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40 Cerebral Responses to Infant-directed Speech in Infants

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I. Infant-directed Speech and Infants' Development

Adults who interact with young infants tend to modify their speech in certain characteristic ways and this type of speech is known as infant-directed speech (IDS) (Cooper and Aslin, 1990; 1994; Pegg et al., 1992; Werker and McLeod, 1989). Relative to normal adult-directed speech (ADS), IDS is higher in pitch, has a wider pitch range, and exhibits exaggerated pitch contours; in addition, IDS are slower and separated by longer pauses (Fernald and Simon, 1984; Snow and Ferguson, 1977; Stern et al., 1982; Stern et al., 1983). Moreover, this manner of producing speech may be universal in that IDS has been observed cross-linguistically (Fernald, 1989; Fernald and Simon, 1984; Grieser and Kuhl, 1988; Kitamura et al., 2002; Papousek and Hwang, 1991; Shute and Wheldall, 1989; Stern et al., 1983).

An adult's strategic use of voice in IDS may play an important role in a child's development. Infants have been shown to be sensitive to word or clause boundaries in IDS, but not to those in ADS (Kemler Nelson et al., 1989; Thiessen et al., 2005). In addition, the degree of exaggeration of vowel sounds in maternal IDS is significantly correlated with performance in phonetic discrimination in 6 to 12 months infants (Liu et al., 2003). These findings suggest that IDS may enhance an infant's ability to extract syntactic units from fluent speech.

In addition, a number of behavioral studies suggest infants prefer IDS to ADS and that they are more likely to attend to IDS than to ADS (e.g. Fernald, 1989; Pegg et al., 1992; Werker and McLeod, 1989). This preference for IDS emerges early in development; it appears even in 2-day-old neonates (Cooper and Aslin, 1990). Because infants show greater attention to IDS versus ADS, it is possible that IDS also contributes to positive adult-infant interactions. If so, this could lead to further opportunities for incidental verbal and social learning for children to occur.

Taken together, previous behavioral studies suggest that IDS plays a more important role in facilitating both: a) speech perception, and b) adult-infant social interactions than does ADS, and hence that IDS contributes to subsequent social and language development.

II. Infants' Brain Responses to Infant-directed Speech

Although a number of behavioral studies suggest IDS plays an important role in developing infants, few studies have examined the neural substrates underlying processing IDS in infants.

A recent developed non-invasive optical imaging technique, near-infrared spectroscopy (NIRS), allows us to measure higher temporal changes in hemoglobin concentration and oxygen saturation in multiple brain regions simultaneously. Very recently, NIRS has been widely used to reveal the neurocognitive functions of the infant brain (e.g. Homae et al., 2006; 2007; Minagawa et al., 2010; Penã et al., 2004; Taga et al., 2004).

1. Infant-directed speech and the talker familiarity

Using a multichannel NIRS, Naoi et al. (2011a) examined infants' cortical response patterns to IDS. Naoi et al. (2011a) independently measured activations in the temporal and frontal brain areas in order to examine the effects of IDS on cortical activation. In addition, Naoi et al. (2011a) compared the infants' cerebral responses when listening to IDS of their own mothers with corresponding responses to IDS of unfamiliar mothers (strangers). Furthermore, the infant hemodynamic responses to IDS were compared in 3 different infant age groups (4–6 months, 7–9 months, and 10–13 months).

A total of 48 infants ranging in age from 4 to 13 months and their mothers participated. The final sample included 26 infants aged 4–6 months (n=9; 5 girls), 7–9 months (n=9; 5 girls), and 10–13 months (n=8; 5 girls) in the temporal area measurement, and 22 infants aged from 4 to 6 months (n=8; 4 girls), 7–9 months (n=7; 3 girls), and 10–13 months (n=7; 5 girls) in the frontal area measurement.

