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7 | Cerebral Responses to Temporally and Spectrally Different Sound Changes in Neonates: A Preliminary Report

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I. Introduction

There have been two distinct trends in understanding how human neural systems implement speech functions. One idea is the domain-specific or modular view of language processing, according to which humans have brain networks dedicated exclusively to speech (e.g., Fodor, 1985). A contrasting idea is the domain-general view of language processing (for reviews, see Liberman & Whalen, 2000; Zatorre & Gandour, 2008), which assumes that speech processing is mediated by the same brain system used for general auditory functions. According to this view, the spectral and temporal characteristics of sounds can predict hemispheric dominance in temporal auditory areas (Zatorre & Belin, 2001; Boemio et al., 2005; Schönwiesner et al., 2005; Jamison et al., 2006). Specifically, the left hemisphere is preferentially involved in processing rapid durational

changes such as those that distinguish phonemes, whereas the right hemisphere is more engaged in fine spectral processing such as that required for discrimination of prosodic changes. It is now apparent that the two views of domain-specific and domain-general language processing are not mutually exclusive, and both function in speech perception and production (Zatorre & Gandour, 2008).

We recently proposed a model of speech acquisition and brain development in which these factors play significant roles in successive developmental stages (Minagawa-Kawai et al., 2007b; Dupoux & Minagawa-Kawai, 2008). This model hypothesizes that domain-general speech processing dominates at an early stage of speech acquisition. Then, domain-specific or language-specific speech process starts functioning after the exposure of language inputs. At the initial stage of development when domain-general processing plays a crucial role, hemispheric dominance in speech perception is primarily determined by the acoustic characteristics of the speech stimuli. This hypothesis can explain many patterns found in the brain activation of young infants as they listen to speech or non-speech. For example, forward, or naturally-ordered, speech elicited left-dominant activations in newborns and 3-month-old infants (Peña et al., 2003; Dehaene-Lambertz et al., 2002). This left-dominant activation has been interpreted as indicating that young infants, including neonates, may already have specific sensitivity to speech. However, it is possible that the properties that activate the left hemisphere are not entirely linguistic, but are rather acoustic. Because speech includes segmental features including consonants and vowels (i.e., rapidly changing segments), these acoustic factors may have modulated the left-dominant networks. The fact that left-dominant activations were also observed for backward speech in young infants supports this idea, because backward speech includes segmental features but no linguistic features. Evidence for the domain-general view of right dominance for spectral (or prosodic) factors comes from near-infrared spectroscopy (NIRS) studies of neonates and 3-month-olds (Homae et al., 2006), which showed a right dominant response to prosodic speech relative to flattened speech without prosody. So far, however, there have been no infant studies which have considered both temporal and spectral properties of stimuli in order to examine the acoustic factors determining neural recruitment. The present study

examines whether newborn infants have an auditory system similar to that of adults in the processing of temporally and spectrally different acoustic stimuli. To this end, we employed non-speech stimuli which differed in their temporal and spectral natures (Zatorre & Belin, 2001) in order to observe newborns' hemispheric dominance.

II. Methods

1. Participants

Thirteen healthy newborns (7 girls and 6 boys) participated. Their average age was 3.6 days old (range: 1-8 days old). Two additional infants also took part in the recording, but were excluded from the final data set because of excessive motion artifacts and loose probe attachment. All were full-term infants without medical problems. Consent forms were obtained from parents before the infants' participation. This study was approved by the University College London (UCL) / University College London Hospital (UCLH) committees on ethics for human research (No. 061Q502141).

