingual phonetic development from a statistical learning perspective (Kuhl, 2007; Kuhl et al., 2008; Kuhl & Rivera-Gaxiola, 2008; Rivera-Gaxiola, Klarman, Garcia-Sierra & Kuhl, 2005). While the studies that have been done have provided an increasingly close look at language processing in the infant brain, they have not provided adequate resolution on whether an exclusive statistical learning account or a pattern-recognition account sufficiently explains early phonetic development. Given the highly complex, and potentially confusing language environment of bilingual infants, examining brain activity in this group should help provide an answer to the looming conflict concerning the biological basis of phonetic discrimination.

Present Study

In the present experiment, for the first time, we compared the pattern of brain activation of monolingual and bilingual infants before and after the developmental time when they typically achieve native-language phonetic perception (Mean ages: 4.79 and 7.28 months old). Neuroimaging was conducted with our new state-of-the-art fNIRS system, using a native (English) and non-native (Hindi) phonetic contrast in an oddball event-related paradigm. It was hoped that comparing bilingual and monolingual infants before and after they reached the stage of native-language phonetic perception would help shed new light on what neural mechanisms allow phonetic development in infancy.
Hypotheses and Predictions

(1) The Statistical Learning Account, when considered from a brain-based perspective, posits that infants progress to a state of neural-attunement to their native-language phonetic units by attending to regularities in the surface structure of their phonetic input. Considering the complexity of monolingual language input, and considering the finding that they show stronger electrical brain activity to native-language phonetic discrimination at a year of age:

(i) While monolingual infants are expected to show changes in brain activity from the first to the second age group studied, it is expected that bilingual infants will not change on the same time-table.

(2) The Pattern-Recognition account posits that infant phonetic development relies on a sensitivity to highly specific rhythmic-temporal patterns in the input, initially corresponding in size and duration to phonetic-syllabic units, but expanding over the first year of life. This is fundamental to the segmentation, attention, and laying down into memory of phonetic units into memory for motor production. Considering this:

(i) Both bilingual and monolingual infants will show development, on the same time-table, in areas thought to subserve the motor-production of speech.

Methods

Stimuli & Design

Participants were presented with stimuli from three distinct categories: native linguistic English phonemes, non-native linguistic Hindi phonemes, and non-linguistic pure tones in separate conditions. To ensure that participant response was due to phonetic category perception, and not a single phonetic vocalization, three different exemplars of each linguistic phoneme were used. The Hindi phoneme contrasts /ta/ (dental t) - /ta/ (retroflex t) were used as
our non-native linguistic stimuli. To provide standardization across labs, and to ensure brain activation associated with discriminable stimuli, our Hindi stimuli were generously shared with us by Janet Werker (personal communication, 2005, e.g., Fennell, Heinlein & Werker, 2007; Werker & Tees, 1984). The English syllables /ba/ and /da/ were recorded by a male native English speaker instructed to pronounce them with flat intonation so that they would all be matched in terms of pitch and amplitude. These were used as our native linguistic stimuli. The Hindi and English stimuli were equated in terms of amplitude and sampling rate (22 KHz). A 250 Hz pure tone was synthesized and used as our non-linguistic stimuli.

Phonological stimuli were presented in an Oddball event-related design so that 60% were “standard” phoneme events, 10% were “deviant” phoneme events, and 30% were catch events, on which only silence was presented. Each phoneme served as “standard” and “deviant” an equal number of times. Tone stimuli were presented in an event-related design so that 65% were tone trials and 35% catch trials.

Previous studies using fNIRS have examined phonetic discrimination (Petitto, 2007; Minagawa-Kawai et al., 2007) and speech perception (Gervain et al., 2008; Pena et al., 2003) in infants using a block design. Although this design is very helpful at eliciting brain activity in response to specific experimental manipulations between blocks of stimulus presentation, it does not target brain activity that responds specifically to changes in stimulus parameters within blocks. In other words, if reanalyzed as a block design, brain data from the present study would represent amalgamated activation in response to the standard and deviant stimuli, in addition to the activation in response to detecting a linguistically relevant change in stimulation. The analysis of this data in event-related form allows us to pinpoint activity that is recruited specifically in response to a frequently presented syllable (the “standard” trial), an infrequently
presented different syllable (the “deviant” trial), and the additional activation occurring only in response to the linguistic change (the difference between “deviant” and “standard” trials).

