Neural Correlates of Verbal Communication using Infant Directed Speech in Language Acquisition: an fNIRS Investigation

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A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Bachelor of Science with Honors in Biopsychology, Cognition & Neuroscience from the University of Michigan 2015

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A big thank you to Dr. Silvia Bisconti, Dr. Frank Hu, Dr. Anne-Michelle Tessier, Dr. Renee Lajiness-O'Neill and members of the Kovelman and the fNIRS lab. A special thank you to my graduate student advisor, Neelima Wagley, for her unwavering support throughout my research endeavor from beginning to the end and to my faculty advisor, Dr. Kovelman, who provided me with the wonderful opportunity to be a part of her extraordinary research and lab. This research was approved by the IRB, IRB ID: HUM00079033.

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Abstract

Infant Directed Speech, or IDS, is often used to address infants and exhibits a variety of properties that differ from adult-directed speech. IDS overemphasizes acoustic cues that aid in segmentation of the continuous speech stream to promote interactions between higher-level linguistic knowledge and bottom-up perceptual processes necessary for successful speech perception thus assisting in the language acquisition process of infants. The present study examined the neural correlates of IDS in infants, particularly focusing on the impact of high and low frequency phoneme clusters. Brain activation levels in the bilateral frontotemporal, temporal, and temporoparietal regions were examined in the infants from monolingual, native English speaking homes using functional Near Infrared Spectroscopy (fNIRS). In general, infants showed neurotypical brain activation in response to both the high frequency and low frequency phoneme clusters in many areas of the brain thought to be used is language processing. The data suggests that infants as young as 8 months old may be able to perceive and process the specific speech cues (e.g. phoneme clusters) within segments of IDS, as part of the natural human language, versus nature sounds or rest. This may provide insight into how infants come to form the cognitive representations of sounds in their environment in aid of the language acquisition process.

Keywords: Infant directed speech, acoustic cues, phoneme clusters, neural correlates, fNIRS, language acquisition

Neural Correlates of Verbal Communication using Infant Directed Speech in Language Acquisition: an fNIRS Investigation

We have all been subject to a pragmatic example of how specific speech cues are picked up by an infant learning language. When addressing infants, caretakers and others in contact with the infants tend to speak to infants in a particular way (Phillips, 1973; Snow & Ferguson, 1977). This style of speech is called Infant Directed Speech (IDS), or what we all know as baby talk, or motherese. IDS is thought to serve three main functions towards the infants: attracting attention, conveying language-specific phonological information and conveying emotional affect (Uther, Knoll, & Burnham, 2007). Several studies have shown that babies pay more attention to IDS than regular or adult directed speech (ADS) (Cooper & Aslin, 1990; Fernald & Simon, 1984; Papousek, Papousek, & Symmes, 1991), prefer it, and are more emotionally responsive to it over ADS (Fernald, 1985; Fernald & Kuhl, 1987; Pegg, Werker, & McLeod, 1992). This preference can be observed in both their native language (Cooper & Aslin, 1990; Fernald, 1985; Papousek, Bornstein, Nuzzo, Papousek, & Symmes, 1990) and foreign languages (Fernald & Morikawa, 1993; Werker, Pegg, & McLeod, 1994).

IDS is particularly interesting to language acquisition researchers due to its properties including, but not limited to, slower rate, higher frequency, higher and greater pitch variation, longer pauses, hyperarticulated vowels, simplified sentence structure and repetitive intonational structures compared to ADS (Albin & Echols, 1996; Fernald & Mazzie, 1991; Fernald & Simon, 1984; Fernald et al., 1989; Garnica, 1977; Grieser & Kuhl, 1988; Papousek, Papousek, & Symmes, 1991). Utterance-final lengthening is more pronounced in IDS than in adult-directed English (Bernstein-Ratner 1986; Fisher & Tokura, 1996; Morgan, 1986). Compared to adult-directed English, pitch variation preceding pauses are more extreme in IDS and pauses between utterances are longer (Fernald & Simon, 1984; Stern, Spieker, Barnett, & MacKain, 1983).

Furthermore, the use of IDS in the language acquisition process of infants can be seen across many different cultures to assist in learning features unique to the native language (Ferguson, 1964). Pitch contours are often flattened and expanded in IDS and this occurs in languages such as Mandarin Chinese, where these pitch contours influence lexical tones (Grieser & Kuhl, 1988; Papousek & Hwang, 1991). It was found that Japanese speaking mothers stress the acoustic changes in pitch while English speaking mothers tend to emphasize acoustic changes in duration (Fisher & Tokura, 1996). These language-specific differences extend to a variation in the distribution of cues between IDS used by Japanese and English mothers which may potentially affect the distinctiveness of these cues (Werker et al., 2007).

The overemphasis of cues in IDS is found to aid in segmentation of the continuous speech stream (e.g. syllable and word boundaries) thus assisting in the language acquisition process (Soderstrom, 2007). Acoustic regularities in phonetic, lexical and discourse structure exhibited in IDS provide timing, pitch and a prosodic "template" as cues for word boundaries for infants (Fisher & Tokura, 1996). For example, the degree to which individual mothers' vowels are exaggerated in IDS correlates positively with the infant’s speech perception performance (Liu, Kuhl, & Tsao, 2003). 7 and l0 month-old infants were found to be sensitive to prosodic cues to clause boundaries in a stream of speech in IDS but not ADS (Hirsh-Pasek et al., 1987; Jusczyk et al., 1992). Since IDS typically places target words in the final position of a sentence, this may assist babies in the segmenting and remembering portions of the linguistic stream as part of the overall lexical acquisition (Golinkoff & Alioto, 1995). Furthermore, it is suggested that IDS helps infants to successfully segment speech in order to learn and recognize syllable and word patterns in their native language (Thiessen, Hill, & Saffran, 2005). The distinctive prosodic structure of IDS facilitates speech segmentation, word learning and recognition in infants (Johnson & Seidl, 2008; Kemler, Hirsh-Pasek, Jusczyk, & Cassidy, 1989; Seidl & Cristiá, 2008; Seidl, 2007; Singh et al., 2009).