2. Stimuli

The stimuli were pure-tone patterns which were systematically manipulated in their spectral (frequency separation: f) and temporal (fastest temporal change: t) properties, as shown in Figure 1. We adopted three stimulus conditions from a previous adult study using PET (Zatorre & Belin, 2001). The acoustic properties of the three stimulus conditions were as follows: control stimulus, f = 1200 cent and t = 667 ms; spectral change stimulus, f = 37.5 cent and t = 667 ms; and temporal change stimulus, f = 1200 cent and t = 21 ms. Each stimulus was 10 sec in duration, alternating with 10 sec of silence (1 trial = 10 sec stimulation and 10 sec silence). Each stimulus condition was repeated 4 times and randomly presented within 1 run. Consequently, 1 run consists of 12 trials. We had 2-4 runs depending on the infant state.
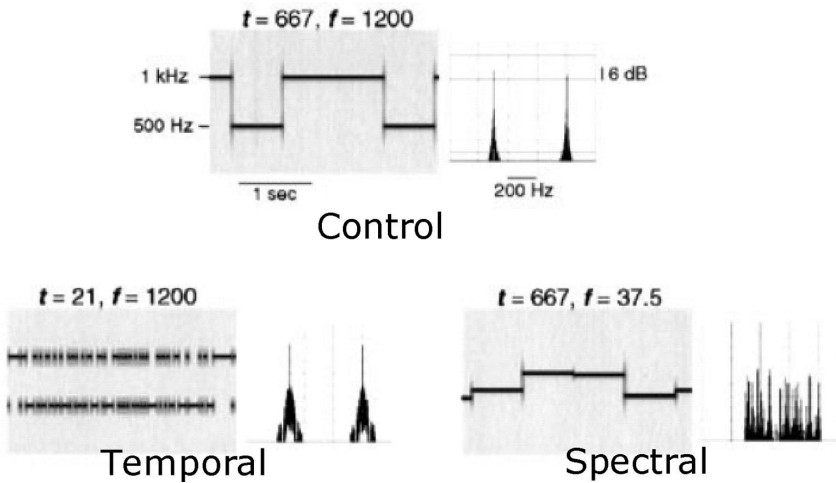
Figure 1. Schematic representation of auditory stimuli. Each pair of panels shows a stimulus sequence represented on the left as a spectrogram and on the right as a Fourier spectrum. The top pair of panels shows the control stimulus: two tones with a maximum frequency separation f of 1200 cents (1 octave) with the fastest temporal change of t = 667 ms. The bottom two panels represent temporal and spectral conditions.
These figures are adopted from (Zatorre & Belin, 2001).

3. Procedures

Changes in hemoglobin concentrations and oxygenation levels in the bilateral temporal and frontal areas were recorded using NIRS. Our NIRS system (UCL-NTS, Department of Medical Physics and Bioengineering, UCL, London, UK; Everdell et al., 2005) continuously emits near-infrared lasers of two wavelengths (780 and 850 nm) from eight sources; the attenuated lasers which are reflected and deflected from the brain are received in 8 detectors. The use of three distances between source and detector (25.0 mm, 29.4 mm and 39.2 mm) made it possible to measure hemodynamic changes within the brain 2.5-3 cm from the surface.

We measured the bilateral temporal area using a transformed 2×4 array on each side, as shown in Figure 2. Although this configuration provides 12 channels on each side, the signals obtained from the 39.2 mm separation were very weak, and these channels were not included in the final data set. Consequently, we used data from 9 channels on each temporal side.

The NIRS recording was performed in a quiet room. In attaching the probes, we used the international 10-20 system as a reference. After probe
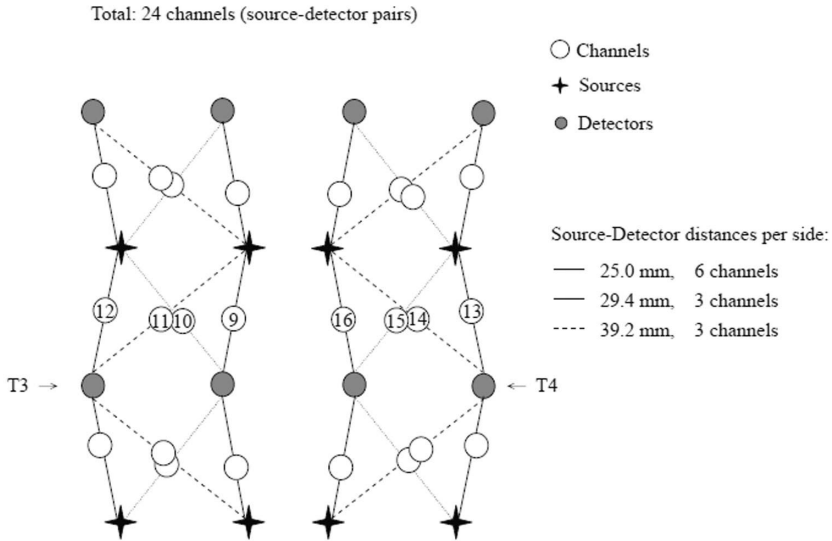
Figure 2. Design of array showing distribution and separation of sources and detectors. T3 and T4 refer to positions in the international 10-20 system.

attachment, the stimuli were presented from a loudspeaker. The sleeping infants were held by their mothers as they listened to the stimuli. During the recording, the mothers listened to different sounds through headphones to mask the experimental stimuli.

