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Language performance and auditory evoked fields in 2- to 5-year-old children

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Keywords:
language conceptual inference, magnetoencephalography, P50m, preschool children, refractoriness

CONTENTS

Abstract

Language development progresses at a dramatic rate in preschool children. As rapid temporal processing of speech signals is important in daily colloquial environments, we performed magnetoencephalography (MEG) to investigate the linkage between speech-evoked responses during rapid-rate stimulus presentation (interstimulus interval < 1 s) and language performance in 2- to 5- year-old children (n = 59). Our results indicated that syllables with this short stimulus interval evoked detectable P50m, but not N100m, in most participants, indicating a marked influence of longer neuronal refractory period for stimulation. The results of equivalent dipole estimation showed that the intensity of the P50m component in the left hemisphere was positively correlated with language performance (conceptual inference ability). The observed positive correlations were suggested to reflect the maturation of synaptic organisation or axonal maturation and myelination underlying the acquisition of linguistic abilities. The present study is among the first to use MEG to study brain maturation pertaining to language abilities in preschool children.

Introduction

Language acquisition in early life is one of the most fundamental human traits, and the developmental changes obviously occur in the brain (Sakai, 2005). Children aged 2–4 years show especially remarkable development in a number of important higher-order brain functions and cognitive abilities with significant changes in brain functions associated with language performance (Le Normand, 1986; Burt et al., 1999). Recent electrophysiological studies support the suggestion that these language abilities undergo further development in a continuous manner from infant to adulthood (Friederici, 2005). However, few studies have investigated brain functional development associated with language ability in young infants. The purpose of this study is to investigate the brain response to auditory stimuli and language ability in preschool children using magnetoencephalography (MEG).

Magnetoencephalography is a non-invasive neuroimaging technique that provides measures of cortical neural activity on a millisecond time scale with high spatial resolution. MEG is also well suited for studying basic auditory activity, as cortical generators of evoked auditory responses are favourably positioned to produce strong currents for MEG recordings (Edgar et al., 2003) even in children (Paetau et al., 1995; Huotilainen et al., 2008). In addition, magnetic field patterns evoked by auditory stimuli are limited to one hemisphere, whereas electrical potentials recorded by electroencephalography (EEG) summate at the vertex and generate only one maximum on the head surface. This property of MEG is particularly advantageous in studies where the activities from left and right auditory cortices must be investigated separately, which is suitable to investigate into the brain lateralised function associated with language processing.

In MEG studies, auditory evoked magnetic fields (AEFs) corresponding to P50 and

N100 reported in EEG studies have been labeled as P50m and N100m, respectively. P50(m) is a prominent component with shorter interstimulus intervals (ISIs) in children aged 1–10 years old (Ponton et al., 2002; Oram Cardy et al., 2004; Gilley et al., 2005), which provides insight into the development of auditory processing in real-world environments (i.e. auditory information at rapid rates) in preschool children. Despite the importance of fast temporal processing in real-world environments (Lalor & Foxe, 2010), however, there have been only a few studies involving the recording of auditory evoked responses in preschool children at rapid rates (ISI < 1000 ms; Gilley et al., 2005; Wang et al., 2005). Previous studies did not focus on correlations between auditory evoked responses with short ISI (< 1000 ms) and language performance in children.

The first aim of the present study was to verify the finding that syllables with short ISIs evoke detectable P50m but poorly detectable N100m in 2- to 5-year-old children, which was predicted by a previous study in older children (Rojas et al., 1998). Second, we further examined the tentative hypothesis that the prominence of syllable-evoked P50m with short ISI (818 ms) is associated with language ability in 2- to 5-year-old children. That is, we expected that diminished (i.e. low-amplitude) syllable-evoked P50m could be a precursor of poorer language ability in 2- to 5-year-old children.

Materials and methods

Participants

Sixty-three right-handed children (34 female and 29 male) were recruited for this study. Four of them could not continue MEG recording because they felt bored and did not wish to undergo the measurements. The remaining 59 participants (31 female, 28 male) had a mean age of 48.6 months (SD ± 8.5), and ranged in age from 33 to 64 months (92% of participants fell within the range of 3–4 years old). All participants were native

Japanese, and had no previous or existing developmental, learning or behavioural problems according to information obtained by a questionnaire completed by their parents. All children participated in cognitive tasks and MEG measurements separately over a period of 2 days. On the first day, participants performed cognitive tests and were introduced to the environment used for MEG measurement. The actual MEG measurements were performed on the second day. Parents agreed to their child's participation in the study with full knowledge of the experimental nature of the research. Written informed consent was obtained prior to participation in this study. The Ethics Committee of Kanazawa University Hospital approved the methods and procedures, all of which were performed in accordance with the Declaration of Helsinki. Demographic data for all participants are presented in Table 1.