While it is known that IDS evokes increased neural activity in 6 and 13 month-old infants compared to ADS (Zangl & Mills, 2007), little is known about the neural mechanisms underlying IDS in infancy in particular brain regions, specifically in conjunction with the use of additional cues naturally present in verbal communication.

IDS and Speech Perception

Processes that contribute to the perception of speech include perceptual grouping, lexical segmentation, statistical learning and categorical perception. By helping infants to organize speech in memory, features of IDS such as rhythm and melody of utterances serve a grouping function (Morgan et al., 1987). Additionally, the difference in the distribution of cues in IDS between languages influences phonetic category learning (Werker et al., 2007). During the infants' language acquisition process, IDS facilitates word mapping (Ma, Golinkoff, Houston, & Hirsh-Pasek, 2011), speech discrimination (Karzon, 1985; Liu, Kuhl, & Tsao, 2003; Trainor & Desjardins, 2002), phoneme categorization (Kuhl et al., 1997; Werker et al., 2007), separation of speech from background noise (Barker & Newman, 2004; Colombo, Frick, Ryther, Coldren, & Mitchell, 1995; Newman & Hussain, 2006), and locating linguistic units (Shady & Gerken, 1999).

Interactions between higher-level linguistic knowledge and bottom-up perceptual processes are necessary for successful speech perception. The prosodic bootstrapping hypothesis suggests that acoustic cues from IDS provide infants with bottom-up processes to segment of speech (Gerken, Jusczyk, & Mandel, 1994; Jusczyk et al., 1992; Kemler, Hirsh-Pasek, Jusczyk, & Cassidy, 1989; Morgan, 1986). Furthermore, top-down interactive mechanisms within auditory networks play an important role in explaining the perception of spoken language (Davis & Johnsrude, 2007). It was found that 8 month-olds are capable of using familiar words and statistical word learning to segment speech; thus showing evidence of the ability to combine top-down and bottom-up speech segmentation processes (Mersad & Nazzi, 2012). Sensory input, auditory search and verbal comprehension, aided by IDS, contribute to cortical activity during speech processing; however, not much is known about the details behind neural mechanisms behind these processes in infants.

Language Brain Correlates

Language processing is thought to be strongly left hemisphere lateralized in adults and involves a network of regions in the frontal, temporal, and parietal lobes (Binder et al., 1997); however, speech processing is also associated with areas in the right hemisphere (Friederici, Meyer, & von Cramon, 2000; Hickok & Poppel, 2000). The comprehension of language involves a distributed cerebral network with different regions preferentially processing certain functions (Price, 2000). This can be observed as aspects of language comprehension, such as phonological and acoustic processing, produce unique electrical brain responses when compared to other aspects of language comprehension, such as semantic and syntactic processing (Friederici, 1998).

Activation associated with language processing is seen in left temporoparietal regions outside the superior temporal gyrus, including the angular gyrus, middle temporal gyrus, and inferior temporal gyrus (Bookheimer et al., 1995; Damasio et al., 1996; Demonet et al., 1992; Frith et al., 1991) and temporoparietal junction (Young, Dodell-Feder, & Saxe, 2010). Processing of phonological information takes place in the left frontolateral cortex (Broca’s area), the inferior precentral gyrus (Price, Moore, Humphreys, & Wise, 1997; Zatorre, Evans, Meyer, & Gjedde, 1992) and supramarginal gyrus (Caplan, Gow, & Makris, 1995) and the left inferior frontal gyrus (Demonet et al., 1996; Indefrey & Levelt, 2000). Speech comprehension occurs in the bilateral medial and inferior temporal regions. Acoustic feature processing takes place in the dorsal temporal regions while acoustic complexity and auditory search shows activation in the left posterior superior temporal cortex (Wernicke's area). Attention and segmentation processes occur primarily in the dorsal part of Broca's area. The interaction of auditory attention and comprehension is present in the bilateral insulae, anterior cingulate and right medial frontal cortex (Giraud et al., 2004). The right frontolateral regions are thought to be sensitive to prosodic cues in speech (Meyer et al., 2003). The posterior superior temporal gyrus shows activation in the presence of acoustic changes in speech and non-speech stimuli, and the supramarginal gyrus is involved in the detection and comparison between changes in phonological units (Celsis et al., 1999). Superior temporal gyrus and middle temporal gyrus may be involved in the processing of acoustic cues (Barrett, 1910; Henschen, 1918; Kanshepolsky et al., 1973; Tanaka et al., 1987). In various studies, the bilateral lateral sulcus is reported as being involved whenever a resting period or auditory non-speech stimuli was used as a baseline (Just, Carpenter, Keller, Eddy, & Thulborn, 1996; Newman, Pancheva, Ozawa, Neville, & Ullman, 2001; Sakai, Hashimoto, & Homae, 2001; Vandenberghe, Nobre, & Price, 2002). Processing of auditory language generally shows activation in the primary auditory cortices and superior temporal gyrus bilaterally (Friederici, Meyer, & von Cramon, 2000). Previous studies have focused on brain activation in adults; however, not much is known about the neural correlates of infants regarding language acquisition.