Ten randomized runs of 40 trials were created for each linguistic condition (English and Hindi), with each of the orders conforming to the above proportions of standard, deviant, and catch trials. One order was created for the Tone condition conforming to the above proportions of stimulus and catch trials. Thus, there were a total of 10 English runs, 10 Hindi runs, and one Tone run possible for presentation. Orders of these runs were randomized for each participant, with the only restriction that the first three runs must be one each of English, Hindi, and Tone.

Each trial had a duration of 1500 ms, with 1000 ms an ISI and 500 ms event, respectively (See Figure 1 for a boxcar example of four trials), and thus each run was 60 seconds long. The trials in each run were randomized such that 1) a deviant trial only was presented after a minimum of three standard trial presentations and 2) no more than two catch trials could occur sequentially.

Figure 1

Oddball Event Design Diagram Example

<table>
<thead>
<tr>
<th>ISI</th>
<th>English-Std</th>
<th>ISI</th>
<th>English-Std</th>
<th>ISI</th>
<th>Catch</th>
<th>ISI</th>
<th>English-Dev</th>
</tr>
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<tbody>
<tr>
<td>1000ms</td>
<td>500ms</td>
<td>1000ms</td>
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Subjects

Infants. Sixty-four (64) infant participants between the ages of 2-16 (mean = 7.5) months were recruited via advertisements in local newspapers, fliers posted in the local area, and from a booth at a local baby fair (as per university ethical approvals and guidelines). Interested participants who replied to these recruitment initiatives participated in exhaustive language background questionnaires, upon which language group criteria were applied. Age group criteria
were applied so that all young infants (ages 2-6 months) were firmly in the developmental stage of language-universal phonetic perception while all old infants (ages 10-14 months) were firmly in the developmental stage of native-language phonetic perception. In the bilingual group, eight participants were disqualified outright due to fussiness, six were disqualified due to optic data conversion issues, leaving 12 remaining infants in the bilingual group. In the monolingual group, six infants were disqualified outright due to fussiness, seven were disqualified due to optic data conversion issues, leaving 21 remaining infants in the monolingual group. Reanalysis of subjects whose data could not be analyzed due to conversion issues is in progress.

This process yielded the following four groups of infants: young monolinguals (n = 14, mean age = 4.71 months), old monolinguals (n = 7, mean age = 11.07 months), young bilinguals (n = 5, mean age = 4.30 months) and old bilinguals (n = 7, mean age = 12.21 months). All participants received a gift and compensation for their time and travel.

Adults. Thirty-nine (39) adults between the ages of 18-38 (mean = 20) years were recruited via the University of Toronto Scarborough participant pool. Interested adult participants were sent a short questionnaire about language exposure over email upon which we based our group assignment. On arrival in our lab, they filled out our Bilingual Language Background and Use screening questionnaire and a standardized English grammaticality judgment task to make sure that all participants had comparable linguistic competence (Kovelman, Shalinsky, Berens & Petitto, 2008; Petitto, Katerelos, et al., 2001). In the bilingual group, one subject was disqualified due to a low score on the grammatical awareness task, leaving 18 subjects remaining. In the monolingual group, one subject was disqualified due to a low score on the grammatical awareness task, and one subject was disqualified due to optic-data conversion issues, leaving 19 subjects remaining. All adult participants received compensation in
accordance with University ethical guidelines. All participants were treated in accordance with ethical standards of APA throughout all research phases.

Procedure

Infants. Parents of the infant participants in the study underwent questionnaires upon which we based their group assignment, followed by the administration of the phonetic discrimination task while undergoing fNIRS brain-scanning. All participants underwent two evaluations that constituted the basis for young vs. old and monolingual vs. bilingual group assignment, including (i) an email screening questionnaire or a telephone screening interview and (ii) a Bilingual Language Background and Use questionnaire.

Email or Telephone Questionnaire: Each potential participant (who contacted us in response to our participant recruitment ads) received a short email questionnaire or verbal telephone interview to determine which languages the infant was exposed to on a regular basis, whether the infant was born full-term, whether the infant was a multiple birth, the infant’s birth date, and whether, in principle, they were interested in participating in our study. Those individuals who indicated that the infant was born no more than three weeks before his or her due date, was not part of a multiple birth, and was exposed to only English or English and a second additional language not related to Hindi (see below) were invited into the laboratory to be administered either the Monolingual or Bilingual Language Background Questionnaire. These two questionnaires were created, piloted, and standardized as per prior lab research (Holowka, Brosseau-Lapré & Petitto, 2002; Kovelman, et al., 2008; Petitto, Zatorre, Gauna, Nikelski, Dostie, & Evans, 2000)

Bilingual Language Background and Use Questionnaire. Before infants underwent fNIRS brain-scanning, parents were asked to fill out our Bilingual Language Background and
Use Questionnaire which asked them for information about their child’s birth date, due-date, and detailed information about the quality and quantity of their child’s exposure to language(s) at home.

