

Cerebral responses to infant-directed speech and the effect of talker familiarity

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ABSTRACT

A number of behavioral studies suggest that infant-directed speech (IDS) plays a more important role in facilitating both: a) speech perception, and b) adult–infant social interactions than does adult-directed speech (ADS), and hence that IDS contributes to subsequent social and language development. However neural substrates that may underlie these IDS functions have not been examined. The present study examined cerebral hemodynamic responses to IDS in 48 infants (4–13 months of age) using near-infrared spectroscopy (NIRS). Japanese sentences uttered by the infants' own mothers and by unfamiliar mothers were used to record activations in temporal and frontal area separately. Increased activations were observed predominantly in infants' left and right temporal areas when they listened to IDS rather than to ADS when both involved voices of their own and unfamiliar mothers. 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. Furthermore, the present results indicate that responses to IDS do vary as a function of the infant's age and the talker familiarity. These findings suggest a differential function for frontal and temporal areas in processing infant-directed speech by the different speakers.

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Introduction

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). Many studies have found that, relative to normal adult-directed speech (ADS), IDS is higher in pitch, has a wider pitch range, and exhibits exaggerated pitch contours; in addition, although IDS tend to be shorter than normal speech, they 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 (Ferguson, 1977; 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). IDS is also called “motherese” (Ferguson, 1977; Grieser and Kuhl, 1988; Kemler Nelson et al., 1989; Masataka, 1992) because it is frequently observed in mother–infant interactions. However, IDS has also been reported in fathers (Fernald,

1989; Jacobson et al., 1983), as well as in individuals who have never borne or raised a child (Nakagawa and Matsumura, 2006). It is even observed in preschool children (Tomasello and Mannle, 1985; Weppelman et al., 2003).

An adult's strategic use of voice in IDS may play an important role in a child's development. In fact, the role of IDS in language acquisition has recently become an issue of great debate. 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 in general may enhance an infant's ability to extract syntactic units from fluent speech.

A second issue concerns the role of IDS in eliciting infant affect and attention. 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). Consistent with this, 4- to 5-month-old infants expressed greater positive affect, such as smiling, to IDS than to ADS produced by unfamiliar male and female actor (Werker and McLeod, 1989). This preference for IDS emerges early in development; it appears even in 2-day-old neonates (Cooper and Aslin, 1990). Although this preference for IDS appears early, infants' preference for IDS changes as they age, Hayashi et al. (2001)

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demonstrated that infants between 4 and 6 months of age prefer IDS of an unfamiliar female but that the preference attenuates between the ages of 7 to 9 months. However, for still older infants the preference for IDS versus ADS re-appears. Because infants show greater attention and more positive affect 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. Therefore, IDS in such indirect ways, may also contribute more broadly to a child's subsequent development in language and social abilities later in life.

Taken together, this account leads to the identification of two potential functions of IDS for a developing child. First, IDS may simply facilitate speech perception by highlighting linguistic structure. Second, IDS may contribute to positive interactions between caregiver and infant by regulating infant arousal and affect.

To date, few neurological studies have addressed these IDS functions. With respect to infant speech perception, one fMRI study has shown that IDS results in larger activation in left temporal brain regions when 2–3 months old infants listen to IDS played forward and backward, compared to silence (Dehaene-Lambertz et al., 2002). Using younger infants aged 2 to 5 days old, Penã et al. (2003) applied near infrared spectroscopy (NIRS) to show significantly larger activation in left temporal area when these infants listened to normal IDS relative to backward IDS. Although these studies converge to indicate an involvement of left temporal area in infant-directed speech perception, relatively few neural studies have directly compared infants' responses to IDS with those to ADS. Using event-related potential (ERP), Zangl and Mills (2007) found that ERP responses between 600 and 800 ms (N600–800), which is linked to attentional processing, was larger to IDS than to ADS for familiar words but not for unfamiliar words in 6-month-old infants, whereas, N600–800 was larger to IDS than to ADS for both familiar and unfamiliar words in infants 13 months of age. Infants of both ages (6 and 13 months) showed increased brain activity to IDS for familiar words only in the left hemisphere. At 13 months, differences between unfamiliar words in IDS versus ADS were significant both in the left and right hemispheres. In addition, ERP responses to IDS from 200 to 400 ms (N200–400), which is linked to word meaning, was larger to IDS than to ADS only for the familiar words in the left temporal and parietal regions of 13-month-old infants. The findings of Zangl and Mills (2007) suggest that the effect of IDS on cerebral function may change with age and experience.

The second function of IDS involves facilitating positive adult–infant interaction. Trainor et al. (2000) suggested that IDS reflects the widespread vocal expression of emotion and IDS is more emotional than ADS. There is some evidence that frontal brain regions are involved in processing emotions. Santesso et al. (2007) examined the electroencephalographic (EEG) responses to emotions including love/comfort, fear, and surprise expressed in IDS and found the greatest activation in response to fear in the frontal region, however, they did not directly compare the response to IDS with that to ADS. Using a two-channel NIRS, Saito et al. (2007) compared neonatal infants' hemodynamic responses in frontal lobe areas while listening to the same stories read by their own mothers in IDS and in ADS. They found that these neonates showed larger frontal activation when they listened to IDS than to ADS. Saito et al. (2007) provides some support for IDS's contribution to infants' frontal activation, however, it is possible that not only the manner of speaking (i.e. adult- or infant-directed) but also the familiarity of a speaker may contribute to an infant's cortical response. Saito et al. (2007) did not compare the cerebral responses to IDS samples read by the infants' own mothers with ones read by unfamiliar mothers, therefore, it remains possible that the effect of IDS on the frontal activations in infants is limited to IDS of infants' own mothers' voice.

Only a few studies have examined infants' responses to maternal stimuli using brain imaging techniques. Using fMRI, Nitschke et al.

