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Toward Understanding Infants' Cerebral Basis for Word Segmentation: A Preliminary NIRS Study with Adult Participants

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I. Introduction

Unlike written language, conversational speech does not have a remarkable interval between words. Specifically, speech rarely has any salient acoustic cues to indicate word boundaries. This becomes an obstacle for infants when they identify spoken words. Similar to adults hearing an unknown foreign language, infants hear the native language as a steady stream of sounds. Hence, the primary step for infants to acquire words is to be able to segment words from continuous speech.

How can an infant determine where one word ends and the next one starts? Extensive studies have been conducted on this issue chiefly using the head-turning procedure. Jusczyk and his colleagues carried out a series of studies and revealed two factors that guide infants to segment words: (1) allophonic variations depending on phoneme position within a word and (2) stress pattern. It seems that stress patterns play a significant role in many languages. Jusczyk and Aslin (1995), for example, showed that 7.5-months-old children were able to identify familiarized English words presented with a strong-weak accent pattern but not with a weak-strong one. Infants whose native language is Dutch also showed a similar tendency at the age of 9 months (Houston et al. 2000). The French language, owing to its lack of lexical accents, does not provide clear acoustic indications to infants. As a

result, infants are unable to find a word boundary before they are 16-months-old (Nazzi et al. 2006). Apart from these behavioral studies, Kooijman et al. (2005) attempted to investigate the neural basis of word segmentation using event-related potentials (ERP). Employing a paradigm similar to the one constructed by Jusczyk and Aslin (1995), they identified a differential electrophysiological signature between familiarized words and control words among 10-months-old Dutch infants. Although this study revealed crucial information regarding the cerebral correlates of word identification, ERP fails to precisely detect the brain region that engages in particular processing. Moreover, it is possible that brain signatures are more sensitive than behavioral results; thus, younger infants' brains (e.g., 5–6-month-olds) could already be responsive to familiarized words when they are inserted in sentences. To explore this issue, we are currently conducting a series of studies on infants' cerebral basis for word segmentation by using near-infrared spectroscopy (NIRS) and a behavioral method. The present report on adult participants is a part of this project.

Before examining infants, we investigated adults' cerebral substrates of word learning and segmentation from sentences by employing NIRS. The aim is to compare the data for infants and adults as well as to determine the appropriate brain region in infants to measure with a limited number of NIRS channels.

II. Methods

1. Participants

A total of 18 students (of which 5 were male) participated in the NIRS measurement. Their ages ranged from 19 to 33 years and the average age was 23 years. They were all right-handed and native speakers of Japanese. Besides these participants, we had 8 additional participants, of whom 7 were excluded from the final data set because they showed inadequate probe attachment in more than 18 channels, and 1 was excluded because he was left-handed.

2. Stimuli

On the basis of our behavioral study of infants and some previous studies, we determined the following criteria for our stimulus words. First, our stimulus words were initial-accented 3-mora words starting with the vowel sequences /a-i/ or /a-u/ (e.g., /tanishi/). Second, the stimulus words had low familiarity scores according to the database for spoken words created by Amano and Kondo (1999). The familiar-

ity score ranged from 5.0 to 5.5 points. These criteria, which were derived on the basis of previous studies, facilitated the infants' identification of the words in the sentences. In our pilot study, we found that infants were able to identify initially-accented words with vowel sequences of both broad vowels such as /a/ and /o/ and narrow vowels such as /i/ and /u/. This was consistent with the results reported by Sato et al. (2007). The second criterion was chosen because the stimulus words should not be ones that the participants were already familiar with. The stimulus words employed in the training session were /zakuro/ (rum blossom) and /tanishi/ (pilidae), and 12 additional words were employed for the control condition. In the test session, we used two previously familiarized words (zakuro and tanishi) as the target words and unfamiliarized words /gaika/ and /aruji/ as the control stimuli.

These words were presented in different contexts in two separate sessions. Specifically, in the training session, the stimulus words—pronounced by three females—were presented in isolation in either the target or the control block. In the target block, one of the target words was continuously presented for 12 seconds, while in the control block, various words were presented randomly. In the test session, familiarized target words were embedded in four types of sentences for the target block, and unfamiliarized words were spoken in the same sentence context for the control block. These sentences were presented for about 12 seconds in each block.