Syllable and Phoneme Clustering

Infants possess powerful mechanisms suited to learning the types of structures exemplified in linguistic systems in their native languages. Newborns have shown the ability to discern between prosodic cues of their native language compared to a non-native language (Mehler et al., 1988). 4 month-old infants are able to differentiate between changes in stress patterns in speech (Jusczyk & Thompson, 1978; Spring & Dale, 1977). Furthermore, 9 month-old infants from native English speaking homes have exhibited preference to disyllabic words with a stress pattern common in English over words with less characteristic patterns (Jusczyk, Cutler, & Redanz, 1993). By this age, native English-hearing infants are able to discern prosodic cues for clause and phrase boundaries in English (Hirsh-Pasek et al., 1987; Jusczyk et al., 1992).

Experience with the phoneme and syllable clustering, and statistical cues pertinent to the native language are important in language acquisition. The syllable in language has often been regarded as the unit that helps humans recognize spoken words (Cutler, Mehler, Norris, & Segui, 1986; Mehler, Dommergues, Frauenfelder, & Segui, 1981; Morais, Content, Cary, Mehler, & Segui, 1989). In each language, certain combinations of consonants and vowels sounds often occur together: these are called high frequency phoneme clusters (e.g. sle; CCV). Other combinations of consonants and vowels sounds are not frequently observed: these are called low frequency phoneme clusters (e.g. ltst, CCCC). When presented with visual recognition tasks, syllable frequency influenced the response times across languages, such as English (Macizo & Petten, 2007), Spanish (Alvarez, Carreiras, & Taft, 2001; Carreiras, Alvarez, & De Vega, 1993; Perea & Carreiras, 1998), French (Mathay & Zagar, 2002) and German (Conrad & Jacobs, 2004). While many studies have focused on visual recognition tasks, little has been done in terms of auditory tasks to observe the effects of frequency of syllables in English. Throughout development, infants learn about the high and low probability of syllable occurrences and are increasingly able to form and distinguish syllable clusters.

As previously mentioned, cues given from IDS help to facilitate the recognition and formation of boundaries of syllables and words (Saffran, Aslin, & Newport, 1996). In addition to being preferred by infants, IDS also assists infants in learning patterns of high frequency and low frequency phonemes. Thus, an in-depth understanding of the perceptual and neural correlates associated with IDS and phoneme clustering may help to better understand the mechanisms behind the earliest milestones of language acquisition.

The Present Study

Little is known about the specific neural mechanisms underlying phoneme clustering and IDS during speech perception at infancy. The present study aims to address the following questions in hopes of shedding light on the complex processes behind language acquisition: 1) What are the neural correlates of IDS early in infancy? 2) How do high and low frequency phoneme clusters impact the neural mechanisms behind speech processing and language acquisition? Furthermore, what implications might this have on typical and atypical language development as infants grow to fully master their native language? We expect to find brain activation in the bilateral frontotemporal, temporal and temporoparietal regions of the brain, given that these are the primary areas used in language processing. Additionally, if infants are able to use cues to infer statistical patterns, and distinguish phoneme cluster patterns, we predict that there will be greater activation for the high frequency clusters compared to the low frequency clusters in the brain regions.

The present study uses functional near-infrared spectroscopy (fNIRS) imaging device to observe brain activity in infants. Although fNIRS imaging has poor spatial resolution (only a few centimeters beyond the scalp) and decreased signal-to-noise ratio in comparison to fMRI, it is ideal for the study of infants because it is non-invasive, provides measurements of both oxygenated and deoxygenated hemoglobin concentrations changes, and exhibits exceptional temporal resolution (Cui et al., 2010; For a review of fNIRS studies of language processing see Quaresima, Bisconti, & Ferrari, 2012; Rossi, Telkemeyer, Wartenburger, & Obrig, 2012). Caregivers complete standardized questionnaires and infants underwent behavioral measures followed by neuroimaging with fNIRS while listening to speech segments in IDS.

Using fNIRS, we measure the hemodynamic response of deoxygenated and oxygenated hemoglobin (HbO and HbR respectively) levels as the analysis variable. We observe the levels of activation in the auditory cortices and language areas, such as the superior temporal gyrus (Wernicke's Area) and inferior frontal gyrus (Broca's Area), in the overall frontotemporal, temporal and temporoparietal brain regions.

To analyze the data, we use the paired t-test to compare groups differences in mean concentrations (HbO and HbR) between the high and low IDS conditions, nature sounds and rest period to determine whether there is significant difference in the hemodynamic levels in specific brain areas between the conditions. This allows the comparison of results to the control in order to determine whether the hemodynamic levels are statistically significant to language processing and not just the result of general auditory stimulation. Furthermore, we administer behavioral measures of receptive language using the The Infant Behavior Questionnaire-Revised and Mullens Scales to further give us an index of the developing brain undergoing language acquisition at infancy. By observing the neural mechanisms that are fundamental to this process, we aim to learn more about the neuro-developmental phenomenon of language acquisition early in infancy.

