DEVELOPMENTAL CHANGES IN CEREBRAL RESPONSES TO NATIVE AND NON-NATIVE VOWELS: A NIRS STUDY

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ABSTRACT

While newborn infants discriminate speech sounds from languages that they have never heard, 6-month-olds demonstrate the beginnings of vowel classification specific to their native-language. The neuronal correlates involved in such a dramatic perceptual reorganization process, however, are not well understood. Using near-infrared spectroscopy (NIRS), this study compares the neural responses of Japanese infants at 3-4 months and 7-8 months of age as well as of adults to native ([i] vs. [ɯ]) and non-native vowel contrasts ([ɯ] vs. [u]) within pseudo-word contexts. The findings demonstrated longitudinal developmental changes of functional temporal cortex asymmetries associated with the exposure of the native language.

Keywords: phonemic perception; vowel; auditory cortex; cerebral lateralization.

1. INTRODUCTION

Infants are born with a capacity to distinguish almost all of the phonemic contrasts that are used in language, regardless of their language environment. Exposure to a native language, however, changes the “language-general” perceptual capacity, and results in reduced sensitivity to non-native phonemes and a refined perceptual ability for native phonemes. Behavioral studies indicate that the developmental shift to language-specific phonemic perception, particularly for vowel contrast, emerges within the first 6 months of life [5, 6]. The present study examine the neural correlates of “language-general” and “language-specific” phonemic processing by comparing infants under 6 months old with those over 6 months old. To evaluate the process of cerebral lateralization in response to a stimulus change of native and non-native vowel contrasts, we used multichannel near-infrared spectroscopy (NIRS), which has sufficient spatial resolution to assess the laterality of the temporal area. NIRS has been indicated to be useful in measuring infants’ cognitive functioning including listening to speech [9]. Furthermore, NIRS has successfully assessed cerebral lateralized functions in processing phonemic and prosodic changes in both adults and infants [7, 10]. In the present study, we measured Japanese infants’ hemodynamic responses to vowel contrasts at 3 to 4 months of age and at 7 to 8 months of age to assess the longitudinal changes of cerebral responses in the same populations. Furthermore, adults group of native speakers of Japanese were tested with a similar paradigm. Our targeted phoneme contrasts were the Japanese vowel contrast [i] vs. [ɯ] and the non-native Korean contrast [ɯ] vs. [u] in pseudo-word contexts. Based on the results of pilot experiments performed to Japanese and Korean adults, these contrasts were produced so as to have the same psycho-acoustic differences but different phonological statuses for the Japanese listeners.

2. METHODS

Participants: The study participants included twelve healthy monolingual Japanese infants (8 girls, 4 boys) who were born at full term with a normal birth weight. They were studied at both 3-4 months of age and at 7-8 months of age. Averaged ages of the NIRS recording were 119 days (SD = 16) for the first experiment and 229 days (SD = 15) for the second experiment. Additional 20 infants were also tested, but were excluded from the final sample because of their excessive motion artifacts or failure of participation in either one of the two tests. Parents provided informed consent in compliance with a protocol approved by the ethics committee of Keio University, Faculty of Literature (No. 04001). Eleven right-handed Japanese adults also participated in the same experiment. They are healthy right-handed monolingual Japanese (4 male and 7 female, 20–23 yrs., mean age: 22 yrs., SD=4) with no history of auditory deficits.

Procedures: The present study used NIRS (ETG-7000, Hitachi Medical Co., Japan), which measures the hemoglobin (Hb) concentration changes of the optical paths in the brain between the nearest pairs of incident and detection probes separated by 3 cm on the scalp surface. For the infants, two incident and two detection probes arranged in a 2 × 2 square grid (4 channels) were fitted on the temporal areas of each side of the head using the international 10-20 system (Fig. 1). Three of these channels approximately covered the auditory area [8].For the adults group, 22 channels with 3 × 5 optodes (incident and detection) were placed on the bilateral temporal area and part of the frontal area according to the international 10-20 system [8].

Stimuli: Stimuli were vowels (V) of [i], [ɯ], and [u] in the framework of an initially accented pseudo-word "gVppa", which was synthesized from a naturally spoken word [gɯppa] by manipulating the second formant value of the first vowel (Analysis-Synthesis Laboratory 5104). First, we synthesized the [gippa] - [gɯppa] - [guppa] continuum differing in the second formant values (220 Hz) in 11 steps and carried out identification, likeliness, and discrimination tests according to the procedure of Iverson & Kuhl [3, 4]. Based on the acoustic information of the Japanese [i], [ɯ] and Korean prototypes [u] revealed from the results, we again synthesized the stimuli of the three vowel prototypes ([gippa], [gɯppa], and [guppa]) so that they had the same psycho-acoustic stimulus differences while still retaining their prototypical natures. Although each [i] vs. [ɯ] and [ɯ] vs. [u] contrast had the same psycho-acoustic differences, only the [i] vs. [ɯ] contrast had phonological value (linguistic meaning) for the Japanese participants.

