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Developmental Changes in the Brain Response to Speech during the First Year of Life: A Near-Infrared Spectroscopy Study

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Author statement

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Declaration of Competing Interest

The authors declare that they have no conflict of interest.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Abstract

Language acquisition in the first year of life plays an important role in human development. Although recent research has increased our knowledge of early language development, the origins and developmental trajectories of language processing during infancy are still being debated. One important issue is whether the infant brain has already developed adult-like functional cortical specialization and lateralization for speech and language processing. Although a relatively large number of previous studies have investigated the cortical specialization for speech processing in newborns by comparing responses to normal speech with responses to time-reversed speech as a control, the subsequent development of this differential response is less well understood. In the current study, our primary goal was, therefore, to expand our knowledge of functional specialization for speech during the first year of life. By using functional near-infrared spectroscopy (fNIRS), we examined the hemodynamic responses in the temporal cortex to forward-going speech in the native language, Dutch, and backward Dutch in seventy-eight infants aged 5 and 10 months. We observed that five-month-old infants show bilateral activation to both forward and backward speech without obvious hemispheric lateralization for language, while ten-month-old infants show greater left-lateralized inverted responses (e.g., reduction in oxyhaemoglobin and increase in deoxyhaemoglobin) to forward speech than to backward speech. Overall, our findings indicate that the neural correlates of language processing undergo developmental changes in the first year of life.

Keywords speech processing, infant, functional near-infrared spectroscopy, brain development

1 Introduction

Speech perception plays an important role in the development of human language in the first year of life. Infants encounter language early, much before the onset of speech production, already in the fetal period in the womb (Benavides-Varela et al., 2011; Gervain, 2018; May et al., 2011, 2017). At birth, infants respond preferentially to speech over non-speech (Shultz et al., 2014; Vouloumanos & Werker, 2007). This preference towards speech lays the foundations of the early neurodevelopment of language processing during infancy. Although recent research has increased our knowledge of the neural basis of early language development (see reviews by Werker, 2018 and Gervain, 2020), the origins and developmental trajectory of the neural correlates of speech and language processing during infancy remain incompletely understood.

An important question is whether the infant brain shows adult-like functional specialization for this cognitive function. One pioneering study used functional near-infrared spectroscopy (fNIRS) to explore the brain responses to speech processing at birth (Peña et al., 2003). It revealed greater activation in the left temporal lobe for speech (in the native language) played forward than backward. Backward (BW) speech is

often used as a control for forward speech (FW) to explore brain responses to language and non-language in infants, because it is spectrally identical to FW speech but it violates its temporal structure, thereby becoming unintelligible and impossible to produce (May et al., 2011; Peña et al., 2003). This left-hemispheric advantage for FW speech as compared to BW speech was later replicated (Sato et al., 2012), but interestingly only for the native language, i.e. the language newborns heard prenatally. Specifically, neonates had greater activation in the left temporal regions to FW than to BW speech in the native language (Japanese), but not in a non-native language (English). This finding suggests that experience may contribute to the neural specialization for language already very early on. Another study (May et al., 2017) comparing the native language (English) with an unfamiliar one (Spanish) also found a forward advantage for the native language over the non-native language, but this advantage was bilateral. It is not clear why the two studies yielded different results, but the acoustic/phonological properties of the languages tested may play a role. Taken together, these studies suggest that the newborn brain is already specialized for processing speech in the native language, and that experience as well as the phonological properties of the languages involved may shape this specialization.

