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19 Early Cerebral Bases of Phonemic and Prosodic Cue Decoding Assessed With Neonate NIRS

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I. Introduction

Speech has segmental (e.g. phonemic) and suprasegmental (e.g. prosodic) levels of regularities. Although language comprehension involves various processes, perceptual analysis of segmental and suprasegmental information comprises a crucial first step in the process leading to successful encoding of lexical, syntactic and pragmatic levels. Indeed, it is well known that learning features associated with these two components is a fundamental initial step for language acquisition in the first year of life. Functional cerebral lateralization in processing of these two kinds of information has been shown in neuroimaging literature on adult speech perception: human adults tend to show a left hemispheric dominance for processing phonemes and a right hemispheric dominance for processing prosodic information (e.g. Zatorre et al., 1992). However, brain development of this specialized system in infants is still poorly understood, even though it may provide various clues to understanding the cerebral basis of linguistic skill acquisition and human language faculties. The present study investigates the early cerebral basis for segments and suprasegments, particularly focusing on brain lateralization in neonates.

What exactly is the developmental process that leads to this functional hemispheric specialization? In recent years multi-channel near-infrared spectroscopy (NIRS) has enabled examination of this issue because this methodology allows us to localize the focus of neural activity. In fact, recent NIRS studies have provided evidence regarding the cerebral response of infants to phonological contrasts. Minagawa-Kawai et al. (2007) compared the neural sensitivities of different age groups to categorical phonemic changes and found that Japanese infants show a left-dominant temporal response to an across-category change after 13 months of age. Similarly, NIRS analyses show that 10 month-old infants exhibit a left-lateralized cerebral response to a difference in lexical pitch accents (Sato et al., 2010). Because younger age groups in these studies did not show a left-dominant response, Sato et al. (2010) hypothesized that exposure of infants to first language (L1) has modulated brains of older infants through the construction of an L1-specific brain network that is located predominantly on the left side. Although previous electrophysiological studies have shown an emergence of language-specific brain response after L1 exposure (Cheour et al., 1998), recent NIRS studies revealed for the first time a developmental change in cerebral lateralization by showing specific brain regions involved. More relevant to the present study, Sato et al. (2003) assessed cerebral lateralization for prosodic as well as phonemic contrasts in different age groups from 7-months to 5-years. Infants older than 11–12-months showed a significant lateralization that resembled that of adults (i.e., the phonemic change evoked a left-dominant response whereas the prosodic contrast evoked a right-dominant response), whereas the hemispheric laterality index for these two conditions did not differ significantly in groups of 7-8 month-olds and 9-10 month-olds. Although these results may indicate that the brain regions required for decoding prosodic information become more specific with maturation, detailed inspection of the laterality index in this study revealed tendencies in younger age groups toward right-dominance lateralization for the prosodic condition while retaining a bilateral response for the phonemic condition. In fact, additional statistical tests on these younger groups showed a laterality index that was significantly below zero only for the prosodic contrast. Furthermore, recent evidence based upon neonates' responses to presentations of frequency modulated non-speech sequences demonstrated rightward dominance with those spectral patterns that received relatively slow modulations (Telkemeyer et al., 2009). These results suggest predominant right hemisphere engagement in processing prosody from the beginning of life. To date, however, no study has investigated the default cerebral basis for processing prosody in real speech stimuli.

The present study is designed to examine this issue by contrasting two distinctive linguistic features (i.e. phonemic and prosodic contrasts) using real speech materials. To this end, the present study employs speech materials used in previous studies (Sato et al., 2003) in which different age groups including infants, children, and adults were examined. This paradigm enables us to assess the laterality for segements and suprasegments in newborn infants who have not been significantly exposed to language. Furthermore, comparisons of data across studies will allow assessment of developmental changes in the functional laterality in human infants as a function of age.

II. Methods

1. Participants

Twenty Japanese neonates were tested with NIRS; four infants did not complete the protocol due to fussiness and too much movement and their data were excluded from further analyses. Thus the final data set included data from 16 infants (average 4.8 days-old, range 3–8 days; 10 females). All neonates were full-term infants (averaged gestation: 271 days) with no history of medical problems. All were from monolingual Japanese families. Consent forms were obtained from parents before the infants' participation. This study was approved by both of the ethic committees of Faculty of letters, Keio University (No. 09049) and Keio University hospital (No. 2009–189).