The stimuli involved the following six Japanese sentences: ‘Ohayo. Kyouwa naniwo shimashouka. Isshoni sanponi ikimashou. Saishoni kouenni ikimashou. Kouenniwa hanaga saite imasu. Kouende asondara okaimononi ikimashou.’, meaning ‘Good morning. What are we going to do today? Let’s go for a walk. Let’s go to the park first. Flowers are blooming in the park. After playing in the park, let’s go to the shopping’. Mothers were given each sentence in writing and were instructed to produce it as if they were either speaking to their babies (IDS sample) or to the female experimenter (ADS sample)

Changes in the concentrations of oxygenated- (Oxy-Hb) and deoxygenated-hemoglobin (Deoxy-Hb) were measured using a multichannel NIRS system (ETG-7000, Hitachi Medical Co., Japan). In measurements of the temporal area, 2 emission and 2 detection probes were arranged in a 2 by 2 square lattice (4 channels) that fit, respectively, on each lateral side of the head (Fig. 1A). The distance between emission and detection probes was 3 cm. In the case of frontal area measurements, 8 emission and 7 detection probes were arranged in a 3 by 5 rectangular lattice (22 channels) and kept in a silicon holder (Fig. 1B). The emission and detection probe distance was 2 cm.

After the placement of the NIRS probes, the infants served in two NIRS sessions: Own mother (OM) and unfamiliar mother (UM) conditions. All infants were held by their mothers and they listened to the stimuli in a sound-attenuated room. Stimuli were presented through a speaker located 1 m front of the infants.

In the OM condition, the infant’s own mother’s ADS was presented in the baseline block and IDS was given in the target block. In UM condition, the infant’s unfamiliar mother’s ADS was presented as a baseline block and this was followed by IDS as target block. Both baseline and target blocks were repeated up to 5 times with an additional baseline block in the end. The order of the OM and UM sessions was counter-balanced among the participants.

NIRS can measure only relative changes in the concentration of the Oxy- and Deoxy-Hb from the baseline value determined at the initiation of each measurement session. Thus, a one-way analysis of variance (ANOVA) with repeated measures for two stimulus conditions (IDS and ADS) was conducted to compare the Hb changes between ADS and IDS in each speaker condition (OM and UM conditions). In order to compare the Hb changes in OM and UM conditions, the Hb changes of the averaged 10 s baseline block were subtracted from the averaged 10 s target block in each condition and each channel. Then we conducted a two-way mixed ANOVA, with age group (4–6 months, 7–9 months, and 10–13 months) as a between-subjects factor and speaker condition (OM and UM) as a within-subject factor.

Increased activations were observed predominantly in infants' bilateral temporal areas when they listened to IDS rather than to ADS when both involved voices of their own and unfamiliar mothers (Fig. 1A). In contrast, significantly greater activations were observed in the frontal area when infants listened to IDS produced by their own mothers, not when IDS arose from unfamiliar mothers (Fig. 1B).

Furthermore, the present results indicate that responses to IDS do vary as a function of the infant's age and the talker familiarity: seven- to 9-month-old infants showed greater activation to maternal IDS in the right temporal area than 4- to 6-month-old infants (Bonferroni test, p=0.028,). In addition, only 7- to 9-month-old infants showed greater activation to maternal IDS than to IDS spoken by the stranger in the inferior frontal area (p=0.014). These results suggest increased sensitivity to maternal IDS in 7- to 9- month-

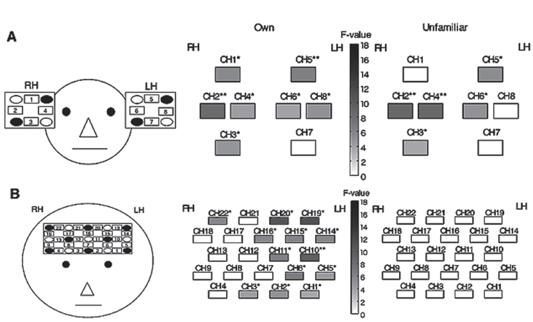

Figure 1. Statistical maps (F-maps) of Oxy-Hb changes of IDS vs. ADS in own and unfamiliar mother condition. (A) Temporal area measurement. (B) Frontal area measurement. LH: left hemisphere, RH: right hemisphere. * $p < 0.05$ and ** $p < 0.01$ (uncorrected).

old infants.

