TRACKING LANGUAGE TUNING ACROSS THE FIRST YEAR OF LIFE USING

NEAR-INFRARED SPECTROSCOPY

A Dissertation

by

ESWEN ELIZABETH FAVA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

December 2011

Major Subject: Psychology

Tracking Language Tuning across the First Year of Life Using Near-infrared

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ABSTRACT

Tracking Language Tuning across the First Year of Life Using

Near-infrared Spectroscopy.

(December 2011)

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Both behavioral and neurophysiological data indicate that many factors contribute to how infants tune to their native language(s) in early infancy. However, substantial debate remains regarding the neural mechanisms that underlie this tuning process. This study was designed to determine whether the behavioral changes in infants' processing of native and non-native speech during the second half of the first year correspond to qualitative neural processing changes that can be measured using near-infrared spectroscopy (NIRS). Specifically, we used NIRS to examine changes in hemodynamic activity in monolingually-exposed infants between the ages of 3 and 14 months while they were exposed to native (English) and non-native (Spanish) speech. In all infants, measurements were taken from the bilateral temporal regions of the cerebral cortex. Three age groups were tested: pre-tuned infants, who should show no sensitivity to phonological differences between the native and non-native speech samples (3-to-6-month-olds), actively tuning infants, who should be beginning to differentiate between the phonology of the native and non-native speech samples (7-to-10-month-olds), and

tuned infants, who should readily distinguish between the phonologies of the native and non-native speech samples (11-to-14-month-olds). Results demonstrated significant differences in hemodynamic activity during the processing of native speech compared to non-native speech in each of the three age groups, with qualitatively different patterns of hemispheric lateralization emerging in response to the two types of speech in each of the three groups. These findings point to a potential neural marker of infants' sensitivity to the phonology of their native language as it emerges with increasing age that will be useful in future research.

ACKNOWLEDGEMENTS

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1. INTRODUCTION: THE IMPORTANCE OF RESEARCH

Infant language development takes place in the context of both language input and biological maturation and there is substantial debate regarding the relative contribution of each. Despite this, it is generally accepted that infants learn language with relative ease. Much of the data concerning specific aspects of the learning process are behavioral in nature, and are therefore limited in what they can tell us about any underlying neural processes. However, the increasing use of neurophysiological techniques in infant research is advancing our understanding of the relationship between infants' behavioral responses to speech and the neural mechanisms that support its processing (Kuhl and Rivera-Gaxiola, 2008). One particular phenomenon, *perceptual tuning,* or *perceptual narrowing,* is traditionally described as the change in infants' relative decrease in sensitivity to non-native phonetic contrasts as a function of some combination of language exposure and biological maturation (Sebastian-Galles, 2002; Werker and Tees, 2005). Within the context of the infant tuning literature it is important to note that the terms "native" and "non-native" refer to the relative amount of exposure to different languages during infancy, such that "native" refers to the language that infants are consistently exposed to a majority of the time, whereas "non-native" refers to the language to which infants experience considerably-less exposure. Taking a broader view of this tuning process, the current study uses perceptual tuning to language, or *language tuning*, to more generally frame how language development transpires in the

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This dissertation follows the style of *Frontiers in Language Science*.

initial years of life.

Behavioral data on language tuning have suggested that infant speech perception begins *in utero* and progresses dramatically across the first year (DeCasper and Fifer, 1980; Werker and Tees, 1984). In particular, according to the literature, infants begin life capable of discriminating between all phonetic contrasts (Eimas et al., 1971; Streeter, 1976) and this discrimination profile narrows before the end of the first year to exclude non-native language (i.e., irrelevant) contrasts (Kuhl et al., 2006). In order to more specifically examine the progression of native language tuning, behavioral research has examined several types of phonetic contrasts and has found exceptions in the timeline of language tuning (Best et al., 1988; Polka et al., 2001), likely due to the relative difficulty or "acoustic salience" of particular phonemes (Narayan et al., 2010). However, infants are generally "tuned" to their native phonemic inventory by the first half of the second year. Specifically, researchers have demonstrated that between 6 and 8 months of age, monolingually-exposed infants are capable of making non-native phonemic distinctions, whereas by between 10 and 12 months of age, they become more adept at discerning native phonemic contrasts with a corresponding loss in sensitivity to non-native contrasts (Werker and Tees, 1984; Tsushima et al., 1994; Best et al., 1995; Best and Mc Roberts, 2003). Therefore, overall, behavioral evidence converges on the window between 8 and 10 months as the time when native language tuning likely occurs, at least in monolingually-exposed infants.

1.1.   Cues useful for discriminating native and non-native speech: prosody

Although language tuning has traditionally been viewed in the context of phonetic narrowing that leads to the development of language-specific sound sensitivity, substantial amounts of behavioral data have demonstrated that even very young infants are capable of discriminating between native and non-native speech, presumably via prosody. Although prosody is a useful language cue throughout infancy, it continues to be important throughout life (Wagner and Watson, 2010), including use during adult second language acquisition (Cutler et al., 1997). Within the context of the infant behavioral literature, evidence suggests that *prosodic cues* are the first cues infants utilize to distinguish between native and non-native speech prior to tuning to language-specific sounds. For example, several studies have demonstrated that neonates prefer their native language over another language with a dissimilar rhythmic structure (Mehler et al., 1978; Mehler et al., 1988; Moon et al., 1993; Nazzi et al., 1998; Ramus et al., 2000). This early preference for the native language's prosodic pattern likely stems from what infants experience in the womb. This is preference likely emerges due to the womb acting as a low pass filter for speech, such that developing infants have substantial prenatal exposure to this particular aspect of their native language by the time they are born (Moon et al., 1993).

In addition to this behavioral evidence, neurophysiological technologies such as electroencephalography (EEG), analyzed as event-related potentials (ERPs) have been successfully utilized with infant populations, as they enable identification of cortical-level regions of activation, and can be paired with behavioral paradigms. One such

example is the oddball paradigm, where participants perceive stimuli of one type (the "standard" item) that are frequently repeated, interspersed with an infrequent item (the "deviant" item). If the participant detects a difference between the standard and the deviant item, a difference in the measured response should be observed (for further explanation of the use of the oddball paradigm with ERPs, see Gibson and Pick, 2000). Utilizing the oddball paradigm with single auditory-only, word-level stimuli, 4-month-olds differentiated words that differed only in stress but not phonology (e.g., pápa and papá) (Friederici, et al., 2007), meaning they demonstrated significantly different neurophysiological responses to speech stimuli with differing stress patterns, even when phonological content was held constant. In terms of related changes in cortical activity, Friederici and colleagues reported differentiation between native compared with the non-native words in bilateral prefrontal and superior temporal sites.

In addition to EEG, other neurophysiological technologies, including near-infrared spectroscopy (NIRS) have also been used to examine language tuning in infants. NIRS in particular is advantageous as it measures hemodynamic activity and thus is able to extend and complement the well-established adult functional magnetic resonance imaging (fMRI) speech perception literature. NIRS studies of infants (Homae et al., 2006; Homae et al., 2007), as well as fMRI studies of children (Plante et al., 2006; Wartenburger et al., 2007) and adults (Zatorre et al., 1999; Friederici, 2002; Gandour et al., 2004), have demonstrated that the processing of prosodic cues in speech is generally lateralized to the right hemisphere. For example, using NIRS to test processing of native, sentence-level stimuli in normal and flattened speech in 3-month-olds, Homae

and colleagues (2006) demonstrated a predominantly right lateralized response to normal compared with the flattened speech. Given that flattened speech is identical to normal speech in every way other than its prosodic structure, this points to the right hemisphere as particularly important to the processing of prosody. Furthermore, this pattern of lateralization for processing prosodic speech cues was also observed in 10-month-olds (Homae et al., 2007), and appears consistently observed in adults (Zatorre et al., 1999; Friederici, 2002; Gandour et al., 2004). Thus, the extant data converge on a pattern of right lateralized processing of prosody in infancy that remains relatively stable throughout life.