2. Stimuli

Phonemic and prosodic differences were contrasted within speech contexts supplied by real words. For this purpose, three different forms of the Japanese verb /iku/ (go) were used as the stimuli: an affirmative form /itta/ (* has /have gone, * can be any subject), an imperative form /itte/ (go away), and a interrogative form /itta?/ (has/ have * gone?) (Imaizumi et al., 1998).

The stimuli were synthesized using ASL (Kay Elemetrics Corp., USA), an analysis-by-synthesis system based upon a speech signal produced by a male adult. These three stimuli have identical first syllables; they differ only in their final syllables. The phonemic contrast, consisting of pair members /iita/ vs. /itte/, is based upon differences in the final vowel due to the manipulation of formants 1 and 2; however both syllables have identical falling pitches. Members of the prosodic contrasting pair /iita/ vs. /itta?/ differ on in pitch contours due to the manipulation of the fundamental frequency; specifically the interrogative form has a rising pitch on the final syllable, whereas the affirmative form has a falling pitch on the last syllable. Two main conditions were: phonemic contrast and prosodic contrast. In both these conditions, participants also received the same baseline block of trials. In the phonemic condition, the stimulus /itta/ was repeated at 1-sec intervals for a total of 15 sec in the baseline block followed by another 15 sec of presentations in the target block. In phonemic target block /itte/ and /itta/ were presented in a pseudo-random order at 1-sec. intervals. In the prosodic condition, a similar procedure was employed using /itta?/ for the target block. The two blocks (baseline and target blocks) in each condition were alternated at least seven times for each condition. The presentation order of these two conditions was counterbalanced within one session. During the stimulation, the newborns were sleeping.

3. Procedure

NIRS experiments were performed in a testing room at Keio University hospital. Evoked auditory responses in bilateral temporal area as well as a part of frontal and parietal regions were recorded using NIRS (ETG 4000, Hitachi Medical Corporation, Tokyo, Japan). This device emits 695 and 850 nm near-infrared lasers modulated at different frequencies and detects them with lock-in amplifiers to measure changes in the concentration and oxygenation of hemoglobin (Hb). A silicon pad with five incident and four detection probes arranged in 3 x 3 square lattice was placed on each lateral side of the head with 2 cm of inter-probe separation. The total number of recording channels on each side was 12. The pad was attached to the head such that the center detector probe in the bottom of horizontal probe-line corresponded to the T3 or T5 position in the international 10/20 system. The bottom horizontal line of the probes was roughly aligned with the T3-Fp1-

Fp2-T5 line.

4. Data analysis

The concentrations of oxygenated and deoxygenated Hb were calculated from the absorption of 695 and 830nm laser beams sampled at 10 Hz, and smoothed with a 5 s moving average. Blocks affected by movement artifacts were automatically removed after detecting rapid changes in oxy-Hb value, which had signal variations more than 0.7 mmol mm between successive samples. To eliminate long-term signal trends due to systemic factors, a first-degree baseline fit was estimated for each channel using a mean of 4 sec each from the onset and offset of the target block. The time course of Hb concentration changes were averaged more than 5 times synchronously to the target stimulus blocks. According to our criteria, a 5 sec time window centered about the 11.1 sec point, was determined for the target block. 5 sec before the stimulus onset was used as a time window for the baseline block. The average concentration of oxy and deoxy-Hb in each time window was calculated for all channels and for each subject. The significance of differences between Hb changes within the baseline and those in target blocks was determined using a t-test (correction for a multiple comparisons with FDR) for each channel under two conditions. We assessed the laterality effect by employing an analysis procedure similar to that used in previous infant NIRS studies. Following the same criteria as in previous studies, we first defined a vicinity of auditory area as CH6, 8, 9 and 11 on the left and CH19, 21, 22 and 24 on the right hemisphere. For each participant, we selected one channel which showed the maximum oxy-Hb responses within a vicinity of auditory areas. The laterality index (LI) was calculated using the formula $(L - R)/(L + R)$, where L and R are peak values on left and right sides, respectively. For spatial estimation of channel location in the brain, we employed the virtual registration method (Tsuzuki et al., 2007) to map NIRS data onto the MNI standard brain space.