For the NIRS recording, the subjects served odd-ball like passive listening tasks with two conditions. In the native contrast ([i] vs. [ɯ]) condition, the stimulus [gippa] was repeated for 20-s as a baseline block and then the stimuli [g ɯ ppa] and [gippa] were presented in a pseudo-random order with equal probabilities for another 20-s period as a target block with a 1.25-s stimulus onset asynchrony. These blocks were repeated at least five times. Similar procedures were performed for the non-native condition ([ɯ] vs. [u]) and the presentation order of these conditions was counterbalanced within the group. The stimulus sounds generated from PC and audio interface (Fire-Wire 410, M-Audio) were presented from a loudspeaker (ca. 70 dB SPL) in a sound-attenuated room, where the infants, held by their mothers, listened to them. To reduce motion artifacts, an experimenter entertained the infants with silent toys during the recording.

Data Analysis: The concentrations of oxy- and deoxygenated (deoxy-) Hb were calculated from absorbance changes at 780 and 830 nm and the response peaks were calculated against the 10-s pre-stimulus period. Here we used the values of total-Hb that indicates the changes in the cerebral blood volume for the analysis, because this parameter was revealed to be suitable in indicating the cerebral lateralization in temporal area [7, 10]. By detecting the sharp changes of Hb movements and also assessing the video recording, we removed the data with motion artifact. After discarding the artifact, total-Hb concentrations were averaged five times synchronously to the stimulus cycles, and smoothed with a 5-s moving average. For the statistical analysis, we chose an auditory channel with maximal peak responses on each side across the conditions. Taking into account of the developmental differences of optical path length due to the anatomical variations of scalp and skin, we did not compare the Hb value in different age group. The Hb values were statistically compared using two-tailed t-test between the conditions.

3. RESULTS

Using a change-detection listening task, we measured total Hb changes from the temporal area (Fig.1). Although in both of the first and second experiments the infants showed the evoked responses to the native and non-native vowel contrasts, the response amplitude varied depending on the age and the stimulus condition. There was no significant difference in total Hb change in the left auditory area between the native and non-native conditions in the infants at 3 to 4 months of age ($t = 0.85$, $p > 0.05$). There was a significantly larger response, however, to the native contrast in the infants at 7 to 8 months of age ($t = 2.24$, $p = 0.047$), as well as in the adults ($t = 2.44$, $p = 0.018$) (Fig.2). The laterality index was calculated from the formula $(L - R) / (L + R)$, where L and R represent the peak total Hb changes in the left and right auditory channels respectively. The laterality index for the native contrast was significantly more left-dominant than for the non-native contrast in the infants at 7 to 8 months of age and the adults (Mann Whitney U-test, 7-8 months; p = 0.008, adults; p = 0.012) (Fig.3).

Figure 1: Four probes and channels in the temporal area and hemodynamic responses obtained from those areas. (A) Four probes were set in each bilateral temporal area. The line connecting T3, F7, F8, and T4 was horizontal to the lowest lines of the NIRS probes, and the posterior probe in the lowest line corresponded to T3 or T4. (B) The average Hb changes in response to the contrasts of [i] vs. [ɯ] and [ɯ] vs. [u] in a 8 month-old infant.

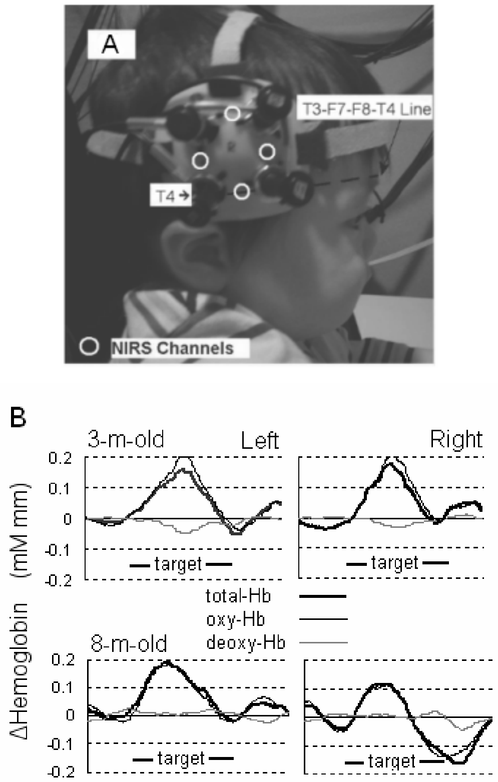


Figure 2: Averaged peak responses in two groups. The total Hb changes in the left auditory area in the infants at 3 to 4 months of age and at 7 to 8 months of age (a), and adults (b) in the native and non-native vowel conditions.