In sum, Naoi et al. (2011a) demonstrated localized brain activities in infants' frontal and temporal areas in response to IDS. IDS generally increases temporal lobe activity when compared to ADS whereas voice familiarity had little impact on this cortical area. In contrast, IDS specific to the voice of an infant's own mother facilitates activity in the frontal areas. These findings suggest a differential function for frontal and temporal areas in processing IDS by the different speakers.

2. Cerebral response to infant-directed speech in full-term neonates

Although Naoi et al. (2011) demonstrated that differential function for frontal and temporal areas in processing IDS in infants aged from 4 to13 months, a previous NIRS study have suggested that IDS increased brain activity even in younger infants.

Using two-channel NIRS, Saito et al. (2007) examined neonatal infants' hemodynamic responses in frontal areas while listening to the same stories read by their own mothers in IDS and in ADS. They found that these neonates showed greater frontal activation in response to IDS than to ADS. Although, Saito et al. (2007) provides some support for IDS's contribution to infants' frontal activation, they measured a limited number of brain areas (only two channels in the frontal area), and it remains unclear which brain regions are primarily involved in the processing of IDS in newborn infants.

In our ongoing study (Naoi et al., 2011b), we examined whether particular brain regions are specifically involved in the processing of IDS in full-term neonates by simultaneously measuring activation in the frontal, temporal, and occipital regions.

Thirty full-term newborn infants (15 girls) participated (mean postnatal age = 4.1 days; mean gestational age = 274.6 days).

Similar to Naoi et al. (2011a), four Japanese female speakers (all mothers of infants who did not participate in the present study) were given six Japanese sentences in writing and were instructed to produce it as if they were either speaking to their babies (IDS sample) or to the female experimenter (ADS sample). The control stimulus was constructed using pink noise, which has a frequency such that its power spectral density is inversely proportional to its frequency (1/f).

We used NIRS probes described in Homae et al. (2010), which were developed for simultaneously measuring the frontal, temporal, and occipital regions in young infants (Fig. 2). Fifteen incident and fifteen detection probes arranged in a 3 by 10 grid (47 channels) were fitted on each side of the head, which resulted in a total of 94 recording channels. The distance between emission and detection probes was ~2 cm.

NIRS recording was carried out in a quiet room in the maternity unit. All infants were in a state of natural sleep during NIRS measurement. During measurement, all infants were held by a pediatrician and listened to the auditory stimuli presented through a speaker located 30 cm front of the infant. A block design was used, and the two experimental conditions (IDS and ADS) alternated with a control condition. IDS samples were presented in the IDS condition and ADS samples were presented in the ADS condition. In the control condition, pink noise was presented. Both ADS and IDS conditions were repeated 8 times with an additional control block at the end. The order of the IDS and ADS conditions was counter-balanced among the participants.

To identify the activated regions under each IDS and ADS condition, we performed *t* tests against a zero baseline for each channel and corrected for multiple comparisons among the 94 measurement channels by using the false discovery rate method (FDR). In order to compare directly the Oxy- and Deoxy-Hb changes between ADS and IDS conditions, a one-way ANOVA with repeated measures for the two stimulus conditions (IDS and ADS) was conducted for each channel that showed significant activation in response to the IDS and ADS conditions.