1.2.   Cues useful for discriminating native and non-native speech: phonology

As infants accrue sufficient experience with their native language, they become increasingly sensitive to cues other than prosody. In particular, behavioral data indicate that *phonological cues* become useful for speech processing in the second half of the first year (Gervain and Mehler, 2010). Phonology describes the speech stream-level patterns of sound combinations of a particular language, including the individual phonemic-level contrasts specific to that language. Therefore, phonology encompasses the phonemic sensitivity characterized by the original findings about language-specific perceptual tuning. For example, by 8 months of age, infants track the relative frequency of the specific phonemes in the speech they hear (Maye et al., 2002; Best and Mc Roberts, 2003; Kuhl, 2004); by 9 months, infants can utilize phonological cues to discriminate between frequent and infrequent phonetic sequences in their native language (Jusczyk et al., 1994). These (and other) results highlight the transition in

infancy from global prosodic processing to more sophisticated, sound-specific processing.

In terms of localizing neural markers of phonological processing, fMRI studies conducted with children have shown that posterior left hemisphere activity is specifically associated with phonological processing (Leonard et al., 1996; Eckert et al., 2001). These data are consistent with the more established fMRI data from adult participants, which have repeatedly demonstrated that the superior temporal gyrus (the posterior portion of which is located in the left posterior temporal area) is important for phonological processing (Binder et al., 1994; Booth et al., 2003; Bitan et al., 2005). This left hemisphere dominance for phonological processing contrasts with the right hemisphere dominance associated with prosodic processing, thereby highlighting a dissociation in the processing of these two cue classes that may be consistent with an initial dissociation in the timeline of early language development.

Therefore, taken together with the evidence of early prosodic cue use, the behavioral data from infants suggest that phonological cues require more experience in order to be useful in language tuning compared with prosodic cues. Likewise, the neurophysiological data demonstrate dissociable processing patterns specific to these two aspects of speech.

1.3.   Is there evidence of neural markers to native language tuning in infancy?

Data from two of the most common neurophysiological techniques used with infants, NIRS and EEG, have demonstrated particular neural indicators, or markers, of discrimination of native and non-native speech. At present, some of these data fit the

behavioral timeline for sound-specific tuning already outlined (i.e., beginning between 8-to-10 months of age), whereas other results suggest much earlier tuning.

Blood flow data collected using NIRS have demonstrated that 4-month-old, monolingually-exposed infants processing auditory-only, sentence-level stimuli show greater hemodynamic responses for native compared with non-native speech (Minagawa-Kawai et al., 2011b). The authors interpreted this hemodynamic response pattern as a possible neural marker of language tuning, as it was similar to that observed in adult data (Minagawa-Kawai et al., 2002). However, when word-level phonemic contrasts were tested, only infants 11 months of age or older showed a greater hemodynamic response to native relative to non-native speech (Minagawa-Kawai et al., 2007). Thus, the type of stimuli used (i.e., sentence-level vs. word-level) may have influenced the observable patterns of activation that correspond to language tuning in infants, such that sentence-level stimuli show evidence of language tuning earlier than word-level stimuli. This is likely due to the more complete speech cues available in the sentence-level signal relative to the isolated cues available at the word-level (for a review of the ecological validity concept in the context of infant research, see Lewkowicz, 2000).

This interpretation is further supported by infant ERP data, where responses indicative of discrimination of both native and non-native phonemic contrasts emerge at 7 months of age, whereas no such sensitivity to non-native contrasts exists by 11 months of age (Rivera-Gaxiola et al., 2005). However, when these same researchers used a different parsing of ERP components in their analyses, 11-month-old infants appeared to

still be sensitive to both types of contrast. Conflicting results like this, particularly given different approaches to data analysis, suggest that differences in infants' differential sensitivity to native and non-native phonemic contrasts may not be as robust as once thought. Nonetheless, these results suggest that infants show evidence of language-specific sensitivity to contrasts with less information (i.e., consonant and word-level stimuli) later (e.g., around 11 months of age) than to sentence-level stimuli with more (e.g., younger than 8 months of age instead). In other words, the latter form of stimuli may provide sufficient information for infants to evince earlier discrimination than the former.

1.4 Relative speed of tuning hypothesis

Several researchers have presented theories about what neural mechanisms underlie the language tuning process (Kuhl et al., 2005; Trainor, 2005; Thomas and Johnson, 2008). However, none have addressed the behavioral evidence reviewed by Werker and Tees (2005), suggesting different aspects of language (e.g., prosody, phonology, syntax, semantics) may each have their *own* critical (or sensitive) period, or at least develop in an "interrelated" or "nested" set of critical periods. Specifically, Werker and Tees asserted that as infants gain more experience with language, they become (incrementally) more aware of progressively complex components and of variability in the speech signal.

In light of this, Fava, Hull, & Bortfeld (in press) have proposed the *Relative Speed of Tuning Hypothesis* (henceforth, the *Speed hypothesis*), which predicts that infants tune faster to more transparent, robust elements of language than to more opaque,

ambiguous aspects of language. The Speed hypothesis predicts that infants tune faster to

prosodic cues than to phonological cues, a view that is consistent with both the

behavioral and neurophysiogical literature just reviewed. Furthermore, this review of

the literature has indicated that stimuli with more information (i.e., unfiltered, sentence-

level speech) elicit evidence of language tuning in infants earlier than stimuli with less

information (i.e., filtered, word-level or contrast-level speech); this is also a prediction of

the Speed hypothesis. Finally, and specifically relevant to the kind of data just reviewed

(e.g., NIRS and ERP data), the Speed hypothesis predicts that neural markers of

language tuning should likewise emerge earlier in response to those faster-tuned

elements of language (e.g., prosody) than to slower-tuned elements (e.g.,

phonetics/phonology).

1.5.   Predictions

In keeping with the Speed hypothesis, infants who rely on prosodic cues to

distinguish between native and non-native speech—that is, infants who are prosodically-

tuned (i.e., 3-to-6-month-olds)—should demonstrate right hemisphere-localized

differences in their hemodynamic responses for native compared with non-native

speech. Infants in a state of transition between processing predominantly prosodic and

phonological cues (i.e., 7-to-10-month-olds) should show a mixed pattern of

hemodynamic activation in the right and left hemisphere depending on the stimuli and

an infant's specific age. This group of infants may also demonstrate neural evidence of

familiarity with their native language, which in previous experiments has manifested

itself as greater hemodynamic responses for native compared with non-native speech

(Minagawa-Kawai et al., 2007; Minagawa-Kawai et al., 2011b). Finally, infants who have predominantly shifted to using phonological cues to distinguish between native and non-native speech (i.e., 11-to-14-month-olds) should have significantly greater hemodynamic responses in the left hemisphere for native compared with non-native speech. The current study was designed to test these predictions by using NIRS to collect hemodynamic data from a wide range of infants during exposure to native and non-native speech stimuli.

2. METHOD

2.1. *Participants*

Participants were 35 infants (17 females; between the ages of 3 and 14 months).

The 3-to-6-month-old group contained 14 infants (mean age 167 days, 7 females).   The

7-to-10-month-old group contained 13 infants (mean age of 252 days, 6 females). The

11-to-14-month-old group contained 8 infants (mean age of 352 days, 4 females).

A total of 45 infants were tested for this experiment, including those who were

lost or eliminated. Five infants were tested but did not contribute enough data to be

included in our sample; this included infants who cried and did not complete the

experiment as well as infants who pulled off the headband mid-run. Data from four

infants were lost due to machine malfunction during the session. One infant's data had

such excessive motion that no trials could be included.