3. NIRS recording

The changes in hemoglobin concentrations and their oxygenation levels in the bilateral temporal areas were recorded using NIRS systems (ETG-7000, Hitachi Medical Co., Japan), which emit continuous near-infrared lasers with fixed wavelengths of approximately 780 nm and 830 nm. The laser beams were modulated at different frequencies and detected using lock-in amplifiers. These devices can measure localized cortical responses of channels that are present in the optical path of the brain between the nearest pairs of emission and detection probes; these probes were separated by 3 cm on the scalp surface (Fukui et al, 2003). 22 channels with 3 x 5 optodes (incident and detection) were placed onto the bilateral temporal area and the part of the frontal area. The international 10-20 system was referred to while attaching these probes, i.e., the line connecting T3, F7, F8, and T4 was horizontal to the lowest lines of the NIRS probes. Further, T3 (4) corresponded to the second optode from the back at the lowest line.

4. Procedure

After the placement of the NIRS probes, two NIRS sessions were held with the participants: training and test sessions. Stimuli were presented in an event-related paradigm. In the training session, participants were familiarized to one of the target words (zakuro and tanishi) for the target block. In the control block, they listened to various words in a random order. They were told to memorize the presented words during the blocks. Each block lasted 12 seconds and was ordered pseudo randomly followed by a silent interval (varying from 8 sec to 16 sec) between each block. Each block, had a unique sentence order and was repeated 5 times. After the training session, the participants were subjected to the test session, where they listened to either familiarized (zakuro or tanishi) or unfamiliarized (aruji or gaika) words embedded in various sentences. They were instructed to find out the words learned before among the sentences. Each target and control block lasted 12 seconds and was presented pseudo randomly with a silent interval between them. The blocks were repeated 6 times in each condition.

5. Data analysis and spatial estimation

Changes in the concentrations of oxygenated (oxy) and deoxygenated (deoxy) Hb were estimated based on the change in absorbance by using laser beams of approximately 780 nm and 830 nm, sampled at 10 Hz. Changes in oxy-Hb and deoxy-Hb were averaged 5–6 times synchronously to the test period for each condition (i.e. target and control conditions). Time window for the base line block was 5 sec immediately prior to the target block and that for the target block was 5–10 sec after the stimulus onset. The average concentration of oxy and deoxy Hb in each time window was calculated for all channels and each subject. The significance of differences between the Hb changes of the baseline and target blocks was determined by a two-tailed t-test for each channel under two conditions.

We employed virtual registration (Tsuzuki et al. 2007) to register the NIRS data in the MNI standard brain space. Briefly, this method, which is based on the international 10–20 system, enables the placement of a virtual probe holder on the scalp by simulating the holder's deformation and by registering probes and channels onto the reference brains according to the information of our channel positions. To estimate the location of the given channels in a group of subjects as accurately as possible, we performed a statistical analysis of the MNI coordinate values for the NIRS channels and assessed the spatial variability associated with the estimation. Finally, these estimated locations were anatomically labeled by using two conventional brain atlases. For macro-structural anatomical spacing, we

referred to a 3D atlas constructed by Tzourio-Mazoyer, et al. (2002), which is the standard anatomical labeling tool of the Statistical Parametric Mapping (SPM) method.

III. Results

Training session: Word familiarization using the target words elicited strong oxy-Hb changes in the dorso-lateral prefrontal cortex (DLPFC) (CH 21 and 22) and the angular gyrus (CH 14) in the left hemisphere (Figure 1 top panel). There were no such DLPFC activations in the right hemisphere but broad and strong activations were observed in the angular gyrus (CH 18), supra-marginal gyrus (SMG) (CH 17, 22), and superior temporal gyrus (CH 13). In the control condition, where many words were presented in random order, Hb responses were significant in DLPFC (CH 22) and the inferior frontal gyrus (IFG) in the left hemisphere and SMG (CH 22) and STG (CH 9) in the right hemisphere.

Test session: Large oxy-Hb changes were observed, particularly in the left DLPFC, in response to the target words, which the participants were familiarized with in advance (Figure 1). The SMG and IFG also showed a significant response in the left hemisphere. A few activations were observed around the DLPFC in the right region of the brain. The control block did not trigger a significant response in the left hemisphere, unlike the target block. Significant activations were observed only in the post central area and the DLPFC. Further, we compared the statistical significances of the response amplitudes between the two conditions (target vs. control). The target condition showed significantly stronger activations in the SMG and DLPFC in the left hemisphere.

IV. Discussion

The present study with adult participants investigated the neural substrate underlying the identification of words embedded in a sentence. We measured cerebral activations while they learned words and identified learned words. In general, the dorsal pathway of the language network was shown to engage in both the processes.