In the IDS condition, statistically significant increases in Oxy-Hb were found in the broad area over the right frontal and the right and left temporal regions at the FDR-corrected $p < 0.05$ level (Fig. 2). In the ADS condition, analyses of Oxy-Hb showed no significant differences at the FDR-corrected 0.05 level. A direct comparison between the IDS and ADS conditions revealed that the measurement channels that showed significant activation for IDS were localized in the right frontal-temporal region (CH73, $F(1, 22) = 6.92$, $p = 0.015$, $\eta_p^2 = 0.24$).

In sum, our recent study demonstrated that the localized region of the right hemisphere is involved in IDS processing at a very early developmental stage.

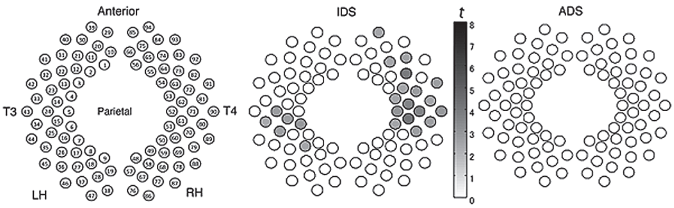

Figure 2. Statistical maps (t-maps) of Oxy-Hb changes in ADS and IDS conditions. $p < 0.05$, FDR corrected. The channels between the fifth and sixth probe in the lowest line corresponded to T3 (channel 43) on the left and T4 (channel 90) on the right. LH: left hemisphere, RH: right hemisphere.

III. General Discussion

Studies of infants' cerebral response to IDS and ADS using multichannel NIRS have found that infants show differential brain response to IDS and ADS, and the responses to IDS do vary as a function of the infant's age and the talker familiarity. In infants aged 4- to 13- month-old, IDS increases temporal lobe activity when compared to ADS. In contrast, IDS specific to the voice of an infant's own mother increases activity in the frontal areas (Naoi et al., 2011a)

Furthermore, our ongoing research found that even newborn infants showed larger and broader activation for the IDS than for the ADS (Naoi et al., 2011b). This finding is consistent with behavioral results showing that neonates have a behavioral preference for IDS (Cooper and Aslin, 1990). Using multichannel NIRS, we provided evidence that human full-term neonates increase brain activations to IDS.

With respect to localization of activation, the present results showed a large and significant activation in the right posterior temporal region and right frontal-temporal region to IDS rather than ADS. The laterality of brain activation in adults and in infants can be explained by the acoustic properties of the stimuli (Boemio et al., 2005; Jamison et al., 2006; Zatorre and Belin, 2001; Zatorre et al., 1992) as well as the linguistic properties, including semantic and syntactic structure (Gandour et al., 2002; Shtyrov et al., 2005). Because full-term neonates are at a very early stage of language acquisition, the asymmetries observed in neonates can be mostly explained by the acoustic properties of stimuli. Generally, in healthy adults, rapid or temporally changing segments of speech, such as phonemes, are processed predominantly in the left hemisphere, whereas slower or spectrally changing suprasegmental features of speech, such as prosody, are preferentially processed in the right hemisphere (Boemio et al., 2005; Poeppel, 2003; Perkins et al., 1996; Zatorre and Belin 2001; Jamison et al., 2006). Similarly, in infants, the left dominant responses to IDS, when compared to silence (Dehaene-Lambertz et al., 2002), backward IDS (Penã et al., 2003, Sato et al., 2006), and music (Dehaene-Lambertz et al., 2010), could be related to processing of segmental features in IDS. In our study (Naoi et al., 2011b), we compared IDS to ADS samples with identical segmental content, and the responses to IDS conditions were examined by comparing the responses to ADS. This resulted in activations associated with processing of the segmental aspects of speech, and sentential prosody in IDS was extracted by comparison with ADS. Thus neonatal responses observed in the present study indicate that the right frontal-temporal activation may reflect processing of prosodic modifications of IDS.

These present study utilized several advantages of NIRS techniques, such as non-invasiveness and higher spatial resolution over ERP techniques, to assess infants. Further study is needed to explore whether these early brain responses to IDS are related to later social and language development.

Footnotes

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