Infants' names were obtained from birth announcements in the local newspaper

and commercially produced lists, and infants and parents were offered a new toy as

compensation for their participation. Informed consent was obtained from the parents

before testing began.

2.2. *Apparatus*

During the experiment, each infant sat on a parent or caretaker's lap in a testing

booth. Infants were positioned facing a 53-cm flat panel computer monitor (Macintosh

G4) 76 cm away (28.1° visual angle at infants' viewing distance based on a 36 cm wide

screen). The monitor was positioned on a shelf, immediately under which audio

speakers and a low-light video camera were positioned, oriented towards infants. The

monitor was framed by a façade that functioned to conceal the rest of the equipment. The façade was made of three sections. The upper third was a black curtain that covered the wall from side to side and dropped down 84 cm from the ceiling. The middle section, measuring 152 cm (wall to wall horizontally) x 69 cm high, was constructed of plywood and covered with black cloth. The plywood had a rectangular hole cut out of its center that coincided with the size of the viewing surface of the computer monitor (48 cm diagonal). A black curtain hung from the bottom edge of the section to the floor. The testing area was separated by a sound-reducing curtain from a control area, where an experimenter operated the NIRS instrument out of the infant's view. Fiber optic cables (15 m each) extended from the instrument to the testing booth and into a custom headband on the infant's head. The cables were bundled together and secured on the wall just over the parent's right shoulder.

The NIRS instrument consisted of three major components: (1) two fiber optic cables that delivered near-infrared light to the scalp of the participant (i.e., emitter fibers); (2) four fiber optic cables that detected the diffusely reflected light at the scalp and transmitted it to the receiver (i.e., detector fibers); and (3) an electronic control box that served both as the source of the near-infrared light and the receiver of the refracted light. The signals received by the electronic control box were processed and relayed to a DELL Inspiron 7000™ laptop computer. A custom computer program recorded and analyzed the signal.

The imaging device used in these studies produced light at 680 and 830 nm wavelengths with two laser-emitting diodes (Boas, Franceschini, Dunn, & Strangman,

2002). Laser power emitted from the end of the fiber was 4 mW. Light was square

wave modulated at audio frequencies of approximately 4 to 12 kHz. Each laser had a

unique frequency so that synchronous detection could uniquely identify each laser

source from the photodetector signal. Any ambient illumination that occurred during the

experiment (e.g., from the visual stimuli) did not interfere with the laser signals because

environmental light sources modulate at a significantly different frequency. No detector

saturation occurred during the experiment.

   The light was delivered via fiber optic cables (i.e., fibers), each 1 mm in diameter

and 15 m in length. These originated at the imaging device and terminated in the

headband that was placed on the infant's head. The headband was made of elasticized

terry cloth and was fitted with the two light emitting and four light-detecting fibers.

These were grouped into two emitter/detector fiber sets (i.e., optical probes), each

containing two detector fibers placed at 2 cm distance on either side from the central

emitter fiber. One optical probe was used to deliver near-infrared light to the left

temporal region at approximately position T_3 according to the International 10-20

system, and the other delivered light to the right temporal region at approximately

position T_4 (see Figure 1). NIRS data were analyzed first by channel within cortical

region, (where one paired emitter and detector fiber within each optical probe constituted

a channel and each optical probe contained two channels). Responses from the 4

channels were compared across cortical regions and conditions.

Schematic of NIRS headband
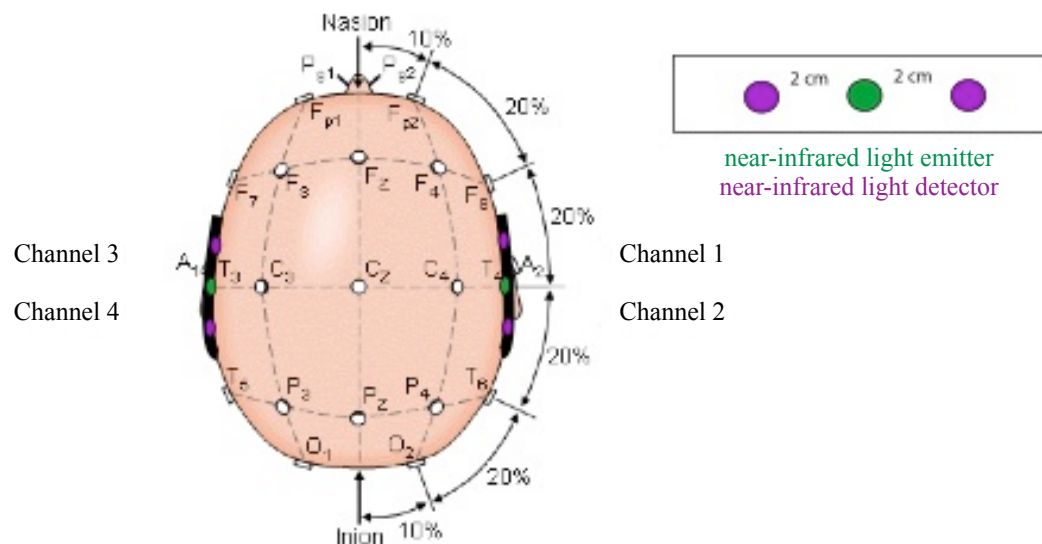
Fig. 1   Schematic of NIRS headband. Infants wore a NIRS headband with 2 sets of bilateral temporal channels. Channel 1 was located over the right anterior temporal area. Channel 2 was located over the right posterior area. Channel 3 was located over the left anterior area. Channel 4 was located over the left posterior area. The emitters were located over the 10-20 system coordinates of T_3 and T_4.

2.3.   Stimuli and design

The stimuli consisted of 20 second long audiovisual stories, delivered in sentence-level infant directed speech by a bilingual female speaker in English or Spanish. Spanish and English were selected as contrastive audiovisual speech stimuli for monolingually-exposed infants, as they have differing prosodic structures, which are important in enabling infants to distinguish between native and non-native speech within the first year.   More specifically, Spanish is an Ibero-Romantic (Latin-based) language that is syllable-timed language, meaning that there is consistency in the duration of each syllable. In contrast, English is a Anglo-Frisian language (West German-based) that is

stress-timed language, where there is a consistent amount of time between each syllable (Roach, 1982).

In addition to the audiovisual speech stimuli, visual-only trials consisted of visual animations (animated shapes on a high-contrast background) without sound. Each trial, regardless of type, was preceded by 10 second long baselines, where no auditory or visual information was presented. Conditions were blocked together, such that infants first saw 5 audiovisual Spanish trials (each preceded by a 10 second long baseline), then 2 visual-only trials (each preceded by a 10 second baseline), and finally 5 audiovisual English trials (each preceded by a 10 second long baseline) (See Figure 2).

Experimental Design

Fig. 2   Experimental Design. Infants observed a blocked-design that consisted of 20 second long audiovisual Spanish and English infant-directed speech. Each trial was preceded by 10 second long baselines. Spanish and English blocks were further separated by 20 second long visual-only trials of animated shapes.

This blocked design was employed to compare dynamic changes in cerebral blood flow across the course of alternating perceptual events (e.g., the 60-second blocks). Given the short run-time of the entire experiment (approximately 5 minutes), it was highly unlikely that infants became fatigued. Nonetheless, infants' responses were coded for anticipatory orientation towards the speaker and screen prior to trial onset (during the baseline period) and did not detect any behavioral anomalies.

All speech stimuli were recorded by the same (bilingual) female speaker, who relayed segments from children's stories using highly animated, infant-directed speech. The content of each speech segment was different, but all contained speech from the same speaker with the same animated intonation variation and positive affective tone. Recordings were made using a Sony digital camcorder, and then converted to .wav sound files using Sound Forge 6.0™ audio editing software (Huettel and McCarthy, 2001).