4. Data Analysis

For the statistical analysis, we used total Hb changes, which roughly correspond to cerebral blood flow (CBF) as measured by PET, in order to compare the results with those of the previous adult study. After any data contaminated with artifacts were removed, the data were entered into a general linear model analysis, with regressors corresponding to each of the three experimental conditions (control, spectral, temporal). The regressor for a given condition was obtained by convolving a boxcar for that condition with the standard hemodynamic response function (used in analysis of fMRI). To remove long-term trends in signal strength, we introduced into the statistical model sine and cosine functions of periods 1, 2 and 4 minutes for each of the runs. The period of the experimental

condition was contrasted against the control period (silence). The resulting t values were transformed to z values.

III. Results

Our study particularly focuses on three brain regions in the temporal area, because the prior PET study with adult participants (Zatorre & Belin, 2001) found significant covariation between CBF and acoustic parameters
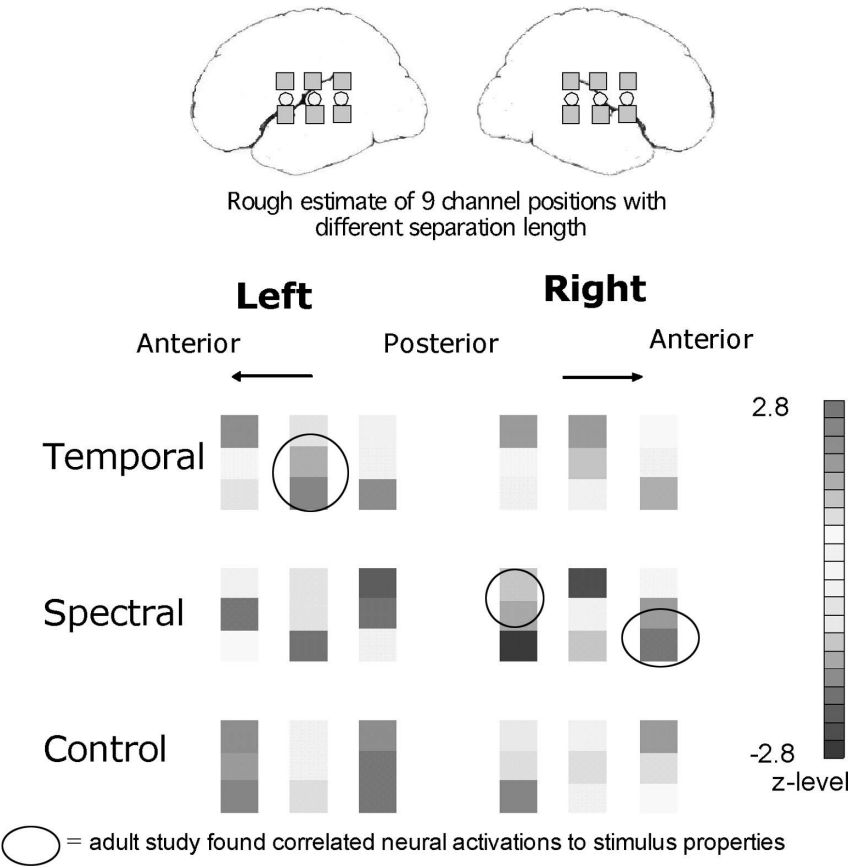

Figure 3. Hb responses to three different stimulus conditions in the bilateral temporal areas. Positions of the channels are shown in the top panel where squares and circles indicate the channels with separations of 25.0mm and 29.4mm respectively.
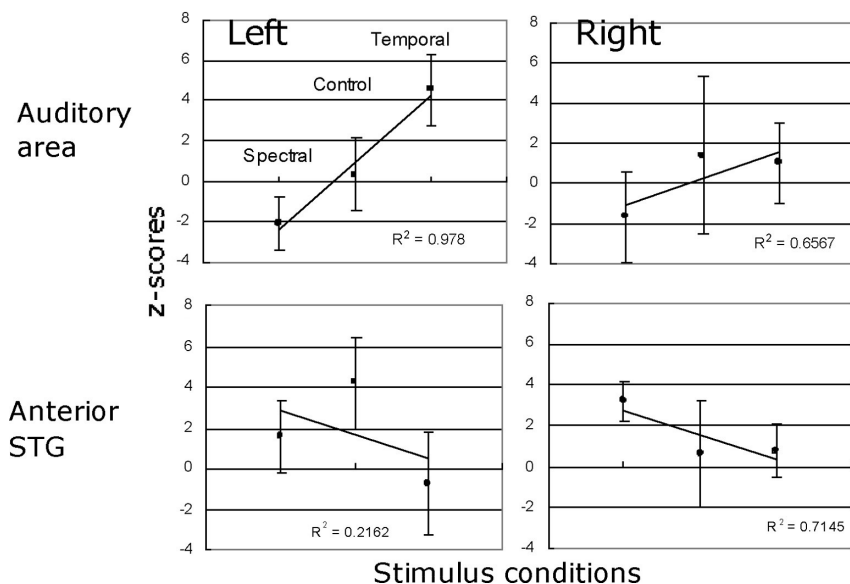
Figure 4. Brain activation levels as a function of stimulus type. The temporal condition has more rapid temporal variation whereas the spectral condition has richer spectral variation.