(2004) found bilateral brain activations in mothers' orbito-frontal cortex (OFC) when they viewed pictures of their own 3- to 5-month-old infants, but not when they viewed photos of unfamiliar infants. In Leibenluft et al. (2004), viewing pictures of one's own child (ages 5 to 12 years) activated various emotion-related brain areas such as the amygdala, insula, anterior paracingulate cortex, and inferior frontal area near the OFC when compared to familiar infants who were not their own, i.e. their children's friends. Furthermore, using NIRS, Minagawa-Kawai et al. (2009) have examined cerebral activations not only in mothers while viewing movies of both their own infants' and of unfamiliar infants' smiling. They also examined cerebral activations in infants while they viewed movies of their own mothers smiling and movies of unfamiliar mothers smiling. The results indicated that viewing one's own infant's smile elicited increased activations around the anterior part of OFC in the mothers. Furthermore, in 9–13 months infants, the prefrontal activation around the anterior OFC was shown to be specific to viewing their mother's smile but not to viewing an unfamiliar mother's smile.

Infants' brain responses to auditory events (e.g., speech, music, etc.) has been rarely examined in cortical responses of the infant member of mother–child interactions. In infants, a preference for the maternal voice appears soon after birth (DeCasper and Fifer, 1980; Hepper et al., 1993). Barker and Newman (2004) found that speech perception in 6- to 8-month infants was facilitated when it was produced by the infant's mother. Using ERP, Purhonen et al. (2004) demonstrated that the latency of earlier ERP components, i.e., those occurring before 350 ms, which are associated with an orienting response, is significantly shorter to infants' own mothers' voice than to the voice of an unfamiliar female in infants at 4 months of age. The latency of the later ERP components (N450 and P600) was longer to the mother's voice than to the unfamiliar voice. In addition, in these infants, the amplitudes of later ERP components (P600) were lower in response to their own mothers' voice than to an unfamiliar voice (Purhonen et al., 2005). Purhonen et al. (2005) interpreted these later ERP components as reflecting cognitive processing; they suggest that functional cortical specialization involved in the familiar maternal voice is already initiated by the age of 4 months. Furthermore, using fMRI, Dehaene-Lambertz et al. (2010) found significantly stronger responses were elicited in the left posterior temporal regions and in the left and right anterior prefrontal cortex when 2-month-old infants listening to their own mothers' voice than to the voice of an unfamiliar female.

In the present study, we examined cerebral responses of infants to IDS and ADS using near-infrared spectroscopy (NIRS). In order to examine the effects of IDS on cortical activation, we independently measured activations in the temporal and frontal brain areas. If an infant's speech perception was generally affected by IDS, we expected to find higher levels of activation for IDS than for ADS in the temporal brain regions.

Furthermore, to determine the role of speaker familiarity, we compared the infants' cerebral responses when listening to IDS of their own mothers with corresponding responses to IDS given by unfamiliar mothers (strangers). If familiarity contributed to an infant's cerebral response, we anticipated heightened activity associated with this variable.

Moreover, we examined whether speaker familiarity contributed to the differential activities in the temporal and frontal cortical areas. If familiarity was primarily linked to arousal and affect in infants, we expected to find heightened activity in response to the mother's familiar voice largely in the arousal regions such as the frontal cortical areas.

Furthermore, we compared the infant hemodynamic responses in 3 different infant age groups (4–6 months, 7–9 months, and 10–13 months) to examine age-related changes in response to IDS. If the infants' brain responses were consistent with Hayashi et al. (2001), who showed that the behavioral preference for IDS attenuates

between the ages of 4–6 months to 7–9 months and re-appears after 10–11 months of age, we expected decreased levels of activation to IDS in 7–9-month-olds.

Materials and methods

Participants

A total of 105 infants ranging in age from 4 to 13 months and their mothers participated in this study. Of the 105, 57 infants participated in the temporal area measurement, and 48 infants participated in the frontal area measurement. Participants were recruited as paid participants from local advertisements. At the time of recruitment, all infants were pre-screened to determine whether or not they exhibited a developmental delay using the Kyoto Scale of Psychological Development (KSPD, Ikuzawa et al., 2002). KSPD is a standardized scale measuring physical, language, and cognitive skills. This instrument yields standard scores for Physical-Movement (PM), Language-Sociability (LS), and Cognitive-Adaptive (CA) subscales as well as total developmental age. In Japan, the KSPD is commonly administered to infants. In addition, mothers of infants all reported having no history of serious illnesses or disorders. Of the 57 infants whose temporal areas were measured, 31 were excluded, and of the 48 infants whose frontal areas were measured, 26 were excluded from the final statistical analysis following refusal to wear the NIRS probe ($n = 9$), failure to obtain more than one useable block of trials due to excessive motion artifacts ($n = 42$), or bad probe attachment due to hair obstruction ($n = 6$).

We excluded channels with waveforms that were linear or those with completely symmetrical Oxy- and Deoxy-Hb waveforms because these waveforms represent the separation of the probes from the skin because of hair obstruction. Infants with more than 5 eliminated channels for temporal measurement and 12 eliminated channels for frontal measurement were excluded from further analysis ($n = 6$). In the frontal probe, data from the most dorsal channels (CH19–CH22) tended to be affected by hair obstruction. The mean numbers of the remaining channels per infant were 6.3 (SD = 1.4) and 16.5 (SD = 2.8) for temporal and frontal measurements, respectively.

The relatively high dropout rate of the participants was because the infants were tested while seated in their parent's lap; hence, they sometimes turned to look at their mother's face when her voice was presented to them. This behavior produced large motion artifacts. Nevertheless, this testing procedure was necessary because it is difficult to measure an infant who has been separated from her/his mother (Minagawa-Kawai et al., 2009; Purhonen et al., 2004, 2005). In addition, this attrition rate is within the normal range for previous NIRS studies that measured awake infants (Grossmann et al., 2010; Homae et al., 2006, 2007; Lloyd-Fox et al., 2011; Minagawa-Kawai et al., 2011).

The final sample included 26 infants aged 4–6 months ($n = 9$; range: 115–194 days; 5 girls and 4 boys), 7–9 months ($n = 9$; range: 205–280 days; 5 girls and 4 boys), and 10–13 months ($n = 8$; range: 309–404 days; 5 girls and 3 boys) in the temporal area measurement, and 22 infants aged from 4 to 6 months ($n = 8$; range: 109–188 days; 4 girls and 4 boys), 7–9 months ($n = 7$; range: 220–270 days; 3 girls and 4 boys), and 10–13 months ($n = 7$; range: 322–396 days; 5 girls and 2 boys) in the frontal area measurement.

The present study was carried out with the informed consent of the parents. The study was also conducted with the approval of the ethics committee of Keio University, Faculty of Literature (No. 04001).