**Group Inclusion Criteria.** Participants whose parents indicated that their child had systematic and varied exposure to English from birth and that any other language exposure was unsystematic and infrequent, were identified as monolinguals. Participants whose parents indicated that their child had systematic and varied exposure to English and another language from birth were identified as bilinguals. Of our 12 infants with bilingual language exposure, 11 were first exposed to English from between birth to two months of age, whereas one was first exposed between two to six months. These same infants were all first exposed to their other language from birth to two months of age. All 21 infants in the monolingual group only had systematic exposure to English from birth.

**Adults.** Adult participants underwent questionnaires for group assignment, followed by the administration of the phonetic discrimination task while undergoing fNIRS brain imaging. The two steps that constituted the monolingual vs. bilingual group assignment included (i) an email questionnaire and (ii) a Bilingual Language Background and Use questionnaire. Lastly, they were given a 28 question English grammaticality judgment task of which they needed to get 80% correct in order to be included in the final analyses.

**Email Questionnaire:** Each potential adult participant who contacted us received a short email questionnaire to determine what language(s) were spoken to him or her by each parent, when the participant was first exposed to each language, handedness, hearing and neurological normality. Those individuals who indicated exposure only to English or English and a second additional language not related to Hindi, left handedness, normal hearing, no neurological
problems, and, if bilingual, exposure to English before age five, were invited into the laboratory to be administered either the Monolingual or Bilingual Adult Language Background and Use Questionnaire (as used in, e.g., Kovelman et al., 2008; Penhune, Cismaru, Dorsaint-Pierre, Petitto, & Zatorre, 2003; Petitto et al., 2000).

**fNIRS Imaging**

To record the hemodynamic response a Hitachi ETG-4000 with 24 channels were used, acquiring data at 10 Hz. The lasers were factory set to 700 nm and 830 nm. The 10 lasers and 8 detectors were segregated into two 3×3 arrays corresponding to 12 channels per array. The fNIRS machine was located in the rear corner of the testing room, behind the participant, blocked from vision by black curtains. The fibre optics cables leading to the fNIRS probes extended three feet away through a slit in the black curtains. Another set of black curtains blocked the participant’s view of the side of the room opposite the fNIRS machine. FNIRS is an optical neuroimaging technique with excellent spatial and temporal resolution. FNIRS runs with minimal noise, which makes it preferable to use with awake infants. Additionally, the fNIRS signal is relatively more tolerant of movement than fMRI. An infant subject can be scanned in the comfort of his or her parent’s lap.

**Data Processing and Analysis**

Each channel, formed by adjacent lasers and detectors in the probe array, yielded light attenuation values from the 700 and 830 nm lasers. The attenuation values for each run were normalized and stored in separate numeric ‘hold’ arrays depending on event type, preserving the information of when they originally occurred. Hold arrays were then averaged in order to construct several time series representing the course of attenuation over 60 seconds for each specific event. The reconstructed time series of optic data were then converted to oxygenated
haemoglobin (oxyHB) values using the Modified Beer-Lambert equation. The data were then convolved to the hemodynamic response function, and a peak of brain activation was searched for between 10 seconds after the beginning of the reconstructed series and 20 seconds before the end.

In order to conduct further analyses, peak data from Standard event time series at each channel were subtracted from peak data from Deviant event time series at each channel to form a score representing the neural sensitivity to phonetic change in the input stimulus. Accordingly, a significantly positive difference resulting from this subtraction meant that the brain area from that channel was sensitive to the phonetic change while a non significant difference represented relative insensitivity.

Apparatus

Infants. Following administration of the language questionnaire, and a description of the experimental session, and voluntary completion of the participant consent form, participant parents were seated on a comfortable chair and infants were seated on their parent’s lap. Once parent and infant were settled, a set of headphones were placed on the parent’s head and a CD playing recorded music was started so that parents would not be able to hear and react to the auditory stimuli.