However, most fNIRS studies on early language processing investigated the newborn brain, and only a few studies focused on the developmental changes in brain specialization for language processing in the subsequent months of life. Existing research on the neural basis of language processing during the first year of life has focused on a variety of linguistic properties. A line of research investigated the specialization for the processing of prosody (Homae et al., 2014). The studies compared normal speech with full prosody, to (1) flattened speech, in which pitch variation was suppressed (Homae et al., 2006) and to (2) sine wave speech (Homae et al., 2014) in 3-month-old infants. These fNIRS studies indicate that 3-month-old infants exhibit adult-like brain lateralization for language: left dominance for processing phonetic structure and right dominance for processing prosodic information. Similarly, an fMRI study with infants aged 2-3 months found the left angular gyrus and parietal lobe to be more activated by forward speech than by backward speech (Dehaene-Lambertz et al., 2002). Using fNIRS, in 4-month-old infants, left-lateralized responses to speech in the native language were revealed in the temporal regions, as well as rightward temporal activation to sounds with emotional valence (Minagawa-Kawai, Van Der Lely, et al., 2011). Infants aged 6-9 months were found to be more sensitive to audio-visual speech sounds, with increased oxy-haemoglobin in the left temporal region, compared to silence and visual-only stimuli (Bortfeld et al., 2007). Furthermore, in a systematic literature review of fNIRS studies, lateralization has been found to increase with age and language experience for the processing of 3 different linguistic contrasts, e.g., phoneme discrimination (Minagawa-Kawai et al., 2011). Lateralization for speech processing, however, has not yet been studied in infants between 4 and 12 months of age with the forward/backward paradigm. Our study seeks to fill this gap by assessing cortical activation, as estimated by changes in haemoglobin concentration measured using

fNIRS, to forward and backward speech in the maternal language in 5- and 10-month-old Dutch-exposed infants. These ages are highly relevant, as they correspond to the beginning and the endpoints of the perceptual attunement to the native language phoneme repertoire (Werker & Tees, 2002), and as such are informative about how native language speech experience shapes the infant brain.

2 Methods

2.1 Participants

A total of 47 5-month-old ($M_{age} = 165 \pm 16.13$ days, age range: 4.5 – 6.8 months, females : males = 21:26) infants and 31 10-month-old ($M_{age} = 321 \pm 15.10$ days, age range: 9.5 – 11.7 months, females : males = 17:14) infants were recruited for the current study. Of these, 9 5-month-old and 8 10-month-old infants were unable to complete the experiment due to crying or excessive movements. To minimize the effects of noise and artefacts on the signal, a rigorous criterion was employed to determine the final data set (see Data Processing and Analysis). Fourteen 5-month-old infants and 7 10-month-old infants were thus further excluded from the analyses due to excessive artefacts, noisy channels or headgear shifting. Exclusion was done in a batch and before the statistical analyses were carried out. Forty infants ($N_{5M} = 24$, $females_{5M} : males_{5M} = 9:15$, $M_{5M-age} = 168 \pm 14.47$ days, $N_{10M} = 16$, $females_{10M} : males_{10M} = 9:7$, $M_{10M-age} = 327 \pm 15.77$ days) were included in the final analyses. The linguistic background of the participants was assessed based on parental reports of participants' language exposure (including Dutch, French, English, German, and others). According to parental estimates, all infants are Dutch monolingual with at least 90% Dutch exposure. All parents of infants were informed about the research content and gave written informed consent before the experiment.

2.2 Stimuli and Procedure

Measurements were taken in each infant under both forward and backward conditions, with each condition lasting approximately 5.5 minutes (Figure 1). Similar to previous fNIRS studies in newborns (May et al., 2011; Peña et al., 2003), a block design was employed. Each condition consisted of seven blocks of 18-20 s each, presented consecutively and separated by silence intervals of 20-25 s. Within each block, five different sentences from the same condition were randomly presented (e.g., five normal Dutch sentences in each block of the FW condition). The silence intervals between sentences within a block varied between 0.5-1 s. The sentences were taken from fairy tale books recorded by a native female speaker using infant-directed intonation. The backward sentences were created by reversing the recorded normal speech using Praat (Boersma, 2001). The length of each sentence ranged from 3.5 to 4 s. All the auditory stimuli were presented via loudspeakers at a distance of 1 m from the infant's head. The entire experiment was controlled by the software Presentation® (Neurobehavioral Systems, Inc.). During the whole experiment, infants sat

on a baby chair or a parent’s lap in a silent room with dim lighting. A silent animation was presented on the monitor in order to attract the infants’ attention. Parents were instructed not to speak to their infant during the study.