Method

Participants

Thirteen typically developing infants participated in the study. There were 8 female (Mean age at testing= 285 days or 9 months and 11 days, SD = 12 days, range= 267-308 days or 8 months and 24 days to 10 months and 4 days) and 5 male participants (Mean age at testing= 283 days or 9 months and 9 days, SD = 14 days, range= 270-303 days or 8 months and 27 days to 9 months and 30 days). Participants were recruited using the OB Registry from the University of Michigan's Department of Psychiatry and tested at the Center for Human Growth and Development. Infants were from monolingual, native English speaking homes, had no history of hearing impairments, and received a monetary compensation for participating in the study.

Inclusion and Exclusion Criteria

Infants were of a 37-42 week gestation, had a birth weight of at least 2500g, no history of prenatal or intrapartum complication, and no brain injury, neurological illnesses or disease (e.g. seizures) or known genetic disorder. Channels were excluded from analysis of the data for excessive signal noise as determined by the fNIRS data files, usually due to poor cap fit, fussiness, displaced probes, or technical difficulties.

All interactions complied with the ethical guidelines and regulations set forth by the University of Michigan. Written informed consent was obtained prior to participation from parents who accompanied the infants. The study was approved by the IRB.

Behavioral Measures of Development

Infant Behavior Questionnaire- Revised (IBQ-R). Parents completed the detailed Infant Behavior Questionnaire - Revised (IBQ-R; Rothbart, 1981). The IBQ collects data from caregivers regarding infants' temperament in terms of activity level, distress to limitations, fear, duration of orienting, smile and laughter, high intensity pleasure, low intensity pleasure, soothability, falling reactivity/rate of recovery from distress, cuddliness, perceptual sensitivity, sadness, approach and vocal reactivity of the infants.

Mullens Scales of Early Learning. In order to examine linguistic, cognitive, and motor development, all infants completed standardized assessment of the Mullens Scales of Early Learning subsets visual reception, fine motor, receptive language and expressive language (Mullen, 1995) in a controlled lab setting with a trained experimenter. For the purpose of this project, only the subsets of receptive and expressive language are discussed. Receptive language measures the infant's ability to understand language and concepts and follow directions (how "receptive" the infant is). Expressive language observes the infant's use of language to productively communicate ideas and ability to engage in abstract thinking and reasoning.

Functional Near Infrared Spectroscopy (fNIRS)

fNIRS. We used functional Near Infrared Spectroscopy (fNIRS) by TechEN to measure infants' brain activation. fNIRS is a relatively new technology for the study of human brain function. There were three reasons for choosing fNIRS brain imaging: first, fNIRS can measure brain oxygenation in frontal, parietal, temporal, and occipital regions of interest; second, fNIRS allows for language testing in an ecologically valid setting (e.g. sitting on a caregiver's lap); third, fNIRS is child friendly and allows for the experimentation to take place with younger populations.

Experimental stimuli were presented using E-Prime 2 (Psychology Software Tools, Inc.) on a 23-inch Philips 230E Wide LCD screen connected to a Dell Optiplex 780 desktop computer. For each infant, pictures of the fNIRS headband placement at the end of the brain imaging session. The study used a TechEN-CW6 system with 690 nm and 830 nm wavelength to measure oxygenated, deoxygenated and total hemoglobin levels while the infant listens to experimental stimuli.

fNIRS Cap Design and Imaging Set-Up. Prior neuroimaging studies on language processing suggest that several areas play a role in language acquisition. For the frontotemporal brain region, we consider the bilateral areas around the inferior frontal gyrus while for the temporal region, we examine the bilateral areas around the superior temporal gyrus and for the temporoparietal region, we observe the bilateral areas around the temporoparietal junction. Thus, our probeset and cap was designed to measure brain signal from these regions. Specifically, the probe configuration thus covered bilateral frontal, temporal, and parietal regions of interest listed above with anchors corresponding to the international 10-20 system (Jurcak, Tsuzuki, & Dan, 2007). There were a total of 30 data channels (Figure 1). For the regions of interest for this project, only 20 channels are analyzed. The bilateral frontotemporal brain regions were investigated by 8 total channels using 4 probe-detector pairs for each of the left and right hemispheres. These probes covered regions that such as the inferior frontal gyrus, Pars opercularis (Broca's area) and lateral sulcus. The bilateral temporal brain regions were investigated by 8 total channels using 4 probe-detector pairs for each of the left and right hemispheres. These probes covered regions such as superior temporal gyrus, middle temporal gyrus and inferior temporal gyrus. The bilateral temporoparietal brain regions were investigated by 4 total channels using 2 probe-detector pairs for each of the left and right hemispheres. These probes covered regions that such as temporoparietal junction, angular gyrus, supramarginal gyrus and Brodmann area 22 (Wernicke's area). The distance between each light emitter and detector was 2.0 cm. The data was acquired at a sampling rate of 50 Hz. The cap was adjustable so it can fit comfortably and causes no pain. Atlas Viewer Gui software was used to design the optode configuration and head caps. TechEN-designed optode-holders were imbedded into the cap to support the optodes. The caps were placed on the infants' heads following the 10-20 system, anchoring on specific coordinates for each participant. Pictures of the infants wearing the cap were taken to ensure uniform cap positioning (Figure 2).

Brain-imaging Tasks

Experimental Task: Infant Directed Speech (IDS). Infants listened to eighteen second segments of infant directed speech recordings presented under two conditions: high-probability nonce words containing two or three English syllables of high-probability onset (C) and high-probability rime (VC), where the stress was placed on the initial syllable; and low-probability nonce words containing two or three English syllables of low-probability onset (C) and low-probability rime (VC), where the stress was placed on the final syllable. The high frequency (HF) and low frequency (LF) conditions were recorded in IDS (i.e. motherese) by a female, native English-speaking linguist.