Parent and baby were seated facing a 22” flat panel monitor at a distance of approximately 120 cm, with a silent Aquarium video playing continuously throughout the session (Plasma Window, 2006). Speakers (Bang & Olufsen, Beolab 4 PC) were placed 30 cm to the right and left of the monitor. A three-inch tall Sony MiniDV camcorder was positioned underneath video camera was positioned under the monitor and faced the infant. Additionally,
this video capture was linked to the fNIRS brain recording, enabling off-line movement artifact detection.

Once the participant was comfortably seated, the fNIRS silicon arrays were placed on to the infant’s head using a comfortable terry cloth headband. Similar to adult participants (see below), positioning of the array was accomplished so that the middle probe of the bottom row of each array was anchored near T3/T4 based on Jasper’s (1957) 10-20 system on both sides of the head (See Figure 2 for a diagrammatic example of probe placement. On the diagram, red circles represent near-infrared light emitters, blue circles represent the near-infrared light detectors, and crosshairs represent the sites (channels) at which brain recordings were taken.) This probe placement was used to ensure that we were maximally over classic language brain tissue and a control site (STG, Broca’s area, DLPFC). Digital photographs were taken of the array positioning prior to and after the recording session to ensure that the arrays did not move during testing.
Prior to beginning the recording session, channels were tested for noise and adjusted until a good signal was obtained from all or most channels, at which time the overhead lights were turned off, and the brain recording session began. Each run of events was preceded by a variable time lead-in to avoid synchronization with stimuli, followed by the 60 s run. At the end of each run, a break of approximately 30 seconds was given prior to the beginning of the next run. To reduce attrition, experimenters visually stimulated infants, and infants were offered a silent toy to hold during the session. The session was ended if participants showed signs of fussiness for more
than 2 sequential runs or refused to continue wearing the headband. Given that session duration was determined by the infant’s temperament, participants widely differed in the number of completed runs with an average of approximately 6 runs completed across groups. The average brain recording session lasted about 16 minutes. It was confirmed via ANOVA that the four infant groups did not vary significantly on the number of runs completed.

Adults. After filling out all questionnaires, and a description of the experimental session, and voluntary completion of the participant consent form, adult participants were invited into the scanning room and seated on a comfortable chair. The scanning room was set up almost identically for the adults as for the infants, except that a video camera was positioned via tripod with its lens right behind a hole in a sheet of black curtains in viewing distance of the participant.

Once the participant was comfortably seated, the fNIRS probe arrays were positioned on the head so that the middle probe of the bottom row of each array was anchored near T3/T4 according to the 10-20 system on both sides of the head (Jasper, 1957). The same probe placement was used with adults as with infants to ensure that we were measuring from similar brain sites (STG, Broca’s area, DLPFC). To ensure that we were maximally over our ROI locations on the adult probe array, we made use of previous anatomical coregistration work (Kovelman et al., 2008). Digital photographs were taken of the array positioning prior to and after the recording session to ensure that the arrays did not move during testing.

Adults were exposed to all 10 randomized stimulus orders for English and Hindi in runs of five each. Each run of five stimulus orders consisted of stimuli from only one language. This created two runs of five orders for English lasting five minutes each, and two runs of five orders for Hindi lasting five minutes each. Each run of five orders was preceded by a variable time lead-in, followed by the five-minute run. At the end of each run, a break of approximately 30
seconds was given prior to the beginning of the next run. The average brain recording session for adults lasted about 25 minutes.

**Results**

*Adult and Infant Hemispheric Asymmetry*

In order to isolate the brain-based mechanisms that contribute to infant phonetic processing, we first conducted a global analysis of brain activation in response to phonetic change in English across both hemispheres overall in young infants, old infants, and adults. Unexpectedly, none of the analyses revealed gross hemispheric differences in response to phonetic change in English, all infant $F$ values < 1, adult $F(1, 29) = 1.443, p = .239$. Principal Components Analysis (PCA) was used for the second set of analyses to identify positively covarying brain activity across left hemisphere channels in young infants, old infants, and adults. Channels identified by PCA as covarying were then averaged and then compared against their right hemisphere homologues. None of the channel groupings in any age group analyzed showed evidence of hemispheric asymmetry, $p > .05$.