III. Results

Both phonemic and prosodic contrasts activated the neonates' brain in substantially broad areas involving superior temporal gyrus, inferior frontal gyrus, and inferior parietal regions. However, the two conditions elicited respectively different time courses of Hb changes as well as revealing different activation foci (Figures 1 and 2). Hb changes in the phonemic condition had 10.2 sec of peak latency with an initial dip, whereas changes in the prosodic condition showed a peak of 12.1 sec without an initial dip (Figure 1). There was no statistically significant difference between these peak times ($t = 0.69$, $p = 0.24$). Phonemic changes activated the inferior frontal, inferior parietal, and temporal areas with less parietal or superior part of activities on the right. In contrast, the prosodic changes evoked responses chiefly around temporal areas. Among these areas, activation foci whose p-value is below 0.01 (corrected) are CH6, CH22 (vicinity of auditory areas on the left and right) and CH5 (inferior parietal area) for the phonemic condition and CH24 (vicinity of auditory areas on the right, superior temporal sulcus/ mid temporal) for the prosodic condition. To examine the laterality difference, we compared Hb changes in these areas to those in contra-lateral channels using a paired t-test. Results revealed laterality effect of left-CH5 ($t = 2.29$, $p < 0.05$, corrected) and right-CH24 ($t = 2.23$, $p < 0.05$, corrected) for phonemic and prosodic condition respectively.

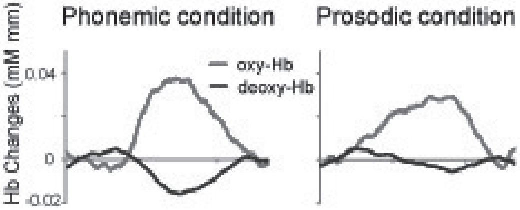

Figure 1. Hemodynamic responses to phonemic and prosodic sound changes. Grand averaged time course of Hb collapsing across all the channels.

In order to compare the neonates' results to those from previous studies using similar methods, we applied the same analysis method employed by those studies to assess the laterality of auditory areas. Laterality indices (calculated for each participant) are plotted in Figure 3 for each of the two conditions. Consistent with the results obtained by the channel by channel analysis, only the prosodic condition showed a significant asymmetry effect. LI for the prosodic condition were significantly lower than zero ($t = 3.07$, $p < 0.01$), indicating rightward dominance.

IV. Discussion

To explore the early neural bases underlying segmental and suprasegmental processing, the present study measured hemodynamic responses to phonemic and prosodic contrasts in neonates. The results showed a large and significant activation to the prosodic change in the right temporal region suggesting
functional specialization for suprasegmental properties in neonates. By contrast, the phonemic (vowel) contrast showed a strong leftward in the inferior parietal region, but it is noteworthy that it also elicited Hb changes in bilateral auditory areas. Here we discuss these results in light of developmental hemispheric specialization of the temporal area for phonemic and prosodic processing by comparing the results from the previous infant studies.

Previous NIRS studies using identical stimulus contrasts reported an absence of functional specialization of the auditory area for two different phonetic contrasts in 7–8 and 9–10 month-olds (e.g., Sato et al., 2003). However, this study showed a tendency of a rightward dominance for prosodic contrasts. In the present study, using neonates as participants, the outcome is clearer. Neonates' NIRS responses revealed significant right dominance around auditory area in response to the prosodic change, suggesting that a specialized function of the right hemisphere for prosody processing is present at birth. The focus of this activation in the right auditory region ranged over 4 channels and was estimated to involve superior temporal sulcus (STS) and mid temporal gyrus.

What kind of cognitive function is reflected with the brain activities in this area? This activity may reflect lower cognitive processing that involves differentiation of acoustic contours of spectral components. There is other evidence to support this account. For instance, Boemio et al. (2005) found in neuroimaging data of adults, a cerebral laterality that reflected differential responding to both fast vs. slow band-noise stimuli and to temporal vs. spectral modulated stimuli (Zatorre and Belin, 2001). Stimuli with periods ranging from 85 to 300 ms, evoked greater activation to those with slower periods occurs in the right STS (Boemio et al., 2005). In addition spectrally rich stimuli elicit activations in the anterior superior temporal gyrus as well as right STS and these activations increase with the richness of spectral