Control Task: Nature Sounds. Eight second long nature sound clips were used as a control condition to measure brain activation given that it can induce auditory stimulation without recruiting brain areas necessary for linguistic or musical processing. The clips were downloaded from the internet and consisted of waves, forests, rain, stream, wind, and river.

Procedure

Caregivers were requested to fill out the written informed consent forms. After parental consent, the infants underwent head measurement and marking of fNIRS cap anchor points. The caregivers and infants then completed behavioral and language tasks. This included the Mullen Scales of Early Learning and the IBQ as described above. The caregivers filled out the Infant Behavior Questionnaire-Revised while the Mullen Scales of Early Learning was administered to the infants according to the standardized format detailed in the Mullen Scales of Early Learning Item Administration Book (Mullen, 1995).

The caregivers and infants were then moved to the testing room with the fNIRS machine for the brain-imaging portion of the experiment. The infant was given time to become familiar with the room and adjust and then underwent fNIRS cap placement procedure. Throughout the task, the infant sat on the lap of the caregiver or parent. Using the anchor points for placing the cap, the cap was fitted accordingly to make sure that the optode to skin contact was maximized. Using the fNIRS machine, the signal was checked to ensure proper fitting and data collection.

Before the start of the presentation of brain imaging tasks, the lighting in the room was dimmed to focus the infant's attention to the stimuli screen. While the brain imaging tasks were presented, a baseline video of moving objects (on mute) was displayed on a monitor at a distance of approximately 100 cm.

Brain imaging tasks were aurally presented by speakers equidistant to the infant in terms of the three conditions: IDS with high-frequency syllables, IDS with low-frequency syllables and nature sounds. IDS speech in each condition was presented eight times, for a total of 24 trials (Figure 3). Additionally, there was an eight second "rest" period of silence between each trial. Thus, the total duration of verbal paradigm was approximately 10 minutes and 30 seconds. The order of conditions was generated in a randomized order and this order was sequentially presented to each participant.

Data Analysis

Behavioral Data Analyses. Raw scores from the IBQ-R were calculated based on the report's scale. Parents rated infant's temperamental characteristics as ranging from 1-7 with 1 being "never", 4 being "sometimes" and 7 being "always" in regards to how much the infant engages in the said activity. Mean, standard deviations, and ranges for each IBQ-R subset are reported in Table 1.

For each infant, raw scores and *t*-scores were calculated for each subset of the Mullens Scales of Early Learning. Statistical mean *t*-score values, standard deviations, ranges, and percentile ranks are reported in Table 2.

fNIRS Data Processing and Analysis. Data processing was completed using Homer2, a free MATLAB-based software (Huppert, Diamond, Franceschini, & Boas, 2009). The fNIRS data signal was first analyzed in terms of pre-processing and then post analysis. In the pre-processing stage, the raw data was converted into hemoglobin levels and filtered to remove motion artifacts, physiological noise or system noise. In post analysis, block averages amd statistical analyses were calculated.

First, raw time course data obtained from the fNIRS system were marked with assigned stimulus markers (high frequency phoneme clusters (HF), low frequency phoneme clusters (LF) and nature sounds (Nat). The data was then converted into units of optical density change (ΔOD). Next, the ΔOD data went through a quality control step to check if there was oversaturation in the signal due to noise or if any participants did not complete the entire experimental session. We then used the Prune Channels function in Homer2 to examine the signal to noise ratio in the ΔOD data. The prune channels exhibit whether the signals in specific channels are too weak, too strong or standard deviation was too great based on the overall mean and standard deviation of the signal. Channels were excluded by setting minimum and maximum threshold values for the Prune Channels function in the processing stream. The established range for the threshold used was the signal to noise ratio being greater than 80 decibels and less than 120 decibels. The channels that did not meet the examination criteria were thus excluded from analysis.

Furthermore, the function was also able to exclude channels with a source-detector separation of less than or greater than the appropriate value of 2.0 cm as discussed previously, which could have occurred due to displacement of the probes as a result of poor cap fitting and/or the infants' movements.

Next, we used the Motion Artifacts by Channel function in Homer2 to identity the motion artifacts in the ΔOD time series. Signals from other sources of noise (e.g. motion artifacts, cardiac pulsations and respiratory noise) could have influenced the target stimulus-evoked response signal. Artifacts were defined by identifying signals above or below the threshold of 10 standard deviations from the mean, with an amplitude threshold of 0.5 within a time period of 5 seconds. We removed trials with associated data identified as artifacts. Subsequently, the data then underwent motion artifact correction through the Motion Correct PCA function. PCA, or principal component analysis, is a method that emphasizes variation and highlight strong patterns in the data to improve visualization. The PCA function decomposed the original data into two principal components based on the assumption that there will be total variation in the data. Each component displayed a pattern. One component was the motion artifacts that were identified in the previous step. The motion artifacts were large in magnitude and thus captured a bigger variation proportion in the signal when compared to the signal from the task involved in the data. The second component was the variation proportion of the stimulus-evoked response signal. By utilizing PCA, the larger variation proportion of the two signals were detected and rejected in order to remove the motion artifact from the dataset. By setting the threshold of 80%, the motion artifact related component was captured in 80% of the variation data while the task involved signal was only captured in 20% of the variation in data. This was the optimal threshold in order to to remove the motion artifact signal while still keeping the target signal and produce a more clear motion-corrected signal with the ideal shape for the hemodynamic response.