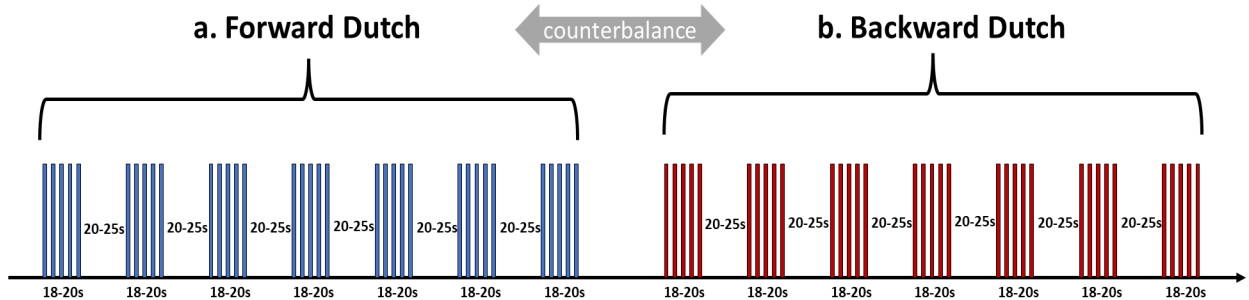


Figure 1 A block design of forward and backward speech experiment. The order of the forward and backward conditions, each containing seven blocks of five sentences, were counterbalanced between the infant participants.

2.3 fNIRS data acquisition

Functional near-infrared spectroscopy was applied to measure neural activity in language-related brain regions through monitoring concentration changes of oxygenated haemoglobin (HbO) and deoxygenated haemoglobin (Hbb). This optical technique has proven to be an effective modality to study brain functions in neonates and young infants (Gervain et al., 2008, 2011; Lloyd-Fox et al., 2010), as well as in persons with developmental disorders (Doi & Shinohara, 2017; Zhang & Roeyers, 2019). The fNIRS signal was collected using a NIRScout system (NIRx Medizintechnik GmbH, Germany) with 760nm and 850nm wavelengths at a 3.29 Hz sampling rate. In the current study, eight sources and ten detectors were employed to cover the bilateral temporal, frontal and inferior parietal areas, similarly to other fNIRS studies in young infants on language processing (Gervain, 2015; May et al., 2011). Each optode was placed in a stretchy cap with a distance of about 3 cm. The head circumference of each infant was measured prior to the experiment ($M_{5M} = 43.41 \pm 1.4$ cm, $M_{10M} = 45.39 \pm 1.55$ cm), and the corresponding cap size was selected. Sources 2 and 6 were positioned to be at the T7 and T8 locations of the international 10-10 system. This resulted in a total of 24 channels (Figure 2). The channels showing significant activation in the analyses were localized anatomically using 3D, age-appropriate structural MRI scans (see details below).