Stimuli

Stimuli spoken by the infant's mother were recorded prior to the NIRS measurements. The recordings were made in a sound-attenuated room. 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). We recorded the ADS sample first. Each mother's speech samples were analyzed using Praat (Boersma and Weenink, 2007) and total duration, intensity, mean pitch, maximum and minimum pitch were calculated. Previous studies have found that IDS utterances are slower than ADS (Fernald and Simon, 1984; Snow and Ferguson, 1977; Stern et al., 1982; Stern et al., 1983). In fact, for many of the participating mothers in this study, the IDS speech samples tended to be about 5 seconds longer than the ADS samples. Since our priority was to keep the natural characteristics of IDS, we did not adjust durations of IDS samples to equalize the length of IDS and ADS. Instead, to remove individual differences, all IDS samples were edited into sequences of 20 s and ADS samples were edited into sequences of 15 s; this was accomplished mainly by adjusting pause durations. The mean intensity of the IDS and ADS samples was equalized by adjusting the energies of the sounds to the same level using Sound Forge 6.0™ audio editing software. The mean pitch was 230.13 Hz (range = 183.01–267.56 Hz) for the ADS samples and 269.25 Hz (range = 205.56–319.18 Hz) for the IDS samples. The mean pitch was significantly higher in mothers' speech to infants than to an adult (paired $t(34) = 10.71, p < 0.001$). The pitch range was calculated by subtracting minimum pitch from maximum pitch. The mean pitch range was 232.79 Hz (range = 117.31–445.54 Hz) in the ADS samples and 338.82 Hz (range = 115.66–650.45 Hz) in the IDS samples. The mean pitch range of the IDS samples is significantly greater than that of the ADS samples (paired $t(34) = 5.47, p < 0.001$). To assess stimulus validity, the degree of "infant-directedness" associated with produced stimuli was quantified using rating scores supplied by two independent raters who were unfamiliar with the purpose of the study. Each rater was asked to rate each speech stimulus on a 5-point Likert-type scale with poles marked (1) 'adult-directed', (3) 'neither adult-directed nor infant-directed', and (5) 'infant-directed'. Raters were blind to all presented items, which occurred randomly with respect to both speaker and IDS/ADS samples. The mean rating score of "infant-directedness" was 1.4 (range = 1–2) for ADS samples and 4.1 (range = 2–5) for the IDS samples. There was significant difference in the degree of "infant-directedness" between the ADS and IDS samples (paired $t(34) = 22.71, p < 0.001$). There was significant correlation between mean pitch of IDS samples and rating score of "infant-directedness" and IDS samples with higher mean pitch were scored as more "infant-directed" (Spearman's $r_s = 0.58, p < 0.001, n = 35$).

Previous studies have found that pitch and pitch range of IDS were modified as a function of infant's age. Thus, maternal IDS to 3–9 month-old infants has a generally higher pitch than does maternal IDS to neonates, and 1–2-year-olds (Kitamura et al., 2002; Stern et al., 1983; Warren-Leubecker and Bohannon, 1984). However, in the present study, we found no significant correlation between pitch and pitch range of IDS samples and age of the infants.

The speech stimuli produced by an infant's own mother was used as the unfamiliar control stimuli for another infant. We matched each infant's own mother's speech with that produced by an unfamiliar mother such that both stimuli had similar mean, maximum and minimum pitch, and mean degree of infant-directedness.

NIRS measurement

We measured changes in the concentrations of oxygenated- (Oxy-Hb) and deoxygenated-hemoglobin (Deoxy-Hb) using a multichannel NIRS system (ETG-7000, Hitachi Medical Co., Japan). The emission

probe (2 mm diameter) emitted near-infrared light with wavelengths of approximately 780 nm and 830 nm. Reflection of infrared light was detected by a detection probe. The sampling rate was 10 Hz. We measured the frontal and bilateral temporal areas separately because our NIRS probe systems for those areas are different type as described below and those two systems cannot be physically attached together.

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 (see Fig. 1A). The line connecting T3, Fp1, Fp2, and T4 was horizontal to the lowest lines of the NIRS probes and the posterior probe in the lowest line corresponded to T3 on the left and T4 on the right according to the international 10–20 electrode system (Homan et al., 1987). Previous studies suggest that these channels approximately covered the right and left auditory areas (Furuya and Mori, 2003; Minagawa-Kawai et al., 2011; Okamoto et al., 2004). 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 (see Fig. 1B). The lowest line of the probes corresponded to the T3-Fp1-Fp2-T4 line according to the international 10–20 electrode system (Homan et al., 1987). The vertical midline of the channels was centered in the nasion–inion line. The emission and detection probe distance was 2 cm.

Procedure

On the first visit to the laboratory, infants were screened using standard tests, and speech samples were collected from each mother. Each infant–mother pair revisited the laboratory for experimental testing. 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. All stimuli were presented at a measured intensity of approximately 60 dB sound pressure level. Mothers wore headphones that prevented their hearing speech stimuli during the experiment. In the OM condition, 15 s of the infant's own mother's ADS was presented in the baseline block and 20 s of IDS was given in the target block. In UM condition, 15 s of the infant's unfamiliar mother's ADS was presented as a baseline block and this was followed by 20 s of 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. All the experiments were DVD-recorded to assess the participant's movement.

Data analysis

We compared brain activation to IDS in OM and UM conditions. Concentration changes in Oxy-Hb provided a strong correlation with the BOLD signals and a more robust and reliable measure of changes in regional cerebral blood flow than did Deoxy-Hb (Bartocci et al., 2001; Chen et al., 2002; Hoshi and Tamura, 1993; Hoshi et al., 2000, 2001; Jaszewski et al., 2003; Kato et al., 1993; Sakatani et al., 1999; Strangman et al., 2002; Strangman et al., 2003; Taga et al., 2003). Therefore, our analysis mainly focused on hemodynamic changes reflected in Oxy-Hb, but we also analyzed Deoxy-Hb.