(spectral and temporal) of the stimuli in those three areas. These regions are Heschl's gyrus (HG) in the left auditory area for the temporal change and, for the spectral change, the anterior part of the superior temporal gyrus (STG) and the posterior part of the superior temporal sulcus (STS) in the right hemisphere. Figure 3 shows activation levels against the silence baseline (as derived from the GLM analysis of total Hb) in the three conditions. Bilateral auditory areas, including HG, were activated more by the temporal changes than by the spectral changes. The responses were notably greater for channel 12, which is located near the auditory area on the left side ($p < 0.05$). In contrast, the cerebral response to the spectral change was strong in the right anterior STG; however, there was no significant response to the spectral stimuli in the posterior STS. Correlation analysis between brain responses and stimulus type (Figure 4) revealed a stronger correlation between the temporal parameter and brain response in the left HG ($R^2 = 0.98$) than that in the corresponding right channel. This correlation suggests that the more rapidly the stimulus changes, the more strongly the left HG is activated. As for the spectral parameter, a

correlation between the spectral properties and brain response was observed in the anterior STG only on the right side.

IV. Discussion

In response to the spectrally and temporally different sounds, newborns showed brain activation patterns similar to those observed in adults (Zatorre & Belin., 2001; Jamison et al., 2005; Poeppel et al., 2003): left-dominant responses in the auditory area to temporal variation and right-dominant responses to spectral variation. This suggests that newborns already exhibit functional hemispheric asymmetry in the superior temporal cortex during processing of different acoustic properties. This extends the long-standing view that hemispheric asymmetry is driven by signal properties by demonstrating its presence even in young infants.

The lack of activation in the posterior STS during processing of spectral changes suggests that the infant neural system may not be quite the same as that of adults. However, another interpretation of this difference between infants and adults is that the posterior STS may indeed respond to spectral variations, but because it resides quite deep in the brain (Zatorre & Belin., 2001; Jamison et al., 2005), NIRS, with its limited depth sensitivity, might not have been able to capture its activations.

From the viewpoint of speech processing and cerebral lateralization in infants, our results have several implications. As discussed in the introduction, young infants, including neonates and 3- and 4-month-olds, have shown left-dominant brain activations in listening to speech (Peña et al., 2003; Dehaene-Lambertz et al., 2002; Minagawa-Kawai et al., 2008), and it has been debated whether the observed left dominance reflects cerebral specialization of the language faculty. On the basis of our results showing stimulus-dependent hemispheric asymmetries in newborns, it is likely that acoustic properties of speech, which include rich sources of temporal variation rather than slow spectral variation, chiefly elicited the left-dominant brain activation. Previous behavioral studies of language-specific phonemic acquisition in infants showed that infants' perception of phonemes changed from language-general to language-specific patterns within the first year of life (Kuhl et al., 2004). Our NIRS studies, as well as

ERP studies of brain development associated with phonemic acquisition, also suggest a process of cerebral specialization from auditory-general to language-specific patterns (Minagawa-Kawai et al., 2007a). Taken together, this evidence implies that infants chiefly exploit language-general (i.e., auditory-general) brain circuits in processing speech at an initial stage, then gradually organize a language-specific network as a result of exposure to language-specific auditory inputs. However, the auditory-general processing system may still remain in older infants and children and even in adults, serving as an early stage of auditory processing. Although these interpretations still require further investigation, our data have added a new piece of evidence to the increasing number of imaging studies on the cerebral bases of auditory-general sound processing, showing that humans are endowed with this auditory capacity from birth.

Acknowledgements

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