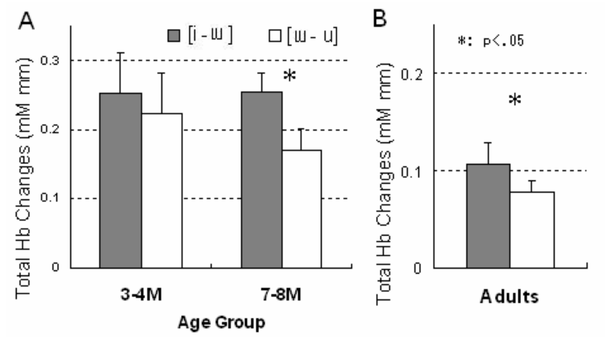
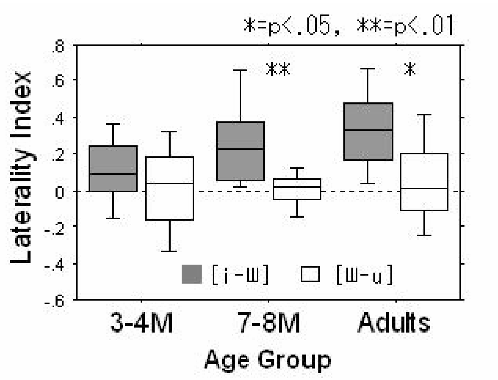


Figure 3: Laterality index calculated using the formula (L-R) / (L+R), where L and R are maximal total Hb changes in the left and right auditory channels, respectively.



4. DISCUSSION

The present NIRS study, in which Japanese infants were longitudinally examined at 3 to 4 months and 7 to 8 months of age, demonstrated that neural responses from the auditory area are specifically sensitive to the native vowel contrast at 7 to 8 months of age as a result of attenuated hemodynamic responses to the non-native contrast. This might be the neurophysiologic basis underlying previous behavioral findings that an infant's perceptual ability to discriminate vowels is altered to a language-specific pattern within 6 months of life [5, 6]. Although the timing for the language-specificity in our study occurred somewhat earlier than that reported by previous event-related potentials (ERP) studies [1], the results are generally consistent. The principal finding in the present study, however, is a cerebral lateralization process associated with acquisition of native phonemic repertories. Infants at 3 to 4 months of age who were revealed to discriminate almost all the phonemic contrasts in the world [5, 6] exhibited bilateral activation for both native and non-native contrasts. On the contrary, at 7 to 8 months of age, which is when infants have language-specific vowel perception, the infants showed left-dominant responses solely to the native contrast. This tendency of left-dominance to the native vowel contrast in a word-like context was similar to the pattern exhibited by the adults in the present study as well as in the previous ones[2, 7, 10]. Since the peak activations found in these previous adult studies were slightly superior and posterior to the lateral boundary between Heschl's gyrus and the planum temporale (part of Wernicke's area), the infants' activations observed in the same corresponding channel may reflect the neural response from Wernicke's area.

These results suggest that "language-general" perception before 6 months might recruit acoustic-general neural pathways organized in both the right and left hemispheres. In contrast, after more than 6 months of exposure to their native phonemic system, infants might have a language-specific neural pathway that efficiently processes native phonemic differences, because the auditory responses to the Japanese phonemic system were left-dominant for the 7 to 8 month-old infants in the present study. Neurophysiologic studies of cross-language phonemic perception also support this view and language-dependent responses to phonemes of the native language are observed in the left auditory area, whereas in many studies no left-dominance is observed for non-native or certain non-linguistic contrasts [2, 7]. The results of previous ERP studies on developmental cerebral lateralization related to infant phonemic perception are somewhat controversial [eg. 2, 11] probably due to the difference in the number of channels or various other methodological differences. By using different parameters (cf. hemodynamic) with the recently developed NIRS, which can assess specific local responses, the present longitudinal study provides the first direct evidence of developmental changes in functional asymmetries for processing native and non-native vowel contrasts. These neural responses in the temporal language area and their developmental differences may be the neural basis of the language-dependent tuning process.

5. REFERENCES

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