The raw data of Oxy- and Deoxy-Hb from individual channels were high-pass filtered at 0.0143 Hz to remove components originating from task design and systematic fluctuations (Fuchino et al., 2006; Taga et al., 2003). We excluded blocks with motion artifacts (signal variations greater than 2 standard deviations from the mean over

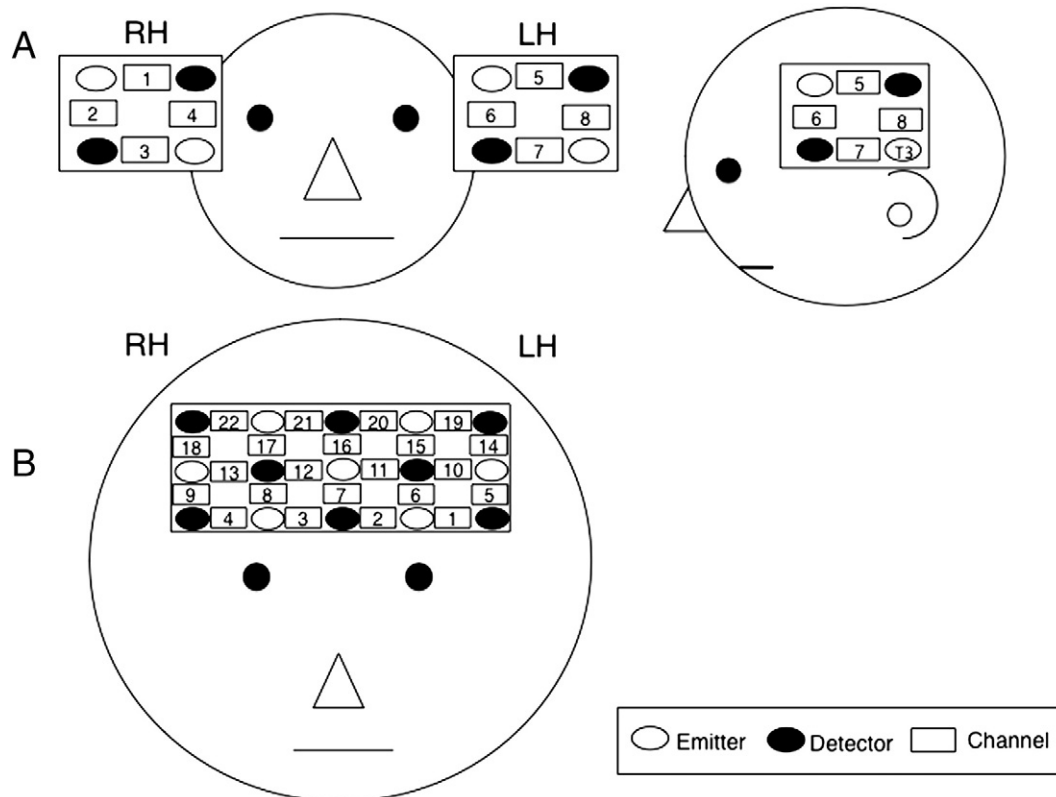


Fig. 1. NIRS probes and channels setting in infants. (A) Temporal measurement. Two emission and two detection probes in a 2 × 2 square lattice were fitted on each lateral side of the head (LH: left hemisphere, RH: right hemisphere). The posterior probe in the lowest line corresponded to T3 on the left and T4 on the right. (B) Frontal measurement. Eight emission and seven detection probes in a 3 × 5 rectangular lattice were located over the frontal area. The lowest line of the probes line corresponded to the T3-Fp1-Fp2-T4 line. The vertical midline of the channels was centered in the nasion–inion line.

0.2 s). The remaining pairs of baseline and target blocks comprised 3.5 blocks, on average, per infant (SD=0.9, range=2–5) for OM condition and also 3.7 blocks (SD=0.9, range=2–5) for UM condition, with no significant difference between them.

The Oxy-Hb and Deoxy-Hb concentrations of the remaining baseline and target blocks were averaged and smoothed with a 5 s moving average over a span of 10 s beginning 5 s from the onset of a block of trials (baseline or target block); this was calculated for each condition and for each channel. Data from the first 5 s from a block's onset were excluded to avoid transition period effects both in OM and UM conditions.

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, we did not compare two of the stimulus conditions (IDS and ADS) in two of the speaker conditions (OM and UM conditions) directly. Instead, an ANOVA with repeated measures for two stimulus conditions (IDS and ADS) was conducted to identify the activated regions under each speaker condition; this allowed us 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. Effect sizes, as indexed by partial eta-squared (η_p^2), were also calculated.

Results

Temporal area measurement

In the initial analysis, we compared the Oxy-Hb changes between ADS and IDS in each speaker condition (OM and UM conditions) using a one-way ANOVA with repeated measures for two stimulus conditions (IDS and ADS samples). The result is shown in Table 1 and Fig. 2A.

Under the OM condition, a one-way ANOVA with repeated measures on stimulus conditions (IDS and ADS) revealed significant differences in the Oxy-Hb changes in CH1, CH2, CH3, and CH4 which are around the right temporal area. Similarly, in the left temporal area, significant differences were found in CH5, CH6, and CH8. Analyses of Deoxy-Hb showed statistically significant differences between ADS and IDS stimuli in CH1 and CH4 in the right temporal area, and CH7 and CH8 in the left temporal area.

Under the UM condition, statistically significant differences were noted in the Oxy-Hb changes between ADS and IDS stimuli in CH2,

CH3, and CH4, in the right temporal area. Similarly, in the left temporal area, significant differences were found in CH5 and CH6. Analyses of Deoxy-Hb showed statistically significant differences between ADS and IDS stimuli in CH8.

In the second analysis, we compared the Oxy-Hb changes (IDS minus ADS) in OM and UM conditions, using 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.

A two-way ANOVA with age group (4–6 months, 7–9 months, and 10–13 months) × speaker condition (OM and UM) on the response magnitude of Oxy-Hb changes (IDS minus ADS) revealed no significant main effects of age group or speaker condition. There was, however, statistically significant interaction effect between age and speaker condition in CH4 in the right temporal area ($F(2, 12) = 3.97, p = 0.047, \eta_p^2 = 0.40$). Hemodynamic responses to IDS against ADS stimuli were observed for OM and UM conditions in CH4 (Figs. 2B and C). A post hoc Bonferroni test revealed that the 7- to 9-month-olds exhibited significantly larger responses than did 4- to 6-month-olds, only under OM condition ($p = 0.028$, Fig. 2D). Analyses of Deoxy-Hb showed no statistically significant differences with any comparison.