*Infant ROI Identification*

To discover which regions of interest showed robust activation in response to the detection of phonetic change in the infants’ native language (English), we subjected infant brain data across all left channels to PCA, which grouped the channels into Broca’s area and STG components. Channels within the components corresponding with our ROI were isolated with the help of our adult fNIRS coregistration, forming two channels for each ROI (Kovelman et al., 2008).
The above channels, and their right hemisphere homologues, were then submitted to eight independent-samples t-tests (Bonferroni correction applied) to determine which brain tissues showed developmental change and which tissues were robustly activated early on. The only channel meeting with the significance criterion was a Broca’s area channel, which showed an age-related change in its sensitivity to phonetic change in babies’ native language, $t(27) = -3.095, p = .005$. Therefore this channel was examined in the first ROI analysis.

Monolingual and Bilingual Phonetic Development (ROI)

Does exposure to two languages from birth affect brain tissue development in Broca’s area? A 2 (Stimulus Language, within-subjects factor) x 2 (Language Group, between-subjects factor) x 2 (Age, between-subjects factor) Mixed ANOVA was carried out to determine the answer. The ANOVA revealed the following two significant interactions: 1) Stimulus Language by Age, $F(1, 24) = 9.381, p = .005$ and 2) Stimulus Language and Language Group, $F(1, 24) = 5.879, p = .023$. As can be seen in Figure 3, whereas there is a significant age-related decline in all infants’ left Broca’s area response to phonetic change in English, $t(27) = -3.095, p = .005$, there is no such decline in Hindi, $t(27) = -.493, p = .626$. As predicted by the pattern-recognition hypothesis, this interaction suggests that both bilinguals and monolinguals are showing a developmental change on the same time-table in their left Broca’s area responses to phonetic change in English, and lack of change, in the same brain area, in their responses to phonetic in Hindi. As can be seen in Figure 4, bilingual infants surprisingly appeared to show higher recruitment of left Broca’s area in response to phonetic change in English than monolinguals across age groups. In contrast, no such difference is evident for phonetic change in Hindi. Examination of Figure 5 reveals that although both monolingual and bilingual infants change their left Broca’s response to English in the same direction, bilinguals appear to show higher
sensitivity to English at both age groups. An independent-samples t-test comparing monolingual and bilingual infants’ left Broca’s area activation in the English condition revealed a non significant effect, $t(27) = 1.718, p = .097$. The ANOVA also revealed significant main effects for Language Group, $F(1,24) = 4.727, p = .04$, and Age Group, $F(1, 24) = 7.396, p = .012$. This confirmed that Bilingual infants across age groups showed higher phonetic change related activity in left Broca’s area than monolinguals. This also confirmed that young infants across language groups showed higher phonetic change related activity in left Broca’s area than older infants.

**Figure 3**
Are the developmental effects seen in the previous analyses linguistic, or due to other cognitive factors? In order to answer this question, data from channel 12 (which can be seen on Figure 2 as the crosshair on the top row of channels closer to the front of the array) was submitted to analysis. Based on Jasper (1957), this channel was considered as overlaying infants’ superior frontal area. A 2 (Stimulus Language, within-subjects factor) x 2 (Language Group, between-subjects factor) x 2 (Age Group, between-subjects factor) was run examining sensitivity to phonetic change in infants’ superior frontal area. No interactions or main effects were found significant in this analysis, indicating that the age-related decline in Left Broca’s area in response to phonetic change in English is linguistic and not due to general cognitive development, all $p$ values > .232.
Figure 5

Bilingual Infant Phonetic Change Sensitivity in Left Broca's Area

Monolingual Infant Phonetic Change Sensitivity in Left Broca's Area
Adult and Infant Brains Compared

Did infants show robust recruitment of classic language brain areas while listening to phonetic change in the experimental stimuli? To answer that question, channels that were identified by the above infant PCA as maximally overlaying left Broca’s area (channels 7 and 9) and left STG (channels 1 and 4) were averaged so that the resulting data could be submitted to four one-sample t-tests. As predicted, left Broca’s area was significantly sensitive to phonetic change in English, $t(32) = 4.320, p < .001$, and so was left STG, $t(32) = 5.356, p < .001$. Further, results confirmed that left Broca’s area was also significantly sensitive to phonetic change in Hindi, $t(30) = 7.428, p < .001$, as was left STG, $t(32) = 7.515, p < .001$. Together these results show that infants recruited classic adult brain tissues in the detection of phonetic change in both English and Hindi.