During the training session, where the participants were auditory familiarized to the target words, the adult participant showed cerebral responses in the SMG, the DLPFC, and the angular gyrus. Particularly in the target condition, during which the target word was repeatedly presented, activations in the right SMG were greater in number. These areas of the brain have been pointed out to engage in the phono-

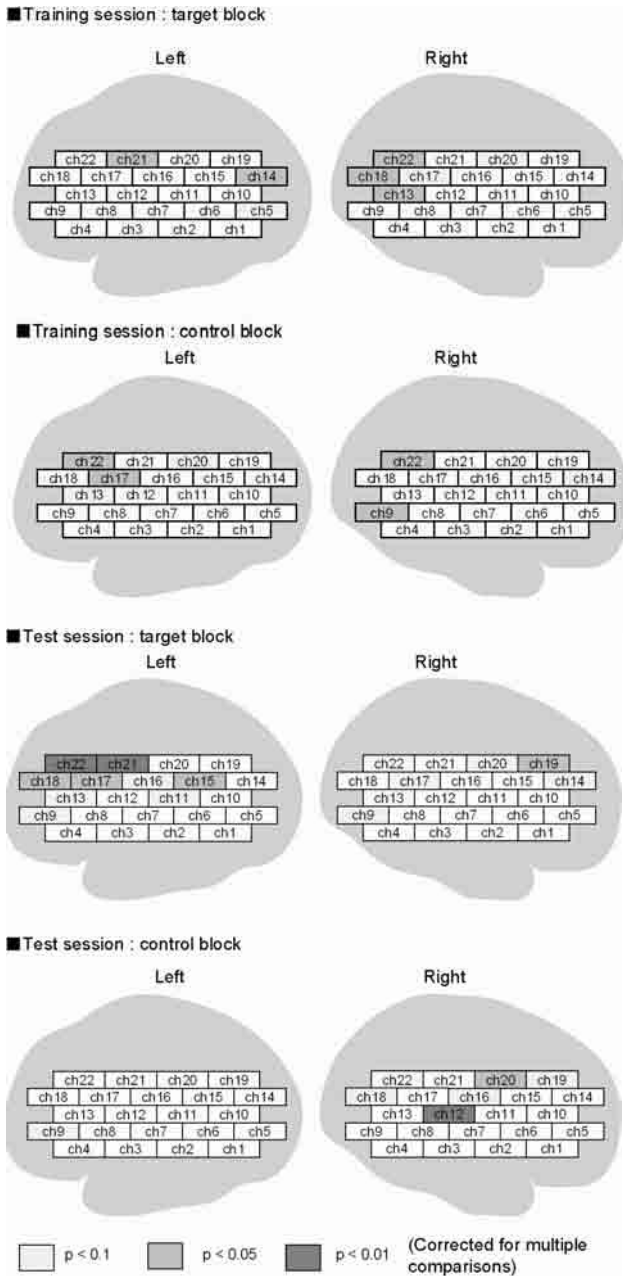


Figure 1. Brain activations during the training sessions (2 top panels) and the test sessions (2 bottom panels)

logical processing of words and the construction of phonological representations (Jacquemot et al. 2003, McNealy et al. 2006). Although there was no clear left hemispheric dominance, these bilateral activations may reflect an encoding process for phonological sequences, namely process of phonological short-term memory.

The activations observed during the test session were similar to those observed during the training session, but the responses to the familiarized words in the test session were essentially stronger and broader than those in the training session. To elaborate, when the participants searched for the familiarized words in the sentences, the SMG, DLPFC, and IFG responded strongly. Furthermore, these responses were generally leftward lateralized when the participants actually found the familiarized word in the target condition. Leftward dominance in the target condition was particularly outstanding in the SMG and DLPFC. The activations in the left SMG and DLPFC are considered to be associated with a network of phonological short-term memory. This is a part of the dorsal pathway in the dual-route model of speech processing (Hickok & Poeppel 2007). The response in the IFG (Broca area) in addition to that in the left SMG suggests both input and output procedures for phonological short-term memory (Chein & Fiez 2001, Jacquemot et al. 2003). Previous functional magnetic resonance (fMRI) studies have reported that the left SMG is crucially related to the phonological loop of working memory (Paulesu et al. 2005) and phonological representations for segmenting a word (McNealy et al. 2006). Overall, the brain activations in the target condition seemed to indicate the process of retrieving the encoded phonological representations of words.

The present study revealed that the network for encoding and retrieving phonological short-term memory was recruited in the segmentation of words. In particular, the dorsal pathway from the angular gyrus-SMG-DLPFC-IFG was employed for the processes of learning and identifying words. These areas are also expected to be engaged in the infants' processing of word segmentation. Therefore, on the basis of this preliminary study, the abovementioned dorsal pathway will be the region of interest in the subsequent studies for infants where NIRS is used. Further, differences in brain activations between adults and infants will be investigated in prospective studies involving infants.

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