Frontal area measurement

A one-way ANOVA with repeated measures for two stimulus conditions (IDS and ADS samples) was conducted to compare the Oxy-Hb changes between ADS and IDS in each speaker condition (OM and UM conditions) (see Table 2. and Fig. 3A).

Under the OM condition, statistically significant differences were noted in the Oxy-Hb changes between ADS and IDS stimuli in broad brain areas (Table 2). Analyses of Deoxy-Hb showed statistically significant differences between ADS and IDS stimuli in CH4, CH8, and CH17. Under the UM condition, no significant differences were noted in the Oxy-Hb changes between ADS and IDS stimuli. Analyses of Deoxy-Hb showed statistically significant differences between ADS and IDS stimuli in CH1, CH3, CH12, and CH15.

A two-way ANOVA with age group (4–6 months, 7–9 months, and 10–13 months) × speaker condition (OM and UM) on the response magnitude of Oxy-Hb changes (IDS minus ADS) revealed a statistically significant main effect of speaker in CH10 ($F(1, 16) = 9.24, p = 0.0078, \eta_p^2 = 0.37$) and CH15 ($F(1, 11) = 6.64, p = 0.026, \eta_p^2 = 0.38$) in the left superior frontal area (Figs. 3B and C). In addition, this analysis revealed a statistically significant interaction effect of age and speaker condition in CH2 ($F(2, 16) = 5.05, p = 0.020, \eta_p^2 = 0.39$) in the inferior prefrontal area. A post hoc Bonferroni test revealed significantly larger responses in OM condition than in UM condition, but only in the 7- to 9-month-olds ($p = 0.014$, see Fig. 3D). A two-way ANOVA with age group (4–6 months, 7–9 months, and 10–13 months) × speaker condition (OM and UM) on the response magnitude of Deoxy-Hb changes (IDS minus ADS) revealed a statistically significant main effect of speaker condition in CH3 ($F(1, 13) = 4.87, p = 0.046, \eta_p^2 = 0.27$).

Discussion

In the present study, we examined infants' cortical response patterns to infant-directed speech in the temporal and frontal cortical areas as well as the effect of speaker familiarity, using NIRS.

With respect to the temporal area, we found that 4–13 months infants showed greater activations in response to IDS than to ADS, and this was true with speech produced by both the infant's own mother and speech produced by an unfamiliar mother. Previous studies have reported that increased temporal activation occurs in response to IDS when compared to a silent baseline (Dehaene-Lambertz et al., 2002; Penã et al., 2003) and to backward IDS (Penã et al., 2003). Our findings were in agreement with the results of these previous studies in that the temporal areas activated in response to IDS. However, our study

Table 1
Channels activated in response to IDS compared to ADS in temporal area.

Conditions	Oxy-Hb				Deoxy-Hb			
	Channel	F	p	η_p^2	Channel	F	P	η_p^2
Own mother	1	6.92	0.015	0.24	1	7.51	0.012	0.25
	2	10.50	0.0034	0.30	4	11.51	0.0037	0.42
	3	6.08	0.0023	0.23	7	5.94	0.027	0.27
	4	5.27	0.036	0.25	8	11.41	0.0033	0.39
	5	8.08	0.010	0.28				
	6	4.72	0.041	0.18				
	8	6.44	0.021	0.26				
	Unfamiliar mother	2	10.98	0.0035	0.35	8	7.05	0.016
3		4.63	0.047	0.22				
4		11.02	0.0041	0.39				
5		6.59	0.019	0.27				
6		6.13	0.022	0.23				