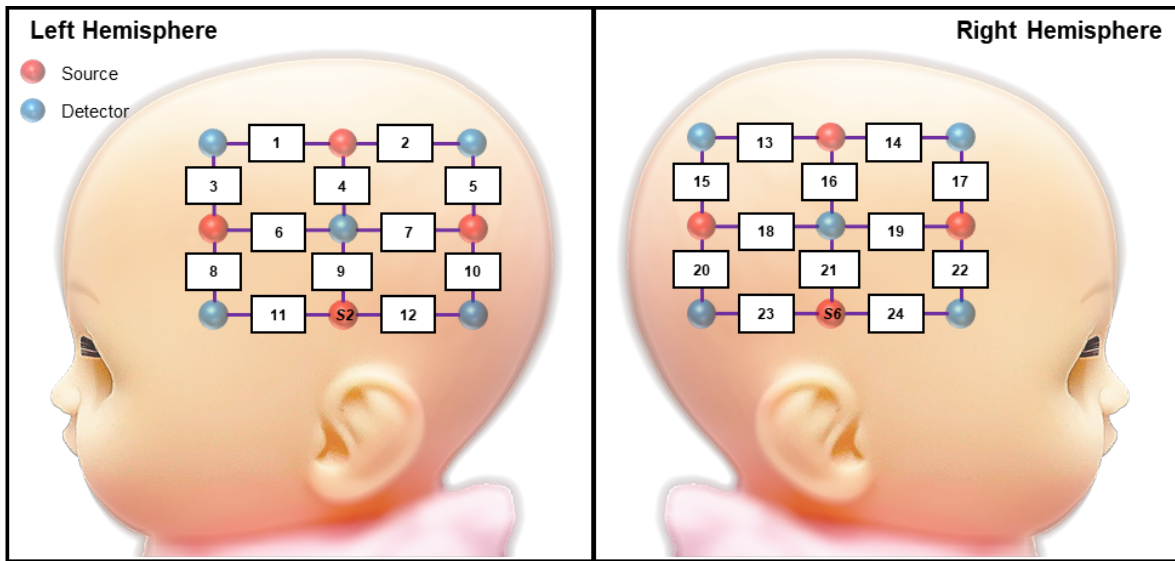


Figure 2 Layout of NIRS probes and channels. Eight sources (red dots) and ten detectors (blue dots) were arranged in a 3×3 matrix over the frontal, bilateral temporal and inferior parietal regions. The locations of the 24 NIRS channels were shown in the black boxes. Sources 2 and 6 were placed at positions T7 and T8 of the international 10-10 system, labeled S2 and S6 respectively.

2.4 Data Analysis

fNIRS measures the haemodynamic correlates of neural activity by quantifying changes in the concentration of haemoglobin. Both HbO and Hbb concentrations were calculated and used as dependent variables in the statistical analyses. The raw data were first converted into optical density (OD). Within each participant, channels with too weak or too strong optical intensity (mean (d) < 0.01 or > 3) and channels with a high standard deviation (i.e., the signal d of a given channel changes 15 times greater than the standard deviation (SD) over 2 seconds) were discarded from the analyses. Wavelet filtering was performed for denoising (Brigadoi et al., 2014; Di Lorenzo et al., 2019). After linear detrending, a motion detection algorithm was applied to identify data points that exceeded 10 times of the SD (d) over one second. These identified artefacted blocks were then rejected. Following previous studies (Braukmann et al., 2017; Lloyd-Fox et al., 2013), only participants with at least 3 retained blocks out of the total of 7 blocks per condition were included in further analyses. A band-pass filter with cut-off frequencies of 0.01–0.5 Hz was applied to remove slow drifts and high frequency noise as well as other physiological noise such as respiration and cardiac activity. The denoised OD signals were then converted into concentration changes using the modified Beer-Lambert law. Data processing was performed using the Homer2 NIRS processing package (Huppert et al., 2009) and the FieldTrip toolbox (Oostenveld et al., 2011) based on MATLAB (Mathworks, MA USA).

The concentrations of HbO and Hbb have been calculated and used for statistical analyses. Cluster-based permutation tests were applied to compare the forward and backward conditions as well as each condition separately to baseline (defined as the 5-second period before stimulus onset). This nonparametric statistical method (Abboub et al., 2016; Ferry et al., 2016) has been used to address the multiple comparisons problem (MCP) in previous fNIRS studies (May et al., 2011; Pellegrino et al., 2016; Vannasing et al., 2016). The empirical distributions, under the null hypothesis of no difference between conditions or between conditions and baseline, were obtained by randomly permuting the data. In total, 1000 permutations were performed for each region of interest (ROI) in each comparison. We then used age-appropriate average MRI templates (Fu & Richards, 2021; Richards et al., 2016) to estimate the brain localization of activated channels. An example of the channel placement in a 5-month-old infant head template is shown in the Supplementary Figure A.1, and an overview of the underlying cortical structure and standard Montreal Neurological Institute (MNI) stereotaxic coordinates for each channel can be found at Supplementary Excel Spreadsheet.

3 Results

The obtained haemodynamic responses are shown in Figure 3. In 5-month-old infants, permutation analyses revealed one cluster in the right hemisphere (channels 13, 14, 16, $t = -7.03$, $p = .021$) showing significantly more decreased HbO to FW than the baseline and two clusters in the left hemisphere showing significantly more decreased HbO (channels 1, 2, 4, 7, $t = -11.39$, $p = .005$) and Hbb (channels 10, 11, 12, $t = -8.27$, $p = .01$) in response to BW as compared to baseline. No clusters showing significant differences between FW and BW speech were found in 5-month-old infants.