Finally, a lowpass filter with cutoff frequency at 0.8 Hz was applied to the ΔOD data to remove extraneous noise signal such as white noise and Mayer waves (cyclic changes in arterial blood pressure). Finally, the hemoglobin concentration change was calculated using the modified Beer-Lambert law, which yielded HbO (oxygenated hemoglobin), HbR (deoxygenated hemoglobin) and HbT (total hemoglobin) values. Thus, the output was the changes in hemodynamic response in terms of percentage of signal change over the duration of the experiment.

In post analysis, block averages of the data were calculated. The changes in HbO, HbR and HbT levels for all trials given in each experimental condition was averaged across all 30 channels. Using SPSS statistical software (IBM), the statistical mean values of HbO, HbR, and HbT, standard deviations, p-values and t-test results were then calculated. The data was evaluated using paired sample t-tests between conditions (IDS with high frequency phoneme clusters, IDS with low frequency phoneme clusters, nature sounds and rest period) and brain regions (Left and Right Temporal, Left and Right Temporoparietal, and Left and Right frontotemporal) as the within subject factors.

Results

Behavioral Measures of Development

Refer to Table 1 for infant's task performances on behavioral measures of the Infant Behavior Questionnaire-Revised and Table 2 for the Mullens Scales of Early Learning. Due to delayed submission, complete data of seven infants for the IBQ-R were available. Similarly, we were only able to report the scores on the Mullens tests for ten of the infants. For the IBQ-R temperament measurements, the means and standard deviation for the infants lie within the average and normal range of values (*M*= 3.01-6.62, *SD*= 0.40-1.36). For the Mullens receptive and expressive language measurements, the means and standard deviations for the infants (*M*= 47.9-55.3, *SD*= 4.8-11.5) and the equivalent percentile ranks lie within the range of "average" descriptive categories.

fNIRS Imaging.

Paired samples t-tests was conducted to compare mean changes in HbO concentration in HF and LF conditions (Figure 4), HF and Nature, HF and Rest, LF and Nature, and LF and Rest. There was a significant difference in mean HbO concentration for HF and LF conditions in the following brain areas: left frontotemporal ($t(39) = 2.77$, $p < 0.01$), right frontotemporal ($t(29) = 3.34$, $p < 0.01$), right temporal ($t(29) = 10.97$, $p < 0.001$), right temporoparietal ($t(13) = 4.29$, $p < 0.001$). There was a significant difference in mean HbO concentration for HF and Nature conditions in the following brain areas: right frontotemporal ($t(28) = -5.89$, $p < 0.001$), right temporal ($t(24) = 4.61$, $p < 0.001$), right temporoparietal ($t(13) = 5.70$, $p < 0.001$). There was a significant difference in mean HbO concentration for HF and Rest conditions in the following brain areas: right frontotemporal ($t(29) = -2.37$, $p < 0.05$) and the right temporoparietal ($t(13) = 5.70$, $p < 0.001$). There was a significant difference in mean HbO concentration for LF and Nature conditions in the following brain areas: left frontotemporal ($t(33) = -7.39$, $p < 0.001$), right frontotemporal ($t(28) = -5.71$, $p < 0.001$), left temporal ($t(29) = -8.39$, $p < 0.001$), right temporal ($t(24) = -5.82$, $p < 0.001$), left temporoparietal ($t(12) = -5.23$, $p < 0.001$). There was a significant difference in mean HbO concentration for LF and Rest conditions in the following brain areas: left frontotemporal ($t(33) = -7.39$, $p < 0.001$), right frontotemporal ($t(31) = -3.37$, $p < 0.01$), right temporal ($t(33) = -2.67$, $p < 0.05$), left temporoparietal ($t(12) = -5.23$, $p < 0.001$).

Discussion

The present study examined the neural correlates of IDS in infants, particularly focusing on the impact of high and low frequency phoneme clusters. The oxygenated and deoxygenated hemoglobin levels in the frontotemporal, temporal and temporoparietal brain regions were observed in the infants between the ages of 8 months to 10 months from monolingual, native English speaking homes using fNIRS. Additionally, behavioral measures of development and brain imaging tasks were conducted.

Previous studies have observed that IDS is preferred by and assists infants during their language learning process (Cooper & Aslin, 1990; Soderstrom, 2007; Thiessen, Hill, & Saffran, 2005). IDS exhibits a wide variety of properties, many of which have been studied in-depth in relation to the influences on infants. This study focused on the ability of infants to perceive phoneme clustering patterns within segments of IDS, which may be important for aiding the language acquisition process and examined the underlying neural mechanisms behind this process.

The data from standardized behavioral measures of development showed that the infants were of term and typically developing for their age group. Primarily, they scored average on all the tasks both in the Infant Behavior Questionnaire- Revised and the Mullens Scales of Early Learning. Particularly of importance, they scored in the range of the average descriptive percentile for the expressive and receptive language tasks.