Do monolingual and bilingual adults show the same pattern of brain recruitment in response to phonetic change in their native and non-native languages? The first adult analyses were based on planned within group comparisons for the left hemisphere regions of interest: posterior IFG, STG and Parietal. Monolinguals: IFG, $t(16) = .262, p = .797$, pSTG, $t(16) = 1.910, p = .074$, Parietal, $t(16) = 1.811, p = .089$. Bilinguals: IFG, $t(16) = .260, p = .798$, pSTG, $t(15) = -.994, p = .336$, Parietal, $t(16) = -.792, p = .440$. As can be seen in Table 1, although monolingual adults tended to show higher recruitment of brain areas for English than Hindi, this result was not significant. Bilingual adults show no evidence for differential recruitment of the analyzed brain areas.
Table 1

*MAB Brain Activation in Response to Phonetic Change as a Function of Region, Stimulus Language and Language Group*

<table>
<thead>
<tr>
<th>Language Group</th>
<th>Posterior STG (English)</th>
<th>Posterior STG (Hindi)</th>
<th>Broca’s Area (English)</th>
<th>Broca’s Area (Hindi)</th>
<th>Parietal Area (English)</th>
<th>Parietal Area (Hindi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bilingual</td>
<td>0.798 (.203)</td>
<td>1.135 (.211)</td>
<td>0.942 (.303)</td>
<td>0.851 (.240)</td>
<td>1.595 (.331)</td>
<td>1.956 (.315)</td>
</tr>
<tr>
<td>Monolingual</td>
<td>1.535 (.243)</td>
<td>0.887 (.215)</td>
<td>0.877 (.193)</td>
<td>0.800 (.192)</td>
<td>1.973 (.366)</td>
<td>1.189 (.251)</td>
</tr>
</tbody>
</table>

1. Standard Error in brackets.

**Monolingual and Bilingual Phonetic Development (ROI 2)**

Lastly, in order to discover the relative recruitment of STG for native and non-native language phonetic processing in both infant age groups, data from channels considered to maximally overlay infant left STG were averaged and submitted to a 2 (Stimulus Language, within-subjects factor) x 2 (Language Group, between-subjects factor) x 2 (Age Group, between-subjects factor) Mixed ANOVA. The ANOVA revealed a significant interaction effect between Stimulus Language and Language Group, $F(1, 29) = 4.965, p = .034$. As can be seen in Figure 6, while there is no apparent language group left STG difference in response to phonetic change in English, bilinguals seem to show lower left STG recruitment in response to phonetic change in Hindi. This result was confirmed as significant by an independent-samples t-test, $t(31) = -2.075$, $p = .046$. Together these results indicate that infants recruit STG for phonetic processing from an early age.
Discussion

In this study we asked what underlies infants’ capacity to achieve the restricted set of phonetic units in their native language. Is the capacity strictly subserved by a statistical learning mechanism, or by an early sensitivity to the rhythmic-temporal patterns of natural language? For the first time, this study examined the neural correlates of phonetic discrimination in monolingual and bilingual infants and adults as a new microscope into early infancy phonetic development. Infants hearing phonetic change in English revealed several very intriguing findings concerning the development of brain activity in both left STG and Broca’s area.

Contributions from Infant Data
As predicted by the *pattern-recognition* account of phonetic development, both monolingual and bilingual infants evidenced no change in relative brain activity in the STG in response to phonetic change in English. This result supports the idea that the STG is predisposed to being able to handle the processing of phonetic segments with similar efficiency whether exposed to one or two languages from birth (Petitto, 1997; Petitto, Katerelos, et al., 2001; Petitto & Holowka, 2002; Petitto & Kovelman, 2003; Kovelman et al., 2008; Petitto & Holowka, 2002; Petitto & Kovelman, 2003; Kovelman et al., 2008; Kovelman et al., 2008). It is fascinating that the STG, the brain area that is said to do the lion’s share of the phonetic processing in adults (e.g. Celsis et al., 1998; Joanisse et al., 2007; Zevin & McCandliss, 2005; Petitto et al., 2000; Petitto et al., 2004; Liebenthal, Binder, Spitzer, Possing & Medler, 2005) shows no change in peaked activation across the age groups studied. This provides tantalizing evidence for the hypothesis that infants are born with neural tissue that is predisposed to the segmentation of language input from their environment (Petitto, 1997).