In contrast, in 10-month-old infants, we found one cluster in the left hemisphere (channels 9, 10, $t = -4.99$, $p = .034$) showing significantly more decreased HbO to FW than BW Dutch (see Figure 4). Also, one cluster in the left hemisphere (channels 7, 10, $t = -7.16$, $p = .014$) and one cluster in the right hemisphere (channels 20, 24, $t = -5.37$, $p = .032$) showing significantly more decreased HbO in response to FW speech as compared to baseline were identified. One cluster in the left hemisphere (channels 4, 7, $t = -5.37$, $p = .029$) showing significantly more decreased Hbb and one cluster in the right hemisphere (channels 14, 17, $t = 5.73$, $p = .017$) showing significantly more increased Hbb in response to BW speech to baseline were identified. Decreases in HbO and concomitant increases in Hbb are defined as an inverted haemodynamic response. An overview of the clusters, showing significant differences between FW and BW conditions or between a condition and the baseline, is shown in the Supplementary Table A.1.

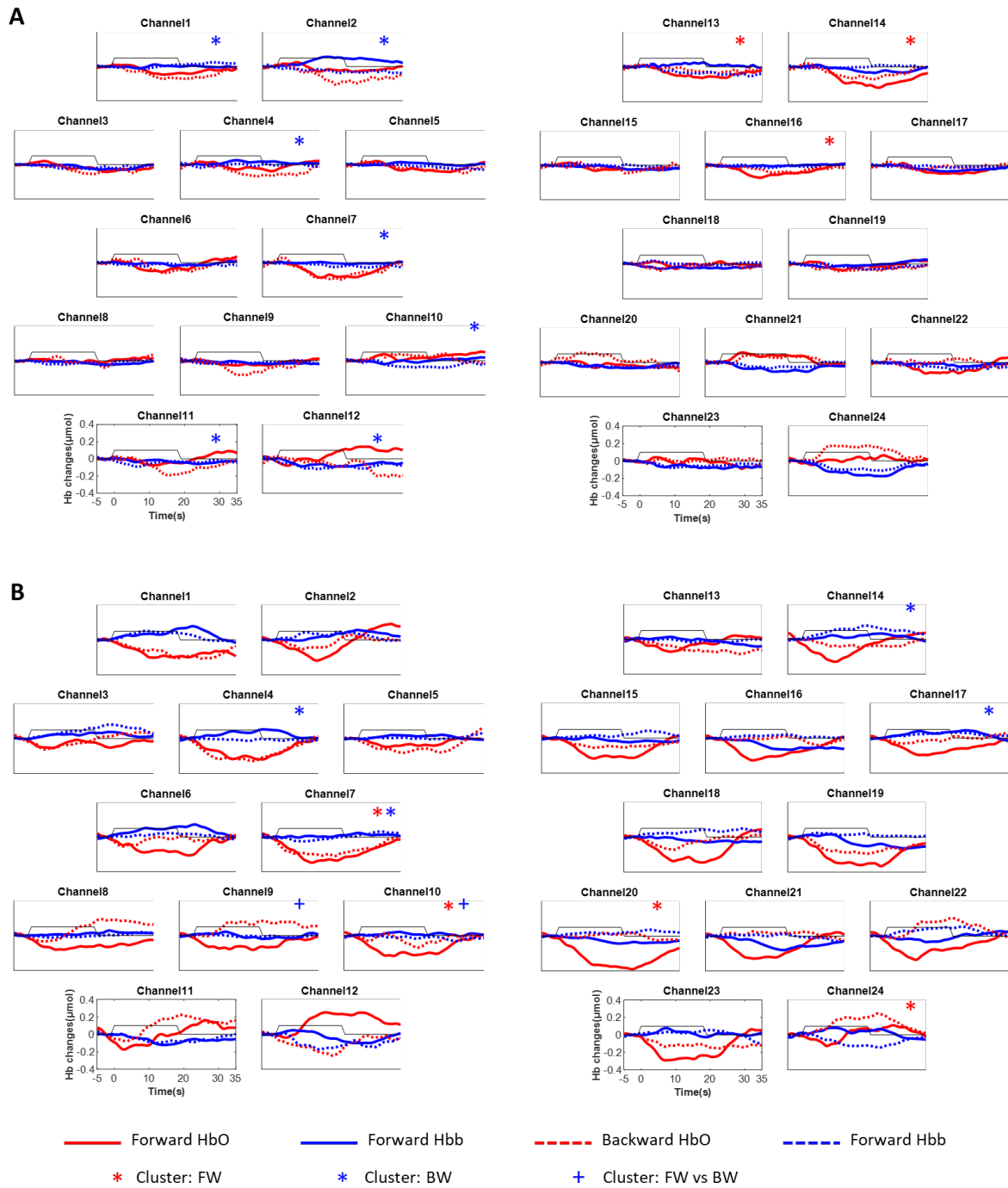


Figure 3. Hemodynamic response obtained for forward and backward speech. The time courses of HbO and Hbb changes in infant were plotted between -5s to 35s from stimulus onset. (A) shows the results for the 5-month-old infants, and (B) represent the results for the 10-month-old infants. The left panel shows the result of the left hemisphere, and the right panel corresponds to the right hemisphere. Using cluster-based permutation approach, clusters were identified in 5- and 10-month-old infants showing significant response to forward and backward speech ($p < .05$). HbO: oxygenated haemoglobin, Hbb: deoxygenated haemoglobin, Hb: haemoglobin. FW: forward speech, BW: backward speech.