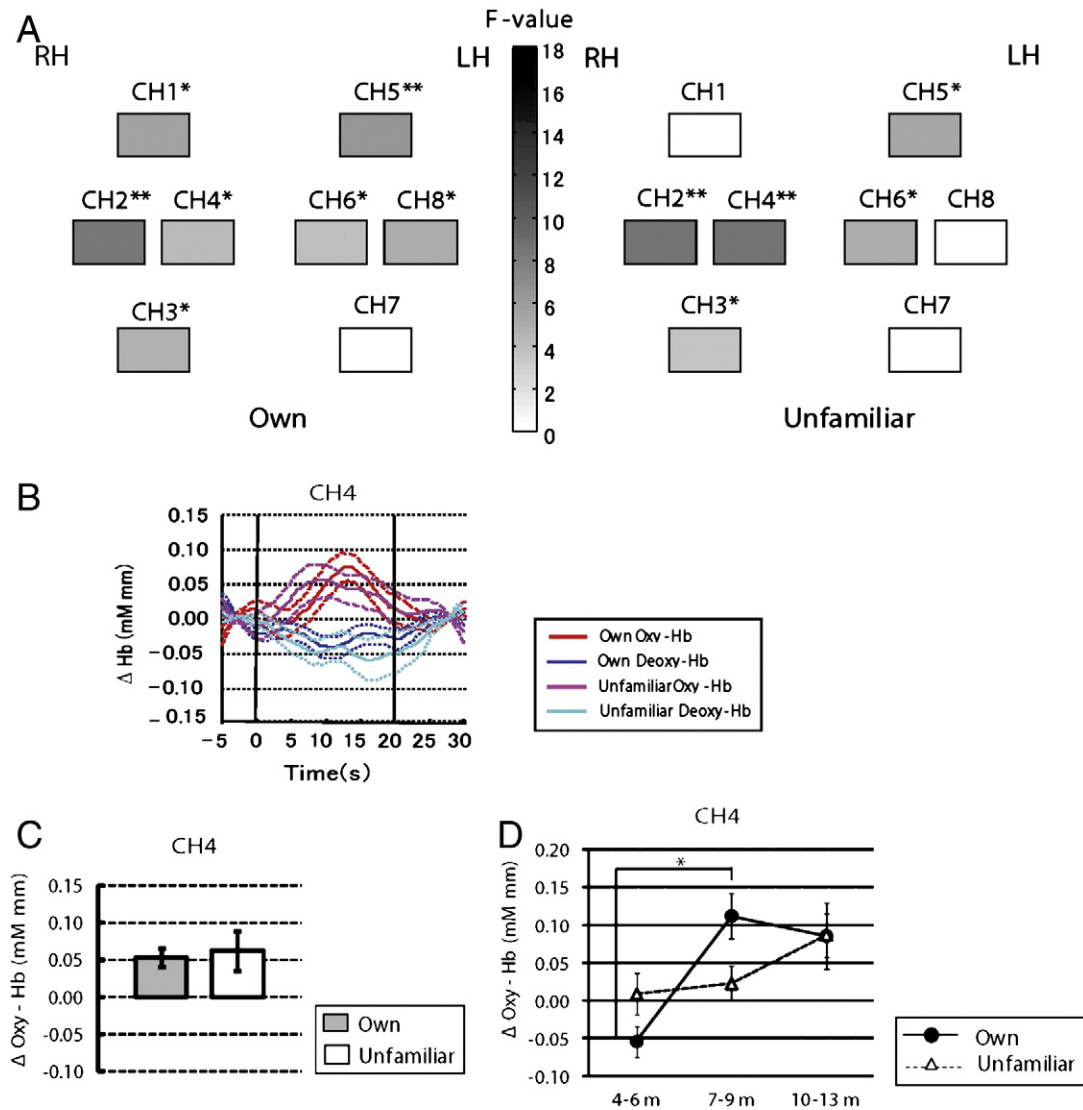


Fig. 2. The infants' hemodynamic responses in the temporal area. (A) Statistical maps (*F*-maps) of Oxy-Hb changes of IDS vs. ADS in own and unfamiliar mother condition. The *F*-values for each channel are color coded as indicated by the color bar. LH: left hemisphere, RH: right hemisphere. * $p < 0.05$ and ** $p < 0.01$ (uncorrected). (B) Grand averaged time courses of Oxy- and Deoxy-Hb changes in CH4. The red and blue solid lines represent Oxy-Hb and Deoxy-Hb, respectively, in response to own mother condition. The magenta and cyan solid lines indicate Oxy-Hb and Deoxy-Hb, in response to unfamiliar mother condition. The dashed lines represent ± 1 standard error of the mean (SE). The two vertical black lines indicate the target block (IDS sample), which has 20 s of duration. For the purpose of display, a baseline was linearly fitted between the means of the 5 s preceding the onset of the target block and the 5 s before the offset of the baseline block (ADS samples). (C) Comparison of Oxy-Hb changes between own and unfamiliar conditions in CH4. Error bars indicate SE. (D) Oxy-Hb changes in CH4 in 4- to 6-, 7- to 9-, and 10- to 13-month-olds under own and unfamiliar conditions. Seven to 9-month-olds exhibited significantly larger responses than did 4- to 6-month-olds, only under own mother condition.

further revealed bilateral temporal activations in response to IDS, when compared to ADS. IDS has wider pitch range than ADS and exhibits exaggerated pitch contours, all of which are presumed to facilitate speech perception in infants (Kemler Nelson et al., 1989; Thiessen et al., 2005). These prosodic features of IDS may affect the increased activation in the temporal area. Our study observed bilateral temporal activations in response to IDS, however, previous studies, using fMRI (Dehaene-Lambertz et al., 2002) and NIRS (Penã et al., 2003), have suggested the involvement of left temporal area in processing speech even in younger infants. These differences might be due to the difference in stimuli and their presentation or differences in measurements of brain responses.

The laterality of brain activation can be explained by the acoustic properties (Poeppe, 2003; Zatorre and Belin, 2001) and the linguistic properties of stimuli such as semantic and syntactic structure (Best and Avery, 1999; Gandour et al., 2002; Shtyrov et al., 2005). In general, 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 (Poeppe, 2003; Perkins et al., 1996; Zatorre et al., 1992). The left dominant responses to IDS, when compared to silence (Dehaene-Lambertz et al., 2002) and backward IDS (Penã et al., 2003), could be related to processing of segmental and lexical features in speech against backward speech and silence. In the present study, we compared IDS to ADS samples with nearly identical segmental and lexical contents. Therefore, it is considered that most of the activations due to segment or lexical processing were subtracted out and bilateral activation may reflect processing of phonetic modifications such as exaggerated vowel formants and prosodic modifications of IDS samples.

When compared ERP responses to words spoken in IDS and to words spoken in ADS, Zangl and Mills (2007) found the N600-800, which is linked to attentional processing, was larger to IDS than to ADS for familiar words only in the left hemisphere at both 6 and 13 months. In addition, the N200-400, which is linked to word

Table 2
Channels activated in response to IDS compared to ADS in frontal area.

Conditions	Oxy-Hb				Deoxy-Hb			
	Channel	F	p	η_p^2	Channel	F	p	η_p^2
Own mother	1	4.38	0.049	0.18	4	5.88	0.025	0.24
	2	6.47	0.021	0.28	8	7.93	0.015	0.38
	3	5.12	0.037	0.23	17	5.97	0.027	0.27
	5	5.46	0.032	0.24				
	6	8.46	0.011	0.36				
	10	12.19	0.0024	0.39				
	11	8.14	0.011	0.32				
	14	7.53	0.014	0.31				
	15	7.92	0.015	0.38				
	16	7.28	0.022	0.50				
	19	14.23	0.0027	0.54				
	20	14.01	0.0022	0.50				
Unfamiliar mother	22	7.32	0.022	0.42				
					1	5.81	0.026	0.23
					3	5.04	0.038	0.22
					12	5.21	0.035	0.22
				15	4.91	0.040	0.21	

meaning, was larger to IDS than to ADS for familiar words only in the left temporal and parietal regions in infants 13 months of age. In Zangl and Mills (2007), words were presented in isolation whereas in the present study words were embedded within sentences. These differences may result in differential left and right hemispheric contributions to the processing of IDS, as suggested by Zangl and Mills (2007). Furthermore, it is likely that cerebral hemodynamic responses measured by NIRS in our study and the electrophysiological responses (N200–400 and N600–800) shown in Zangl and Mills (2007) do not exactly reflect the identical neural activities.

In addition, prosodic modifications of IDS convey a more positive affect than ADS; IDS and ADS differ in their emotional prosody (Trainor et al., 2000). Using NIRS, Grossmann et al. (2010) demonstrated that 7-month-old infants showed an increase in cerebral activations in the right temporal region in response to words spoken with emotional prosody (happy and angry) compared with those spoken with neutral prosody. Therefore, the bilateral activation pattern to IDS compared to ADS may partly be due to right temporal activations in response to emotional prosodic modifications in IDS.