Secondly, also as predicted by the *pattern-recognition* account of phonetic development, both monolingual and bilingual infants showed a significant age difference in peaked Broca’s area activity in response to phonetic change in English. That this age-related decline did not also happen in response to phonetic change in Hindi suggests the role of native-language experience in the development of brain activity in left Broca’s area. The fact that this effect was true for both monolingual and bilingual infants lends tantalizing support to the hypothesis that infants are able to lay down their native-language phonetic distinctions in memory on-time, regardless of monolingual or bilingual language exposure.

*Theoretical Significance*

The results of this study are inconsistent with the predictions according to a brain-based *statistical learning* account of phonetic development in the case of bilingual infants. According
to this account, infants exposed to two languages from birth should take longer to settle on the restricted set of phonetic units in their language (e.g. Kuhl & Rivera-Gaxiola, 2008; Werker, 2007). Infants in this study showed no evidence for developing on different time courses depending on whether they were learning one language or two. This constitutes fascinating, first time neural evidence corroborating the findings in a study done by Petitto and colleagues (2001) who found no behavioural evidence for differences in language development in monolingual and bilingual infants. Interestingly, a study done by Imada et al. (2006) found evidence using MEG that monolingual infants do not show electrical activity in left Broca’s area until the same age range as the older infants in the current study. Taken together, these results reveal the early phonetic processing of left STG and the readiness of left Broca’s area to adapt to a native-language. In other words, they show the function of the human infant’s biological endowment in the brain and the ways in which it is specifically moulded by experience.

From these results it is appears that the process of the honing in on the restricted set of phonetic units in an infant’s native language proceeds similarly regardless of one or two language exposure. Also, it appears that the neural response to a non-native contrast shows changes in the same fashion regardless of language group. Importantly, these results do not negate role for statistical learning in phonetic development. Rather, it seems more likely that statistical learning may serve as a supplement to the infant’s early sensitivity to the highly specific rhythmic-temporal patterns of natural language.

**General Conclusion**

The current study has revealed the fascinating finding that superior temporal tissue in monolinguals and bilingual infants is dedicated to phonetic discrimination from before the achievement of native-language phonetic perception. Development in both the STG and Broca’s
area appears to be under biological control, reaching their goals despite variation in environmental input (Lenneberg, 1967). Most importantly, bilingual parents can rest at ease knowing that exposing their infants to two languages from birth causes no harm.
References


Sebastián-Gallés, N., & Bosch, L. (In press). Developmental Shift in the Discrimination of Vowel Contrasts in Bilingual Infants: Is the distributional account all there is to it?

*Developmental Science*


Email Script for Screening of Parents

Dear

Thank you so much for your interest in our study on how babies learn language! To give you a little bit of information about our study, we are looking at the brain activity of children who are learning to speak. To do this we use an imaging technology called Near Infrared Spectroscopy (NIRS). NIRS tells us which parts of the brain are active by using light that is similar in intensity to a flashlight. This light measures changes in blood flow associated with brain activity. Your baby will wear a cloth headband cap with non-sticky probes while watching a video and hearing language sounds. This is a very safe and noninvasive way to study brain activity and has been approved by Health Canada and by University of Toronto Scarborough. More information on NIRS also is available on our laboratory website (see below). The study involves just one 30 minute visit and your baby will sit on your lap throughout the session.

May I ask you a few questions about your baby?

1. What is your baby's name?
2. What is your baby's birthdate?
3. Do you remember what date your baby was due?
4. Is your baby a twin or a triplet?
5. Does your baby hear any language other than English on a regular basis?
5b. If so, which language and what percentage of the time?
6. Does your baby have any hearing problems that you are aware of?
7. What is your telephone number?
8. Lastly, do you happen to remember where you saw our ad from?

I am happy to answer any other questions you might have about our study. I hope to hear from you soon!

Best wishes,
**Phone Script for Screening of Parents**

“Thank you for calling! We would love to have your baby participate in our study. To make sure that your baby is eligible for our study, can I ask your baby’s birthdate?”

Eligibility: Born October 2006 through now. (2-16 months)

If NOT ELIGIBLE:
“Unfortunately, we are not currently doing any studies with that age group. Would you like to be added to our contact list in case we have studies with that age group in the future?
If yes ask questions 1-10.