Table 1 Demographic characteristics of all participants

Number of subjects	59
Age (range)	48.6 months (33–64)
Gender (M/F)	28/31
K-ABC mental processing scale (± SD)	100.3 (± 13.2)
K-ABC achievement scale (± SD)	105.3 (± 16.7)*
Head circumference (range)	50.1 cm (46.6–54.0)

* Two subjects were not available for assessment of achievement scale because they were younger than 36 month old (*i.e.*, $n = 57$). K-ABC, Kaufman Assessment Battery for Children.

Cognitive and language performance measurements

The children performed the Japanese adaptation of the Kaufman Assessment Battery for Children (K-ABC), which assesses cognitive skills of children aged 30–155 months. To confirm the standardized score of the mental processing scale and the achievement scale in children, subtests complementary to the children's age were used in this battery. As we were especially interested in the relations between AEF and development of language performance in children, we used each raw score of the subtests 'number recall', 'expressive vocabulary' and 'riddles' in this battery. 'Number recall' reflects the ability of language phonological repetition, 'expressive vocabulary' reflects the expressive ability to speak the correct names of objects and illustrations, and 'riddles' reflects language conceptual inference ability (Kaufman & Kaufman, 1983).

MEG recordings

Magnetoencephalography data were recorded with a 151-channel Superconducting Quantum Interference Device (SQUID), whole-head coaxial gradiometer MEG system for children (PQ 1151R; Yokogawa/KIT, Kanazawa, Japan) in a magnetically shielded room (Daido Steel, Nagoya, Japan), installed at the MEG Centre of Yokogawa Electric Corporation (Kanazawa, Japan). The custom child-sized MEG system allows measurement of the brain responses in young children, which would be difficult with conventional adult-sized MEG systems. The child MEG system ensures that sensors are easily and effectively positioned within the range of the brain and that head movement is well constrained (Johnson et al., 2010). We determined the position of the head within the helmet by measuring the magnetic fields after passing currents through coils attached at three locations on the head surface as fiduciary points with respect to the landmarks (bilateral mastoid processes and nasion). Although we could not take into account how the individual head shape would influence the accuracy of dipole estimation, to calculate equivalent current dipoles (ECD) without magnetic resonance imaging anatomical data, a sphere as a spherical model of the volume conductor was fitted to the centre of the helmet after confirmation that the head of each subject was located in the centre of the MEG helmet by measuring three locations on the surface of the head as described above (Fig. 1A). To assess the individual locations of ECDs for each individual head, we employed a coordinate system in which the midpoint of the bilateral mastoid processes is the origin, and positive values on the x-, y- and z-axes represent the leftward direction, the occipital direction and the vertex, respectively (Fig. 1B). An examiner remained in the room to encourage children and to prevent movement throughout measurements. Stimuli were presented while children lay in the supine position on the bed and viewed silent video programs projected onto a screen.

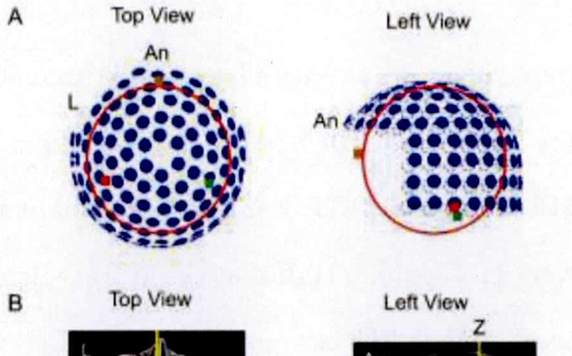


Fig.1. (A) Positions of the MEG sensors (blue circles) and a sphere (red circle) for a spherical model of the volume conductor fitted to the centre of the helmet. (B) Coordinate system in which the midpoint of the bilateral mastoid processes is the origin. Positive values on the x-, y- and z-axes represent the leftward direction, the occipital direction and the vertex, respectively. Three coloured squares indicate fiduciary points (bilateral mastoid processes and forehead) in one subject. Red square, left mastoid process; green square, right mastoid process; brown square, forehead. An, anterior; L, left