The visual-only stimuli consisted of simple, 3-dimensional objects (e.g., spirals, circles, and rectangles) similar in color contrast and motion parameters, and which rotated and moved slowly in front of a high-contrast, colored background. The animations were produced using 3-D Studio Max™ computer graphics software.

All auditory and animated digital files were combined using Adobe Premier 6.5™ video editing software, which produced .avi movie files that were then recorded onto a blank DVD. The recorded DVD was then played through the computer monitor and speakers. The hidden speakers were 82 cm from infants, facing them and producing audio stimuli at 75 dB SPL when measured from the approximate location of the infant.

2.4.   Procedure

After the parent and infant were seated, a head circumference measurement was taken from the infant using a standard cloth tape measure. Each parent was instructed to refrain from talking and interacting with the infant during the course of the experiment, and to hold the infant up so that they were able to comfortably view the screen. Parents

were also asked to guide infants' hands down and away from the headband if they began

to reach up during the experiment.

The experimenter then placed the NIRS headband on the infant. Following the

10-20 system, the two optical probes were adjusted over the left and right temporal

areas, centered over the T_3 position (on the left) and T_4 position (on the right). The

experimenter moved to the control area. The room lights in both the experimental and

control areas were turned off, leaving only a low intensity light to sufficiently illuminate

the experimental area, and light from the computer monitor to light the control area.

The source lights of the imaging device were turned on, and stimulus presentation and

optical recordings began. Infants were video recorded for the duration of the

experimental session for later coding of behavioral looking-times. See Figure 3 for

photograph of infant in testing booth during testing, with NIRS headband in place.

Testing Booth Set-Up

Fig. 3   Testing Booth Set-Up. Infants wearing the NIRS headband observed the audiovisual stimuli while seated on their caregiver's lap. A camera (outlined in yellow) directly below the audiovisual display recorded looking times.

3. RESULTS

A repeated-measures 2 (Condition: Spanish, English) x 4 (Channel: 1= right anterior temporal, 2= right posterior temporal, 3= left anterior temporal, 4= left posterior temporal) x 15 (timepoints per trial[1]) x 3 (Age: 3-to-6-month-olds, 7-to-10-month-olds, 11-to-14-month-olds) within-subject ANOVA was conducted (See Table 1).

Table 1

Repeated-Measures ANOVA

	Sum of Squares	df	Mean Square	F
Condition	666594.4	1	6665.94.4	19.95***
Channel	1453069.5	3	484356.5	14.5***
Age	286989	2	143494.5	4.29**
Conditon x Channel	335303.7	3	111767.9	3.34*
Condition x Age	291201.4	2	145600.7	4.36**
Channel x Age	3176986	6	529497.7	15.85**
Condition x Channel x Age	1680044.2	6	280007.4	8.38***

*$p < .05$. **$p < .01$. ***$p < .001$.

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[1] The timepoints utilized in this analysis were 6 seconds after stimulus onset through 20 seconds after stimulus onset (i.e. timepoints 6 through 20 seconds). The first 5 seconds were excluded from the analyses because the hemodynamic function is unlikely to begin during the first 5 seconds after stimulus presentation.

3.1.   Main effects

The main effect for Condition, $F(1, 1) = 19.95$, $p < .001$, demonstrated that, when considering the entire infant population of this study, different hemodynamic responses were elicited in response to processing native (English) and non-native (Spanish) speech (see Table 1). The main effect of Channel, $F(1, 3) = 14.5$, $p < .001$, indicated that over the course of the first year, infants generated different hemodynamic responses within the four channels (i.e., in left and right temporal cortices) during speech processing. Finally, the main effect of Age, $F(1, 2) = 4.29$, $p < .01$, indicated that infant hemodynamic responses to speech in general (regardless of native or non-native status) changed significantly over the course of the first year of life.

3.2. Interactions

Analyses also revealed several 2-way interactions, as well as a significant 3-way interaction between Condition, Channel, and Age (see Table 1). The first 2-way interaction for Condition and Age showed that infants in the different age groups generated different hemodynamic responses when perceiving native and non-native speech $F(1, 2) = 4.36$, $p < .01$ (see Figure 4). Paired t-tests showed that the oldest group (11-to-14-month-olds) demonstrated greater hemodynamic responses during native speech compared with non-native speech processing, $t(5) = 15.05$, $p < .0001$. In contrast, both the 3-to-6-month-olds, $t(5) = 0.45$, $p = 0.67$, and the 7-to-10-month-olds, $t(5) = 1.66$, $p = 0.16$, showed no significant difference between English and Spanish processing.
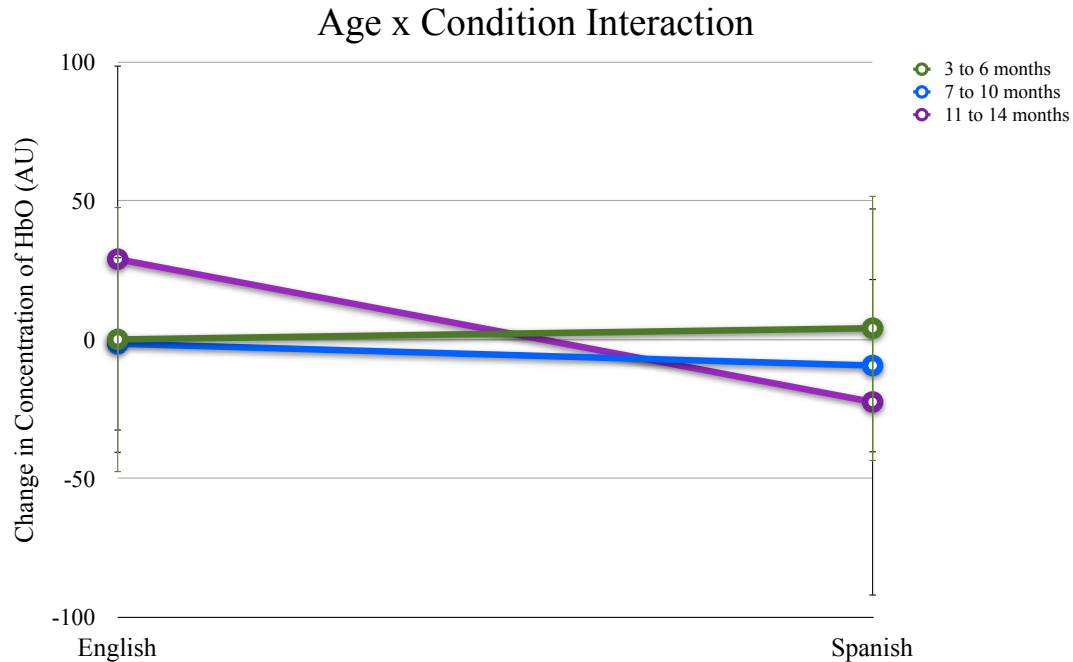
Fig. 4 Age x Condition Interaction. Data points represent the average number amount of HbO₂ between 6 and 20 seconds after stimulus onset for English and Spanish conditions in each of the three age groups (3-to-6-month-olds, 7-to-10-month-olds and 11-to-14-month-olds). Error bars represent standard error of the estimate.

The second 2-way interaction of Channel and Age, showed that hemodynamic responses over the course of the first year differed such that during speech processing infants differentially utilized the four temporal channels (and presumably the corresponding cortical resources), $F(1, 6) = 15.85$, $p < .001$. Bonferroni-corrected paired t-tests showed that the right anterior channel was utilized significantly more by 3-to-6-month-olds compared with both 7-to-10-month-olds, $t(11) = 3.78$, $p < .003$, and 11-to-14-month-olds, $t(11) = 16.03$, $p < .0001$. These analyses revealed further age-related differentiation, as the 7-to-10-month-old group generated significantly greater

hemodynamic responses than the 11-to-14-month-olds, $t(11) = 6.31$, $p < .0001$. This pattern indicated that the right anterior channel was utilized significantly less with age.