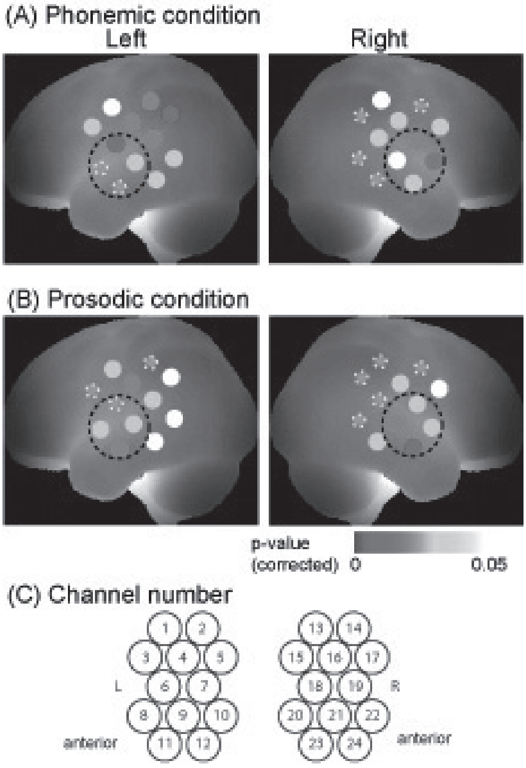

Figure 2. Activation amplitude indicated by p-values for phonemic (A) and prosodic (B) conditions. Channel location of 12 channels for each hemisphere was estimated based on the virtual spatial registration (Tsuzuki et al., 2007). Channels without a circle did not reach statistical significant level. p-values were corrected for multiple comparisons. Channel numbers are indicated for both hemisphere (C).

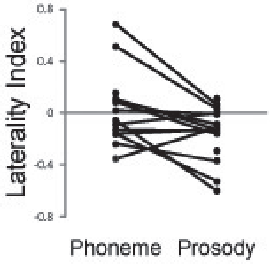

Figure 3. Laterality indices for phonemic and prosodic conditions for each participant.

variations (Zatorre and Belin, 2001). In the present study, it is assumed that contrasts between stimuli ending in a rising versus those with an unchanging pitch contour are chiefly processed around the right STS in neonates.

With respect to the vowel contrast /itta/ vs /itte/, a cross-sectional study (Sato et al., 2003) showed that their youngest groups of 7–8 month- and 9–10 month-olds evoked temporal activations equally in bilateral hemispheres. It was only when infants reached about 11 months of age that they showed a lateralization of the vowel difference in the form of leftward dominance. Our results provide additional evidence that the auditory region functions as an innate starting for the development of auditory processing in neonates. On the basis of these findings, a continuous bilateral engagement for processing vowel contrast from birth to 7 month-olds is assumed. Although we lack in the data for 2–6 month-olds, the previous results for different vowel types showing a bilateral temporal response in 3–4 and 6–7 month-olds (Minagawa-Kawai et al., 2007) supports the idea that developmental holds through these months.

To this point our discussion of lateralization has been confined to the vicinity of auditory areas. However, another rather unexpected finding in the present study involves dominant activations observed in the left parietal region during vowel discrimination. This activation seems to be in the supra marginal gyrus (SMG) according to the probabilistic spatial estimation (Tsuzuki et al., 2004). The SMG is often referred to in neuroimaging literature in relation to speech perception. An fMRI study of lesions in aphasic patients by Caplan et al. (1995) indicates that the left SMG is the principal site of phonemic processing. Zatorre et al. (1992) also showed that discrimination of consonant types in CVC syllable, activated the left SMG. It seems left SMG is involved in tasks requiring verbal or auditory short-term memory (Paulesu et al., 1993). Although the neonates did not engage in any particular task in this study, auditory short-term memory may be a most-likely candidate to explain the SMG activations. Cognitive process of discrimination during the target block; i.e. comparing two words differed in vowels by memorizing and detecting them, may underlie in the activities of left SMG even in sleeping neonates. Thus this study may be indirect evidence that a neuronal substrate implicated in short-term memory may also functional in newborns.

In summary, by presenting segmental vs suprasegmental (phoneme vs prosody) contrasts to newborn infants, the present study revealed a functional lateralization to right temporal area for prosody processing and bilateral engagement of the auditory areas for vowel contrast. This is the first evidence showing that neonates elicit localized cerebral responses to phonemic contrasts of vowel and prosody. We further showed a left dominant activation around inferior parietal region suggesting an early neuronal basis for auditory-verbal short-term memory. This study suggests possible brain mechanisms for both signal-driven system and domain-driven system from birth and raised several important issues to explore language acquisition and development of infant's neurocognitive system.

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