The data from the fNIRS brain imaging tasks showed that there was neurotypical brain response to language, as expected, in the infants within the specific language processing regions of the brain. Previous research has shown language processing activations in specific areas within the brain regions as observed in this study such as: phonological information processing in the inferior frontal gyrus (Demonet et al., 1996) and the Pars opercularis or Broca's area (Zatorre, Evans, Meyer, & Gjedde, 1992) in the frontotemporal region, acoustic cues processing in the superior and middle temporal gyrus (Barrett, 1910; Kanshepolsky et al., 1973) in the temporal region and acoustic complexity activation in Wernicke's area (Giraud et al., 2004) in the temporoparietal region. Preliminary analyses of the data showed differences in activation (as measured by Hb0 concentration) between high frequency phonemes and nature sounds in the right frontotemporal, right temporal and right temporoparietal areas and between low frequency phonemes and nature sounds in the bilateral frontotemporal, bilateral temporal and left temporoparietal brain regions. Furthermore, there appears to be differences in activation between high frequency phonemes and the rest condition in the right frontotemporal and right temporoparietal regions and between low frequency phonemes and the rest condition in the bilateral frontotemporal, right temporal and left temporoparietal brain regions. The data suggests that infants as young as 8 months old may be able to perceive and process the specific speech cues (e.g. phoneme clusters) within segments of IDS differently, versus nature sounds or rest. This may provide insight into how infants come to form the cognitive representations of sounds in their environment in aid of the language acquisition process.

Given the preliminary nature of the study and analyses methods, only limited generalizations can be made. The data supports that the neural mechanism involved in language processing show differential response to language versus nature sounds and language sounds versus rest. With regards to the ability to distinguish between high frequency and low frequency phoneme clusters, the brain activation show that the infants may be processing these two conditions in distinct regions. The findings show differences in processing in bilateral frontotemporal, right temporal and right temporoparietal brain regions. However, it is important to note that this difference could be the result of infants already having been more exposed to the high frequency phonemes and less exposed to the low frequency phonemes by the time they reach 8 months of age. Thus, we cannot really know if the representations of high frequency and low frequency phonemes are different in the infant brain by solely measuring brain activation. More in-depth research is necessary in order to fully observe the differences in processing of high frequency and low frequency phonemes. One approach to assessing this issue could be by using a behavioral paradigm, specifically a head turn preference paradigm, to take into account the effects of familiarization.

Limitations

One of the limitations in the methodology of this study is the sample size. A larger number of participants would greatly help to compile cleaner data and produce more concrete results. Furthermore, it would also assist in minimizing certain concerns with the infants that may have influenced the data. One of these issues is the fact that some infant participants ended their trials earlier than the intended total duration due to discomfort or fussiness. Thus, some participants only produced partial data. Another topic of concern is the question of whether the infants were really paying attention to the stimuli while passively listening. While participants were from monolingual, native English speaking homes, there is the possibility that the infants had been exposed to sounds from other languages in foreign environments. Depending on the frequency, this may or may not have impacted the neural processing of syllable conditions in English.

In terms of the fNIRS technique, although the probe configurations were arranged in a defined way for all of the participants, the arrangement may or may not have been able to efficiently and best collect the data. The spacing of the source and detectors can be altered to maximize the depth of the brain and measure more of the brain tissue for infants. While this is ideal, the available space on the cap for an infant head is constrained and limited. Furthermore, while steps were taken to ensure the minimization of the probe shifts, this could have still occurred as some participants were more active than others, causing large motion artifacts.

A general concern of the field is the topic of subjective analysis as data analysis parameters are set by the experimenters based on previous literature. This may guide the experimenters choices and influence decisions that may impact the data.

Future directions

A potential progression of this study may be to perform a similar study with participants who are grouped by age in terms of months. In infancy, development takes place rapidly and even a month-long development has a large influence on brain and language development. Thus, by performing a longitudinal study, the progression and changes of neural correlates of language acquisition can be observed.

Another possibility would be to examine other qualities of speech such as prosodic features of pitch, rhythm, stress and intonation of speech among others mentioned in the Introduction. By studying the neural correlates of these properties as well as the comparison between properties, the interactions of how cues aid infants in language acquisition can be perceived. Additionally, the study could be extended to include other languages and speech properties unique to certain languages. This might help to further understanding of language development across cultures.

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Tables

Table 1

Parent-report Data from Infant Behavior Questionnaire-Revised.

IBQ-R Subset	N	Range	Mean	Std. Deviation
Act	7	3.93-6.20	5.19	0.68
Dist	7	2.94-4.88	3.57	0.78
Fear	7	1.50-3.63	3.01	0.78
Dura	7	2.90-5.50	4.21	1.07
Smil	7	4.30-6.70	5.63	0.85
HIP	7	5.82-7.00	6.62	0.42
LIP	7	4.62-6.63	5.65	0.82
Soot	7	4.06-6.47	5.11	0.83
Fall	7	4.33-6.45	5.53	0.67
Cudd	7	5.12-6.24	5.74	0.40
Perc	7	3.88-7.00	4.90	1.36
Sad	7	1.54-4.50	3.24	1.15
App	7	5.38-7.00	6.22	0.69
Voc	7	4.73-6.58	5.54	0.67

Table 2

Infant Performance on Mullens Scales of Early Learning.