The last 2-way interaction of Condition and Channel demonstrated that hemodynamic response levels in bilateral temporal locations were influenced by the language infants attended, $F(1, 3) = 3.34$, $p < .05$. Specifically, analyses uncovered significantly greater hemodynamic responses for English compared with Spanish in the left anterior channel, $t(7) = 9.52$, $p < .001$. In contrast, significantly greater hemodynamic responses were generated for Spanish compared with English in the right anterior channel, $t(7) = 4.66$, $p < 0.05$.

A 3-way interaction of Condition and Channel and Age, $F(1, 6) = 8.38$, $p < .001$, qualified the main effects and 2-way interactions (see Figure 5). The two youngest age groups demonstrated significant differences between English and Spanish processing in the right hemisphere, whereas the oldest group demonstrated no significant difference in processing between conditions in the right hemisphere. Specifically, paired t-tests revealed that in the right anterior channel (i.e., 1) only 3-to-6-month-olds demonstrated a significant difference between speech conditions, such that a greater hemodynamic response was observed during Spanish compared with English speech processing, $t(23) = 7.07$, $p < 0.001$. In the right posterior channel (i.e., 2) both younger groups demonstrate significant differences between speech conditions, however the processing patterns differed. 7-to-10-month-olds' hemodynamic responses were greater for Spanish

compared with English, $t(23) = 3.36$, $p < 0.01$, however both values were negative.[2] In

contrast, 3-to-6-month-olds showed a greater hemodynamic response for English

compared with Spanish; these responses were also both negative and the comparison

was only partially significant, $t(23) = 3.12$, $p = 0.005$.

Only the oldest group (i.e., 11-to-14-month-olds) demonstrated significant

differences in processing of native and non-native speech in the *left* hemisphere. In the

left anterior channel (i.e., 3), 11-to-14-month-olds demonstrated hemodynamic response

difference for English and Spanish speech, such that a greater hemodynamic response

was generated for Spanish compared with English, $t(23) = 7.21$, $p < 0.001$. In the left

posterior channel (i.e., 4), all three groups demonstrated significant difference in

processing patterns for English and Spanish. Both the 7-to-10-month-olds and the 11-

to-14-month-olds demonstrated significantly different hemodynamic responses to

English compared with Spanish, $t(23) = 4.98$, $p < 0.001$, and, $t(23) = 3.70$, $p < 0.001$,

respectively. In contrast to the pattern found in the two older groups, the 3-to-6-month-

olds generated a greater hemodynamic response for Spanish compared with English,

$t(23) = 3.56$, $p < 0.01$.

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[2] The implications of negative hemodynamic responses will be explored in the
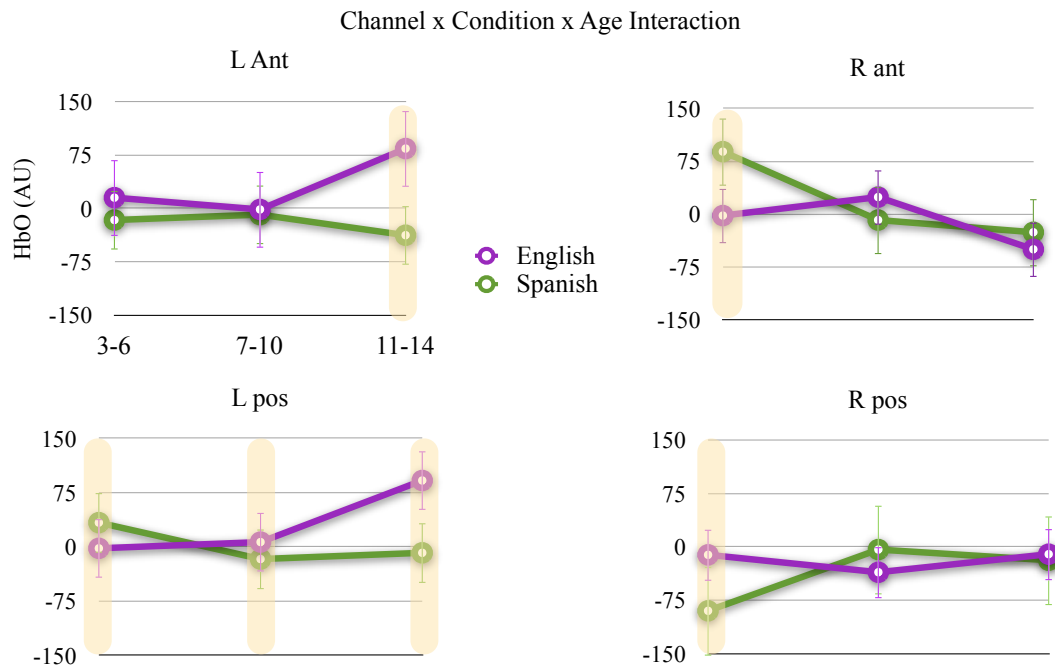discussion.

Fig. 5 Channel x Condition x Age Interaction. Data points represent the average amount of HbO2 between 6 and 20 seconds after stimulus onset for English and Spanish conditions in each of the three age groups (3-to-6-month-olds, 7-to-10-month-olds and 11-to-14-month-olds). Each channel location (right anterior, right posterior, left anterior, left posterior) is separately represented. Error bars represent standard error of the estimate. Significant results are highlighted with yellow.

3.3.   Planned comparisons

Whereas the ANOVA analyses have demonstrated clear differences between the age groups (i.e., 3-to-6-month-olds, 7-to-10-month-olds, 11-to-14-month-olds) in the context of channel (i.e., bilateral temporal cortical location), and condition (i.e., native and non-native speech perception), planned comparisons have the ability to analyze only the peak of the hemodynamic response functions. It was our *a priori* intention to examine these data for age-related differences in native and non-native speech processing during this specific interval, as this type of analysis enables examination of a more telling portion of the response, rather than comparing overall response levels

averaged across the entire stimulus duration and collapsing across time. Planned comparisons values were obtained by averaging hemodynamic responses for each age group during the interval 10-15 s after stimulus onset, as previous research with similar stimuli indicated that this time epoch typically includes the peak of the hemodynamic function (Bortfeld et al., 2007, 2009).

3.4.   3-to-6-month-olds' planned comparisons

Within the context of the planned comparisons, 3-to-6-month-olds demonstrated clear right lateralized differences in native compared with non-native speech hemodynamic responses (see Figure 6). However, the relative allocation of hemodynamic resources for these conditions differed. Specifically, in the right anterior channel (i.e., 1), Spanish elicited a greater hemodynamic response than English, $t(7) = 9.22$, $p < .001$. In contrast, in the right posterior channel (i.e., 2) English elicited a greater hemodynamic response compared with Spanish, $t(7) = 9.68$, $p < .001$.[3] No significant difference in the two conditions was observed in either left hemisphere channel (i.e., 3 and 4).

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[3] The implications of negative hemodynamic responses will be explored in the discussion.

Fig. 6 3-to-6-month-olds' planned comparisons. Statistical comparisons represent the average number amount of HbO2 between 10 and 15 seconds after stimulus onset for English and Spanish conditions in 3-to-6-month-olds. Each channel location (right anterior, right posterior, left anterior, left posterior) is separately represented. Error bars represent standard error of the estimate.