In summary, the present data indicate that the neural substrate for processing IDS involves the bilateral temporal lobe regions, and activations in these regions are independent of the familiarity of a speaker's voice. Lack of left dominance in this study, in contrast to previous studies, can be explained by the absence of the neural processing of lexical items in the comparison of IDS and ADS. Furthermore, even if the responses to IDS contained larger neural components dedicated to lexical processing than ADS, our stimulus forms of sentences may have diminished these differences because of the inclusion of other components such as emotional and sentential prosody and vowel quality.

With respect to the frontal area, our study showed that greater activity in response to IDS stimuli only occurs when these stimuli were produced by the infants' own mothers. It has been shown that neonates exhibit selectively increased hemodynamic responses in frontal cortical area in response to maternal IDS versus ADS stimuli (Saito et al., 2007); using well controlled stimuli, the present data replicate this finding with older infants. In addition, the present study suggests that the effect of IDS on frontal activations may interact with talker familiarity because increments in hemodynamic responses to IDS relative to ADS were observed only in response to IDS that was produced by infants' own mothers. It is unlikely that this effect is due to differences in physical properties or degree of "infant-directedness" between familiar and unfamiliar speech samples because differences between these samples (i.e., in these properties) were minimized.

Using ERP, Purhonen et al. (2004) have demonstrated that latency and amplitude of the ERP components differed in response to both the mother's voice and to an unfamiliar female's voice in infants at 4 months of age. In addition, using fMRI, Dehaene-Lambertz et al. (2010) found significantly stronger responses were elicited in the left posterior temporal regions and in the left and right anterior prefrontal cortex when 2-month-old infants listening to their own mothers' voice than to the voice of a stranger. Data of the present study converge with these to indicate that infants under 1 year of age are sensitive not only to the manner of speaking (i.e. adult- or infant-directed), but also to the speaker.

Although activity in frontal areas could be linked to many cognitive functions such as working memory, emotion, attention, as well as affect, the current data suggest that infants' interactive experience with their mothers may influence infant hemodynamic activations in the left superior frontal area.

It must be mentioned that the experimental setting in the present study may be relevant to the left frontal activation observed in infants. In the present study, the mother's voice was presented to the infants while the mother was holding them. Therefore, the left prefrontal activation of infants in response to their mother's IDS may be caused by this novel strange social situation. However, even if the infants' responses to the voices of their mothers contained neural components related to the oddly disembodied voice of the mother, this response could be subtracted by comparison with infants responses to maternal ADS. In the present study, ADS samples of the infants' own mothers and unfamiliar speakers were used as baseline stimuli. The responses to IDS were derived by subtracting the responses to these baseline stimuli. In other words, the hemodynamic response of an infant to maternal IDS was derived by subtracting the response of the infant to maternal ADS. Therefore, the effect of the experimental setting alone cannot explain the frontal activations of infants in response to the maternal IDS observed in the present study.

Similarly, infant's frontal activations to the maternal IDS cannot be explained by familiarity of a speaker's voice alone. Rather, infants' responses to IDS indicate that the neural correlates for processing IDS are simply stronger for their own mother. Although infants had experience listening to both ADS and IDS of infant's own mother in everyday situations, it is likely that infants had far more experience with IDS rather than ADS spoken by their own mothers in everyday mother–infant interactions, and these interactive experiences between the infant and mother may influence reinforcing properties of the maternal infant-directed speech in infants. This selective familiarity effect has also been observed in the mother's neural response to visual stimuli of the mother's own infant (Leibenluft et al., 2004; Minagawa-Kawai et al., 2009; Nitschke et al., 2004) and in the infant's cerebral response to visual stimuli of the infant's own mother (Minagawa-Kawai et al., 2009). Using NIRS, Minagawa-Kawai et al. (2009) demonstrated that activations, specific to their mother's positive facial expression, were observed in infants' frontal areas. In the current study, where we used auditory stimulation, we observed hemodynamic activations in the left superior frontal the area when infants listened to their own mothers' IDS. Nevertheless, there remains a possibility that this selective familiarity effect may not be specific to infant's primary caregiver, the mother, but may also appear in response to IDS of any familiar adults, such as infant's father and grandparents. Further study is needed to examine this issue.

Furthermore, this finding is reminiscent of previous studies indicating that left frontal activation is related to the processing of positive emotion or approach motivation and positive interactions between mothers and infants (Davidson and Fox, 1982; Dawson et al., 1999; Fox and Davidson, 1987; Grossmann et al., 2010; Harmon-Jones et al., 2010). Therefore, along with the results of the present study, this raises the possibility that the increased left prefrontal response to the mother's IDS may reflect the infant's response to the positive affective stimuli directed at them with the motivation to approach.