If ELIGIBLE:
“Great! Would you like to hear some more information about our study? We are interested in which part of the brain is activated in infants when they listen to different language sounds. So in this study, we will be showing your baby some videos with different language sounds while he or she is sitting on your lap. We will be using a safe and non-invasive technique called Near Infrared Spectroscopy (NIRS), which has been approved by Health Canada. It is basically a headband that shines very low-intensity light, similar to that of a flashlight, on to the surface of your baby’s head. This allows us to see which areas of your baby’s brain are active while we play different types of language sounds. It’s a one-time visit to the University of Toronto Scarborough campus that takes a maximum of 30 minutes. After the session, your baby will receive a small gift for his or her participation and you will be reimbursed for your time and travel ($20 per hour).

Would you be interested in participating?

If NOT INTERESTED:
“That’s no problem. Can we contact you in the future for other studies?
If yes:
Ask questions 1-10.
 “Thank you for your time and interest.”
 If no:
 “Thank you for your time and interest”

If INTERESTED:
“Great! Can I get a little more information from you?”

1) “Do you have a little boy or a girl?”
2) “What is his/her name?”
3) “What is your name?”
4) “Do you happen to remember your baby’s due date?”
   If more than 3 weeks premature:
   “Unfortunately, we are only testing babies who were born full-time in this particular study. Would you like to be added to our contact list for future studies?”
   If yes:
   Ask the rest of the questions.
   If no:
   “Thank you again for your interest in our study.”
5) “Does your baby hear any language other than English in the home on a regular basis?”
   If yes:
   “What language does your baby hear?”
   “How often or approximately what percentage of the time?”
6) “Does your baby have any hearing problems that you are aware of?”
   If yes:
   “Unfortunately, we are only looking at babies with normal hearing for this study. Can we add you to our list for future studies?”
   If yes:
   Ask the rest of the questions.
7) “Is your baby a twin or triplet? “
   If yes:
   “Unfortunately, we are not looking at multiple birth babies for this study. Can we add you to our list for future studies?”
   If yes:
   Ask the rest of the questions.
8) “Could I have your phone number please?”
9) “And your Email address please?”
10) “Could I also have your address please?”

“Great! We will add you to our contact list and call you when we begin scheduling appointments for this study. At that time, we can schedule an appointment time that is convenient for you and your baby. Then we will send you directions to our lab and information about your appointment.”

“Do you have any other questions I can answer for you right now? If you have any questions, feel free to give us a call. Our number is 416 208 4870. My name is __________, but anyone who answers the phone should be able to answer your questions.”

“Thank you again for your interest! We will be in touch with you about scheduling an appointment.”
Email Script for Screening of Adults

1. What is the native language of your mother?
2. What is the native language of your father?
3. At what age were you first exposed to English?
4. Where were you first exposed to English (home, school)?
5. Do you fluently speak any other languages?
5b. If so, which language(s), and when did you first start learning that language?
6. Are you right-handed or left-handed?
7. Do you have normal hearing?
8. Do you have any history of neurological problems?

Thank you very much and we look forward to hearing back from you!
Bilingual Language Background and Use Questionnaire

Bilingual Questionnaire for Child Language Study
University of Toronto
Laboratory Director: Dr. Laura-Ann Petitto

Child’s Name ____________________________
Child’s Age _____
Child’s Date of Birth ______________
Child’s Due Date ___________________

1. How often does your child hear English? (Please circle one)
   Never  1-20%  20-50%  50-80%  80-100%

2. From whom does your child hear English? (Please circle all that apply)
   Mom    Dad    Grandparent(s)    Babysitter/Daycare
   Other (please specify) ___________

3. How often does your child hear ______________? (Please circle one)
   (language)
   Never  1-20%  20-50%  50-80%  80-100%

4. From whom does your child hear ______________? (Please circle all that apply)
   (language)
   Mom    Dad    Grandparent(s)    Babysitter/Daycare
   Other (Please specify) ___________

5. What language(s) do you read to your child in? (Please circle all that apply)
   English    Other ____________    Neither/Not applicable
   (language)
6. What language(s) does your child watch Television or videos in? (Please circle all that apply)
   English   Other _________   Neither/Not applicable
   (language)

7. At what age did you first start speaking to your child in English? (Please circle one)
   Birth-2 months  2-6 months  6-10 months  10-14 months

8. At what age did you first start speaking to your child in _________?
   (Please circle one)
   (language)
   Birth-2 months  2-6 months  6-10 months  10-14 months