3.5.   7-to-10-month-olds' planned comparisons

As with the youngest age group, the 7-to-10-month-old group's left hemisphere channels (i.e., 4 and 3) showed no significant difference between native and non-native speech (see Figure 7). In contrast to the results observed in 3-to-6-month-olds, 7-to-10-month-olds' hemodynamic response in the right posterior channel (i.e., 2) was greater for native compared with non-native speech, $t(7) = 4.02$, $p < .001$, and was partially significant. No significant difference in condition was observed in the right posterior channel (i.e., 1).
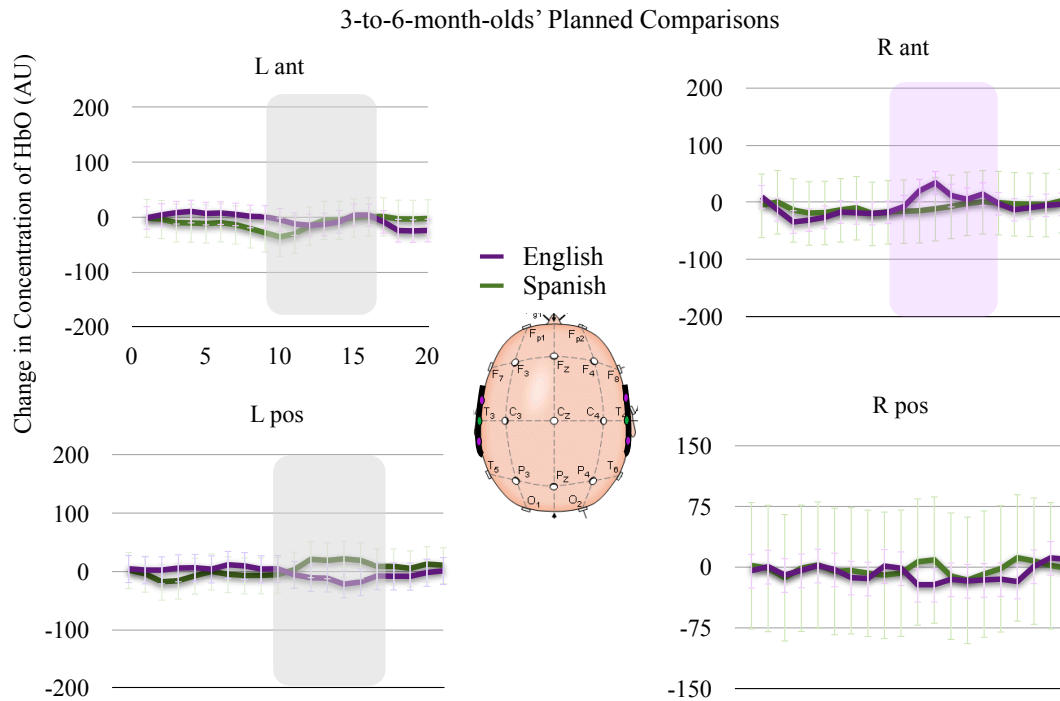
Fig. 7 7-to-10-month-olds' planned comparisons. Statistical comparisons represent the average number amount of HbO2 between 10 and 15 seconds after stimulus onset for English and Spanish conditions in 7-to-10-month-olds. Each channel location (right anterior, right posterior, left anterior, left posterior) is separately represented. Error bars represent standard error of the estimate.

3.6.   11-to-14-month-olds' planned comparisons

In contrast to the hemodynamic responses of both younger groups, the 11-to-14-month-olds were the only group to show *left* lateralized significant differences in their hemodynamic responses to native compared with non-native speech (see Figure 8). Furthermore, the oldest group alone demonstrated no significant differences between our speech conditions in the right hemisphere (as was the case with both younger groups). Specifically, the 11-to-14-month-olds showed significantly greater hemodynamic responses to native compared with non-native speech in the left anterior (i.e., 3), $t(7) = 10.10$, $p < .0001$, and the left posterior channels (i.e., 4), $t(7) = 12.90$, $p < .0001$.
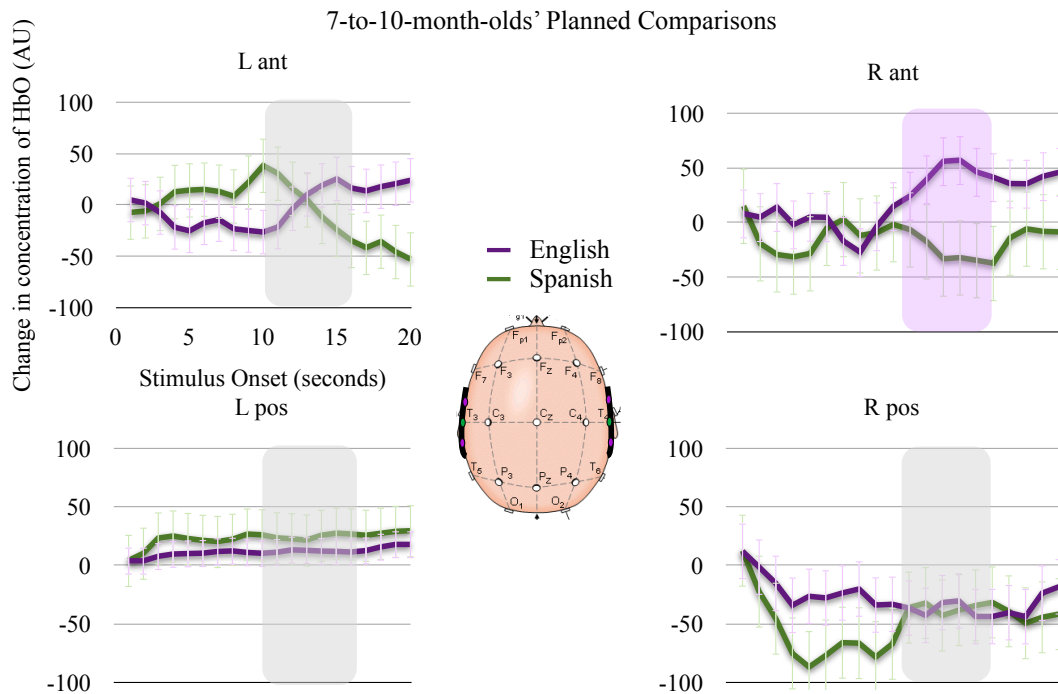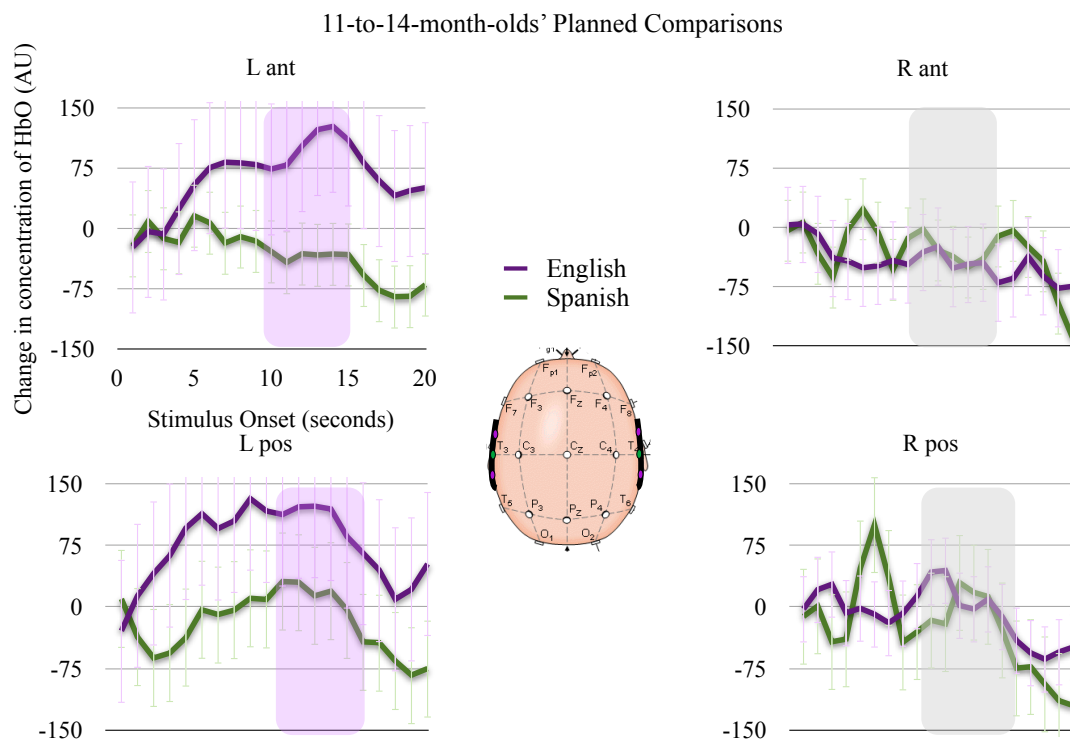
Fig. 8 11-to-14-month-olds' planned comparisons. Statistical comparisons represent the average number amount of HbO2 between 10 and 15 seconds after stimulus onset for English and Spanish conditions in 11-to-14-month-olds. Each channel location (right anterior, right posterior, left anterior, left posterior) is separately represented. Error bars represent standard error of the estimate.