Mullens Scale	N	T-score Range	Mean T-score	Std. Deviation	Percentile Rank	Percentile Descriptive
Receptive Language	10	44-56	47.9	4.8	42	Average
Expressive Language	10	33-76	55.3	11.5	69	Average

Figures

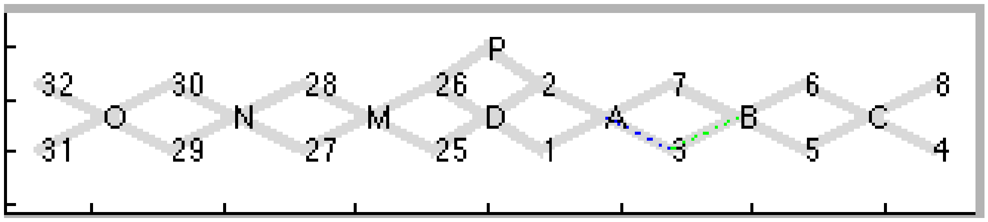

Figure 1. Probe configuration for the total of 30 data channels with source and detector pairs as visualized in Homer-2.

Figure 2. Caps containing optodes placed on the infants' heads following the international 10-20 system, anchoring on specific coordinates for each participant.

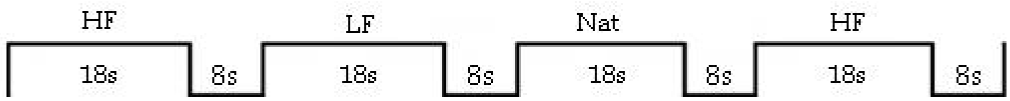

Figure 3. Brain imaging task. Stimulus presentation order (randomized order and sequentially presented to each participant).

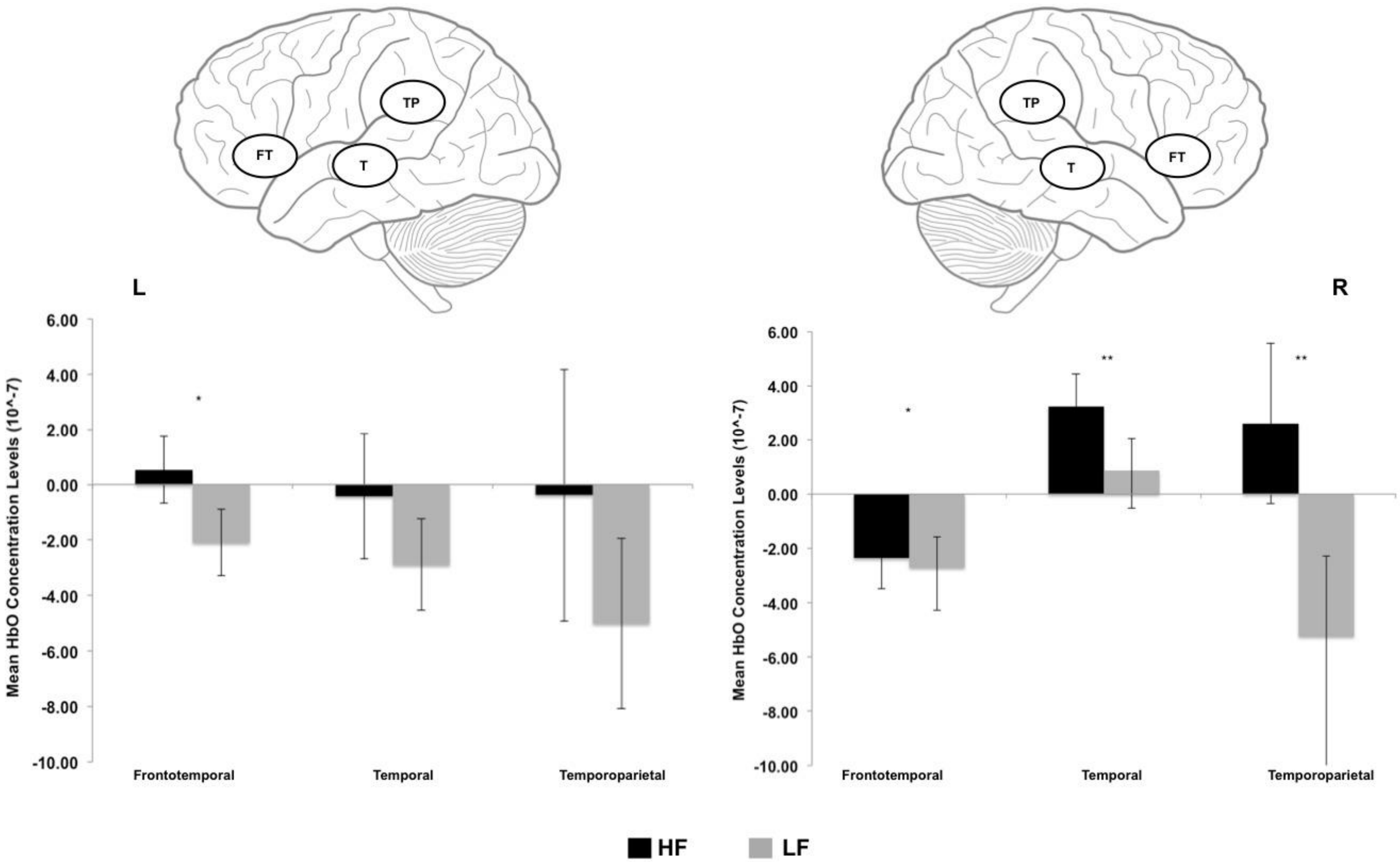

Figure 4. Mean oxygenated hemoglobin (HbO) levels for high frequency (HF) and low frequency (LF) phoneme clusters in bilateral frontotemporal, temporal and tempoparietal brain regions. Error bars represent standard error of the mean. *$p \leq 0.05$; **$p \leq 0.01$