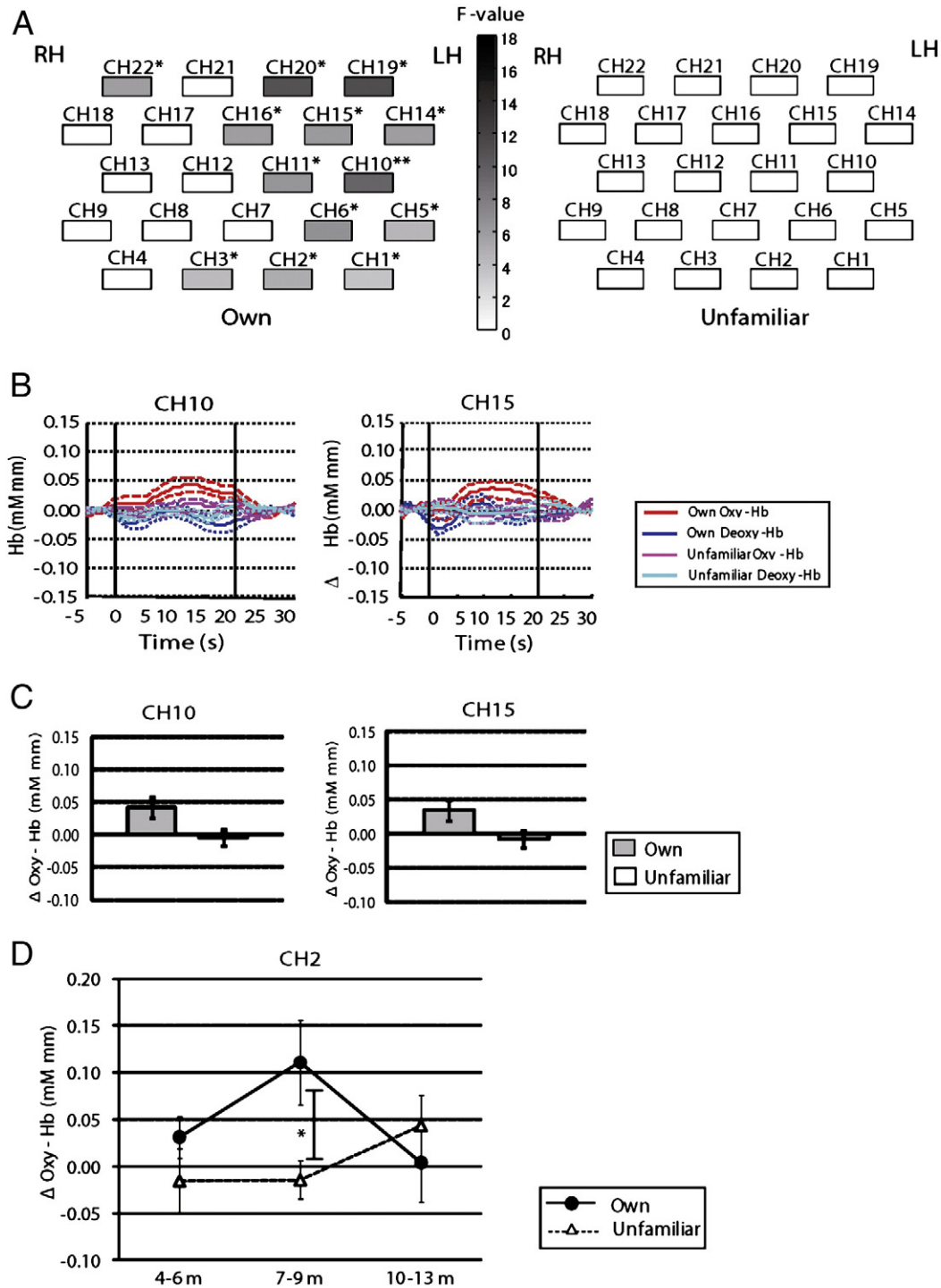


Fig. 3. The infants' hemodynamic responses in the frontal area. (A) Statistical maps (F-maps) of Oxy-Hb changes of IDS vs. ADS in own and unfamiliar mother condition. The F-values for each channel are color coded as indicated by the color bar. LH: left hemisphere, RH: right hemisphere. * $p < 0.05$ and ** $p < 0.01$ (uncorrected). (B) Grand averaged time courses of Oxy- and Deoxy-Hb changes in CH10 and CH15. The red and blue solid lines represent Oxy-Hb and Deoxy-Hb, respectively, in response to own mother condition. The magenta and cyan solid lines indicate Oxy-Hb and Deoxy-Hb, in response to unfamiliar mother condition. The dashed lines represent SE. The two vertical black lines indicate the target block (IDS sample), which has 20 s of duration. For the purpose of display, a baseline was linearly fitted between the means of the 5 s preceding the onset of the target block and the 5 s before the offset of the baseline block (ADS samples). (C) Comparison of Oxy-Hb changes between own and unfamiliar conditions in CH10 and CH15. Error bars indicate SE. (D) Oxy-Hb changes in CH2 in 4- to 6-, 7- to 9-, and 10- to 13-month-olds under own and unfamiliar conditions. Only the 7- to 9-month-olds exhibited significantly larger responses in own mother condition than in unfamiliar mother condition.

With regard to age-related differences, previous NIRS studies have demonstrated that there were developmental changes in temporal cortical activities related to phonemic or prosodic changes in infants (Furuya and Mori, 2003; Homae et al., 2006, 2007; Minagawa-Kawai et al., 2007; Sato et al., 2003). The present results indicate that responses to maternal IDS do vary as a function of the infant's age and

7- to 9-month-old infants showed greater activation to maternal IDS in the right temporal area than 4- to 6-month-old infants. 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. These results suggest increased sensitivity to maternal IDS in 7- to 9-month-old infants.

This finding is consistent with the behavioral results showing that infants in this age range begin to show a strong behavioral preference for their caregivers and show anxiety behaviors such as crying when approached by a stranger, this is commonly called “stranger anxiety.” Although there are individual differences, previous studies have reported that the severity of infant stranger anxiety peaks at approximately 8 months and diminishes toward the end of the first year (Gaensbauer et al., 1976; Spitz, 1965).

However, this result was inconsistent with Hayashi et al. (2001) who showed that the behavioral preference for IDS attenuates between the ages of 4–6 months to 7–9 months, and re-appears after 10–11 months of age. The discrepancies in the results might be accounted for the difference in the experimental paradigms, methodology or stimulus form. In terms of stimulus form, IDS sample was a mother's talking to her infant and ADS sample was recorded when the mother was talking to a researcher in Hayashi et al. (2001), i.e., not only prosodic but also other linguistic information in IDS and ADS stimuli was different. In contrast to Hayashi et al. (2001), the same sentences were spoken in IDS and ADS samples, i.e., IDS differs from ADS mainly in prosodic features in the present study. It is possible that the preference for ADS over IDS in 7–9 months demonstrated in Hayashi et al. (2001) may be due to infants' preference for unfamiliar novel words included in ADS stimuli over familiar words in IDS stimuli. Further study is needed to explore age-related changes in hemodynamic responses to IDS, perhaps with larger sample sizes, to ascertain whether these early brain responses to IDS in temporal and frontal are related to later social and language development.

The present study utilized several advantages provided by NIRS techniques, such as non-invasiveness and higher spatial resolution, than ERP techniques to test infants under natural experimental setting. To our knowledge, this is the first study to demonstrate localized brain activities in infants' frontal and temporal areas in response to IDS and ADS. Infant-directed speech generally increases temporal lobe activity when compared to adult-directed speech 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 infant-directed speech by the different speakers.

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