4. DISCUSSION

The present study examined neural markers of language tuning in monolingually-exposed infants. To this end, infants were exposed to audiovisual English (native) and Spanish (non-native) speech as their hemodynamic response functions in four bilateral temporal channels were recorded and later compared.

4.1. *Left posterior response as a potential marker of advanced language tuning*

According to the behavioral literature, the oldest group of infants (11-to-14-month-olds) should have been capable of utilizing phonological cues to discriminate between native and non-native speech (Gervain and Mehler, 2010). Furthermore, previous neuroimaging data from children suggest that the left posterior temporal area is an important region for processing phonology-specific aspects of speech (Leonard et al., 1996; Eckert et al., 2001). Consistent with these data, both sets of analyses (i.e., ANOVA and planned comparisons) demonstrated that 11-to-14-month-olds displayed significantly greater hemodynamic responses for native compared with non-native speech in this channel. This pattern of hemodynamic response suggests that the left posterior temporal area is particularly involved in, and thus active during, the processing of native relative to non-native speech. In support of this observation, other researchers have likewise reported a pattern whereby native speech elicited greater hemodynamic responses than non-native speech, and they suggested that such a pattern of activation may serve as a neural marker of relatively mature language tuning (Minagawa-Kawai et al., 2007; Minagawa-Kawai et al., 2011b). Our own data support this characterization of a neural marker of language tuning.

Fascinating left posterior temporal results emerged from the younger groups (i.e., 3-to-6 and 7-to-10-month-olds) that may help to explain the conflicting nature of the infant tuning literature. The complex and nuanced nature of hemodynamic data means that different aspects of the hemodynamic response can be revealed with different methods of analysis. For example, averaging over the *entire course* of stimulus presentation in a "zoomed out" view results in a more general, gross measure of change in blood flow. This dataset likely represents more stable estimates of the hemodynamic responses with reduced effects of random error due to artificial effects (e.g., motion artifacts), which in turn increases the likelihood of detecting a significant effect of condition (i.e., native compared with non-native speech in our own experiment). These analyses showed differentiation between native and non-native speech for both younger groups, consistent with several published findings (e.g., Minagawa-Kawai et al., 2011b). More specifically, we observed an orientation toward novelty (i.e., greater response for non-native Spanish over native English) in 3-to-6-month-olds, whereas 7-to-10-month-olds demonstrate an orientation toward familiarty (i.e., greater response for English over non-native Spanish). Thus, when considering the entire averaged hemodynamic response, the data showed differentiation in response to native and non-native speech before phonological tuning in 3-to-6- and 7-to-10-month-olds.

However, when instead utilizing a "zoomed in" set of analyses, where the averaged *peak amplitude of the response* is compared, a more precise picture of the culmination of the hemodynamic response was present. Averaging over the peak results in the likelihood of a higher standard error term since fewer observations are used,

which in turn decreases the likelihood of detecting a significant effect of condition. This more stringent peak dataset demonstrated *no* evidence of language tuning in the posterior left channel for either 3-to-6 or 7-to-10-month-olds, consistent with the behavioral tuning timeline as well as published results in the neurophysiological tuning literature (e.g., Minagawa-Kawai et al., 2007).

Therefore, whereas the overall levels of hemodynamic activity in the left posterior channel reflected significant changes in the processing of native and non-native speech for younger infants (i.e., 3-to-6- and 7-to-10-month-olds), a more refined and accurate view of the peaks of the hemodynamic functions showed no difference between conditions for these same infants. Moreover, these peak analyses further support the notion that elevated hemodynamic activity in the left posterior channel in response to speech can serve as a neural marker of mature phonology-specific language tuning, as neither group demonstrated significant difference for native compared with non-native speech (in contrast to the 11-to-14-month-olds).

Overall, the left posterior data demonstrated that, for infants unlikely to use phonological cues to discriminate between native and non-native speech, hemodynamic resources were not specifically allocated to the left posterior temporal region, thereby leaving a relatively constant activation level in this region across speech conditions. The hemodynamic responses in the left posterior channel in infants between 3 and 10 months of age suggest that this region was not yet being engaged during processing to distinguish native from non-native speech.

One caveat to this interpretation is that the number of channels utilized in this study was quite low, thus limiting regions of focus to only left and right, anterior and posterior temporal areas. Clearly, further investigation is needed to determine the role of other cortical regions in the phonology-specific aspect of language tuning, in particular the prefrontal and frontal, as well as posterior temporal regions of the brain. Moreover, neural markers of language tuning may differ for infants with exposure to multiple languages or infants with sensory deprivation, such as congenitally deaf infants who subsequently receive a cochlear implant (Fava et al., in press) and thus are exposed to speech at a later maturational stage.   However, the current data suggest that the left posterior temporal region plays a unique role in distinguishing familiar and unfamiliar phonologies, thereby showing heightened levels of activity in those infants who are already tuned to the phonology specific to their native language (i.e., 11-to-14-month-olds). Heightened levels of activation in this region in response to one over another language thus appear to be a neural marker of relatively mature phonological processing.

4.2.   Consistent left anterior activation for language over the first year

Thus far, research using NIRS to study early speech processing has demonstrated a consistent left lateralized hemodynamic response to native speech in the first year of life (Peña et al., 2003; Bortfeld et al., 2007; Gervain et al., 2008; Bortfeld et al., 2009). Findings from the present research, in particular the interaction between age, condition and channel, are consistent with this, since infants in all three age groups that were tested showed similar hemodynamic responses to speech in the left anterior channel.

In the context of language tuning, both sets of analyses (i.e., ANOVA and planned comparisons) confirmed that only the 11-to-14-month-old group showed a significant difference in the hemodynamic response in the left anterior channel to native compared with non-native speech, suggesting that the left anterior region may be involved in some capacity in mature phonological language processing (i.e., a marker of mature language tuning). This mimics the hemodynamic response pattern seen in the left *posterior* temporal channel, with a greater hemodynamic response for native compared with non-native speech processing in this same age group. Both the 3-to-6- and 7-to-10-month-olds showed no difference in hemodynamic activity for native compared with non-native processing in this channel, as was also the case in the planned comparisons of the left posterior channel.

However, in terms of general speech processing (that is, collapsing across languages), there was no significant difference in hemodynamic responses in the left anterior region of the temporal cortex across age groups. Given this lack of regional differentiation for more general speech processing, as well as the consistent pattern of differentiation for phonological tuning observed in the left posterior channel for both language-specific and language-general processing, a more measured interpretation is appropriate. The absence of an age-related difference in the recruitment of the left anterior temporal region for any form of speech suggests that this area may be involved in processing low-level features of language that may not necessarily be tied to language tuning per se (Minagawa-Kawai et al., 2011a).