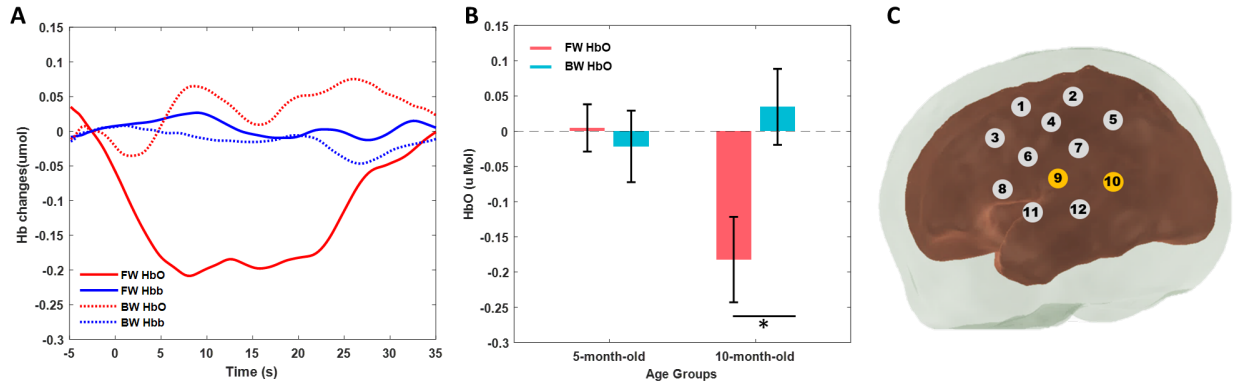


Figure 4. Results of the left-side cluster showing significant difference between forward and backward conditions in 10-month-old infants as defined by permutation tests. (A) The time courses of haemoglobin changes of identified cluster in 10-months infants (channels 9 and 10, * $p < .05$). (B) The HbO activation of this cluster with error bar represents standard error of the mean. (C) Clustering channels on an infant head template. Hbb: deoxygenated haemoglobin, Hb: haemoglobin. FW: forward speech, BW: backward speech.

Age-appropriate (i.e., 5- and 10-months) average MRI templates were used to register scalp surface fNIRS channels with underlying anatomy (Richards et al., 2016). The fNIRS optodes and the four fiducial landmarks (nasion,inion, left and right tragi) were located over the head 3-D reconstruction. The left-lateralized clusters found in 5-month-old infants were mainly located in the inferior frontal gyrus (IFG), the middle frontal gyrus (MFG), the precentral gyrus (PreCG), the postcentral gyrus (PoCG), the supramarginal gyrus (SMG) and the angular gyrus, while the right-side cluster covered the IFG, the MFG, the PreCG and the PoCG. In terms of 10-month-old infants, the channels of the left-side clusters are mainly located in the superior temporal gyrus (STG), the PreCG, the PoCG, and the SMG, while the right-clustering channels covered the middle temporal gyrus (MTG), the IFG, the STG, the SMG and the PoCG.