4.3.   Right hemisphere activity as an indicator of prosodic cues used for language

tuning

The present data revealed interesting age-specific differences in the right

hemisphere, where activity measured in the right anterior channel showed a significant

decreasing pattern across the three groups, consistent across both types sets of analyses

(i.e., ANOVA and planned comparisons). More specifically, 3-to-6-month-olds

demonstrated significantly greater hemodynamic responses for non-native compared to

native speech. However, the 7-to-10-month-old group showed significantly greater

hemodynamic responses for native than non-native speech (in contrast to the 3-to-6-

month-old infants, who showed the reverse pattern). Finally, the 11-to-14-month-olds

demonstrated no significant difference in hemodynamic responses for native compared

with non-native speech in the right hemisphere channels, suggesting this area was

utilized less as infants aged over the course of the first year to discriminate and process

native/ non-native speech stimuli.

Taken together, these results suggest that different patterns of hemodynamic

activity during processing of native and non-native speech can be used as neural

markers, or indicators, of the maturational state of language tuning. Behavioral evidence

of initial reliance on prosodic cues in order to differentiate native from non-native

speech, in addition to neurophysiological evidence of right lateralized pattern of

hemodynamic activation for processing of prosodic information, suggest that the current

data may present preliminary neurophysiological evidence of prosodic processing aiding

in language tuning. This could indicate that reliance on prosody as a cue to discriminate

between native and non-native speech changes over time, such that reliance on phonology may *increase* relative to the reliance on prosody, as infant gain more exposure and experience with speech. Therefore, 3-to-6-month-olds may have demonstrated significantly greater hemodynamic responses to non-native compared with native speech due to less experience with language, whereas 7-to-10-month-olds showed greater hemodynamic responses to native compared with non-native speech perhaps due to more experience with language. These results are consistent with neurophysiological studies that utilize the oddball paradigm, where a consistent stimulus set is contrasted with an inconsistent stimulus that elicits a significant change in the dependent variable (Gibson and Pick, 2000). In the case of the current data, "consistent" (i.e., familiar or native) speech stimuli evoke a lesser hemodynamic response than the "inconsistent" (i.e., unfamiliar or non-native) speech stimuli. In this context, it is reasonable to consider that the right anterior temporal area may be one of the first areas to demonstrate a shift toward tuning to the native language, at least within bilateral temporal cortices of monolingually-exposed infants.

4.4.   Interpretation of deactivated hemodynamic functions

In contrast to the right anterior area, 3-to-6-month-olds showed a deactivation in the hemodynamic responses for both speech conditions in the right posterior channel. Although deactivations have been reported in several NIRS studies (Sangrigoli and de Schonen, 2004), there is no current consensus in the field as to what these decreases in oxygenated hemoglobin indicate (Gallagher et al., 2007). Some researchers have proposed that decreases in oxygenated hemoglobin denote a decrease in the activity of

large neural populations (Enager et al., 2004). Others suggest that decreases in

oxygenated hemoglobin are the result of reduction in cerebral blood flow due to

redistribution of blood flow to different areas of the brain (Shmuel et al., 2002). In this

case, "redistribution" implies a measure of overall or global flow of blood, and is not

specific to a particular local area of activity (i.e., the "blood steal" phenomenon)

(Shmuel et al., 2002).   Still others propose deactivations could represent inhibitory

neural connections traveling to another region (Chen et al., 2005).

In the context of 4 measurement channels, it is difficult to pinpoint the root of the

observed decrease in hemodynamic response. Utilizing the current data, it appears that

the blood stealing explanation fits well, as within this context the deactivations make

sense if the right anterior channel is active and is obtaining HbO_2 from neighboring

regions to "fuel" its processing of the speech stimuli. Research from animal models

(e.g, Iadecola et al., 1997; Harrison et al., 2002) and adult fMRI (e.g., Smith et al.,

2004) investigations demonstrate that it is unlikely that deactivations cause a general

change in direction of blood flow (e.g., posterior to anterior) as several mechanisms and

structures within the brain regulate blood flow (e.g., Rodriguez-Baeza et al., 1998).

4.5.   Interpretation of the data in the context of the relative speed of tuning hypothesis

Overall, the current data provide support for the Speed Hypothesis (Fava et al., in

press), as infants of all ages, including those not old enough to have undergone

phonologically-specific language tuning, demonstrated significant differences in the

allocation of hemodynamic resources to native and non-native speech.

Specifically, the current data have provided evidence that neural markers of early language tuning may be present in the form of right lateralized differentiation of native/non-native speech processing in very young infants (e.g., 3-to-6-month-olds). Infants in this age range traditionally are not viewed as having tuned to the phonological cues of their native language (Werker and Tees, 2005; Fava et al., in press). However, behavioral evidence suggests that infants of this age are capable of distinguishing their native from another language using prosodic cues (Gervain and Mehler, 2010). Furthermore, neurophysiological evidence has demonstrated that infants in this age range may process prosodic information in a right lateralized fashion (Homae et al., 2006; Homae et al., 2007). Thus, taken together the current data can be taken as evidence of prosodic sensitivity in 3-to-6-month-olds. Surprisingly, this pattern held for the 7-to-10-month-olds as well, though the effect in this group was somewhat subdued.

The current data also add to the existing literature by demonstrating that hemodynamic responses to native compared with non-native speech are significantly more left lateralized, adding support to the view that left temporal area may be associated with more mature phonological sensitivity (Minagawa-Kawai et al., 2007; Minagawa-Kawai et al., 2011b). The fact that only infants over the age of 11 months demonstrated a possible neural marker for phonological language tuning suggests that this aspect of language tuning may require at least 11 months of typical speech experience, a view that is consistent with behavioral findings (e.g., Werker and Tees, 1984). The dynamic (i.e., shifting from right to left) pattern of hemispheric lateralization observed with increasing age suggests that neural markers of language

tuning are in a state of flux throughout the first year of life. Obviously, this means that other neural markers of language tuning can be found, above and beyond the left posterior temporal indicator of phonological language tuning observed here. It is likely that neural markers of language tuning that develop in a continuous fashion will be uncovered. In this sense, the current neurophysiological data are consistent with behavioral evidence of nested language tuning for different (e.g., prosodic, phonological) aspects of speech processing (Werker and Tees, 2005; Fava et al., in press).

Future research is needed in order to better understand the neurophysiological markers of progression of language tuning in infancy. In particular, one way to further study the potentially nested aspects of prosodic and phonological language tuning would be to first assign infants to tuning categories using behavioral measures, then compare and contrast these groups using neurophysiological technologies. Future experiments using this method of assigning infants to tuning categories could potentially reduce variability due to individual differences in language tuning. This reduction in variability could in turn provide clearer neurophysiological evidence of neural markers of language tuning. Another future direction for the investigation would be to compare and contrast the neural markers of language tuning for bilingually- and monolingually-exposed infants. This comparison would allow researchers to examine how experience with language and language environment impact the neural markers of language tuning while keeping biological maturation constant through comparison of similarly aged infants with monolingual or bilingual language profiles.

5. CONCLUSION

The present research revealed that the left posterior temporal region of the neocortex is a good candidate as a neural marker of relatively sophisticated, phonology-specific language tuning in infants. Indeed, increased left hemisphere activity for native compared with non-native speech may be evidence that phonology-specific language tuning has taken place. There is also evidence that the right anterior temporal area is utilized less and less over the first year of infancy, perhaps due to a reduction in reliance on prosodic cues across the first year.

More specific analyses revealed evidence of language tuning in infants who, according to the extant behavioral literature, should not yet be tuned to their native speech. In particular, 3-to-6-month-olds allocated more HbO_2 for non-native compared with native speech processing, whereas 7-to-10-month-olds also demonstrated language tuning in the right hemisphere, but used more HbO_2 to process native compared with non-native speech.

Overall, the present data support behavioral findings that different aspects (e.g., prosody, phonology) of the language elicit tuning at different rates, which suggests that language tuning is a nested process. Furthermore, neurophysiological technologies appear able to capture neural markers of these nested states of language tuning.

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