4 Discussion

The present study examined early developmental changes of language processing in infants aged 5 months and 10 months by measuring relative changes of haemoglobin concentration triggered by native language speech sounds played forward and backward. We have found no difference between the two conditions in 5-month-old infants, but significant decreases in oxy- and deoxy-haemoglobin with respect to baseline for both FW and BW speech, whereas in 10-month-olds, there was a greater left-lateralized inverted response to FW than to BW speech, as well as significant inverted response with respect to baseline in the FW and BW condition. We observed bilateral responses to forward and backward speech in 5-month-old infants, while 10-month-old infants displayed left-lateralized inverted responses to native forward speech. These responses were located in the brain regions (e.g., the superior temporal gyrus) that were found to be active during speech processing in fMRI studies (Friederici & Wartenburger, 2010; Price, 2010). The

inverted haemodynamic response is often observed in developmental populations (Issard & Gervain, 2018), although its physiological and functional meaning is still not fully understood. Existing studies suggest that in certain cases, it may represent a genuine functional response, not simply a reflection of the immaturity of the neuro-vascular coupling. In particular, inverted responses have been linked to deactivation, i.e. decreased processing effort, for instance in the case of simple, overlearned or repetitive stimuli (Issard & Gervain, 2018).

The current study suggests that the shape of the haemodynamic response to FW as compared to BW speech changes with brain development in the first year of life. At birth, previous studies have found greater canonical response to forward speech versus backward speech in the bilateral temporal regions (May et al., 2017; Sato et al., 2012) or in the left temporal regions (Peña et al., 2003). By contrast, in the current study, bilateral temporal responses were observed without a difference between FW and BW speech at 5 months, and a left-lateralized FW speech advantage was found at 10 months, manifesting in an inverted response. Two aspects of these findings, the lateralization and the shape of the hemodynamic response, invite further discussion.

Although a left hemispheric dominance for speech and language processing has typically been found in most studies with children (Norrelgen et al., 2012; Szaflarski et al., 2006) and adults (Kotilahti et al., 2010; Price, 2010), the origin and developmental trajectory of this specialization remain an open question. We assume a U-shaped trajectory based on the findings of the present study and previous literature, with lateralization appearing in the neonatal period, weakening around 5 months and re-emerging at 10 months. Such a pattern is often associated with perceptual re-organization both at the behavioural (Werker et al., 2004) and the neural level (Minagawa-Kawai, Van Der Lely, et al., 2011). This perceptual reorganization is the result of infants' increasing experience with and attunement to the native language, as processing shifts from an auditory to a more linguistic level. Our findings thus suggest that the perception of FW vs. BW speech also undergoes 'perceptual narrowing' (Palmer et al., 2012; Werker and Hensch, 2014), that is, infants' attunement to native speech brings a reorganization, where infants switch from universal auditory to linguistic processing of speech, which shapes the specialized brain functions. This perceptual narrowing to native speech may happen during the second half of the first year of life for the FW vs. BW comparison, as is the case for the perception of other linguistic units such as consonants, tone etc.

The observed inverted response also supports this interpretation as the processing of regular forward speech in the native language and its discrimination from backward speech arguably becomes increasingly easy, as infants gain more experience, thus requiring less processing effort.

To elucidate the developmental changes in response to speech in young infants, the present study used fNIRS to investigate the neural activity for forward as compared to backward speech in bilateral temporal areas in infants. We found that 5-month-old infants show similar auditory processing to speech regardless of whether it is played forward or backward, while infants aged 10 months are able to distinguish between forward and backward speech exhibiting a greater inverted left-lateralized response to forward speech. Our study demonstrates remarkable neural developmental changes in speech processing during the first year of infancy.

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