AEF stimuli and procedures

Magnetoencephalography recordings were obtained from all participants during auditory syllable sound stimulation consisting of the Japanese syllable/ne/(Fig. 2). We employed this syllable because/ne/is one of the Japanese sentence-final particles carrying prosodic information (Cook, 1990; Anderson et al., 2007). The syllable/ne/is often used in Japanese mother–child conversation, and it expresses the speaker's request for acknowledgement or empathy from the listener (Kajikawa et al., 2004; Squires, 2009). In the present study, we used typical oddball sequences consisting of standard stimuli at a rate of 83% (456 times) and deviant stimuli at a rate of 17% (90 times). In the standard stimulus,/ne/was pronounced with a steady pitch contour (Fig. 2), whereas in the deviant condition/ne/had a falling pitch. Eventually, we adopted only standard stimuli for subsequent ECD estimation, because only for these stimuli sufficient numbers of periods to calculate ECD remained after rejection of artefacts in all children. The/ne/sounds were produced by a female native Japanese speaker and recorded for stimulus presentation with a condenser microphone (NT1-A; Rode, Silverwater, NSW, Australia) onto a personal computer. The duration of the stimulus was 342 ms, and the duration of consonant/n/was 65 ms. In this study, the beginning of the vowel sound/e/was defined as the onset time (Fig. 2). ISI was 818 ms at a level of approximately 65 dB (A-weighted) against a background noise of 43 dB on average as measured with an integrating sound level meter (LY20; Yokogawa, Tokyo, Japan). The stimulus was carried to participants binaurally through a hole in the MEG chamber using speakers (HK195 Speakers; Harman Kardon, Stamford, CT, USA) placed outside the shielded room. The stimulus was presented for 12 min.

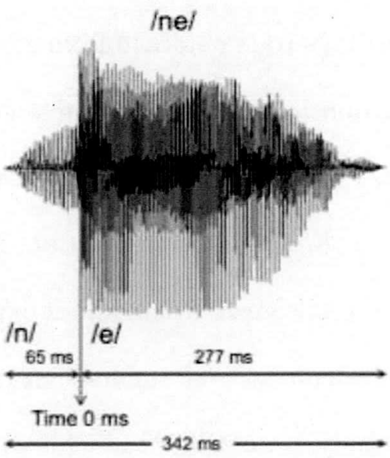


Fig.2. Waveform of the / ne / speech stimulus. The total duration was 342 ms, with 65 ms for the consonant / n / and 277 ms for the post-consonantal vowel sound / e /. The onset time for MEG averaging was set at the start of the vowel.

AEF acquisition and analysis

The participant's head was placed in a whole-head dewar, in which 151 magnetic sensors were arranged concentrically. MEG data were acquired with a sampling rate of 1000 Hz and filtered with a 200-Hz low-pass filter. Time series around the onset of the syllable stimulus from) 150 to 1000 ms and segments (at least 300 for standard stimuli) were averaged for each of the sensors after baseline correction (-50 to 0 ms). Segments contaminated by artefacts (eye-blink, eye-movement and body movement, typically over ± 4 pT) were excluded from the analysis. The single ECD model was used to estimate the current sources in the activated cerebral cortex over 42 sensors for each emisphere (Elberling et al., 1982). For identification of the P50m component, we accepted estimated ECDs when: (i) the goodness of fit exceeded 90%, during the target period of the response; (ii) the location of estimated dipoles with the single ECD model was stabilised within ± 5 mm of each coordinate for at least 6 ms; and (iii) dipole intensities were ≦ 80 nA. ECDs were estimated using 42 channels each over the left and right hemisphere. The time point was identified as the latency, when the estimated dipole intensity value had reached a maximum and met the above criteria within the time window from 40 to 150 ms. An N100m component was defined as detectable when: (i) a response occurred after a detectable P50m within 210 ms after onset of the stimulus; (ii) its magnetic field showed a sign opposite to that of P50m; and (iii) the peak of a plausible N100 magnetic field could be discriminated from that of the following sustained field. In addition, we accepted estimated ECDs only when they fulfilled the same criteria of ECDs for the P50m as described above.

Statistical methods

First, to evaluate the relationships between log-transformed dipole intensity (or latency) and the K-ABC subtest scores on language performance (i.e. 'number recall', 'expressive vocabulary' and 'riddles'), a Pearson's correlation coefficient was used. Second, a hierarchical regression analysis was used to investigate the association between the P50m component and the language-related sub-score(s) in which significant correlations were found, if any, in the first analysis. Separate analyses were performed to investigate the impact of such language-related sub-scores on P50m for the right and left hemisphere, respectively. In this hierarchical regression analysis, we included between-person covariates that were of theoretical importance in a study of brain development and cognitive function. These variables were age and non-verbal performance (i.e. total score of K-ABC subtests in 'face recognition' and 'hand movement'). The demographic variable (i.e. age) was entered at the first step in this model, non-verbal performance was entered at the second step, and the language-related sub-score(s) at the third step. In all analyses, $P < 0.05$ was taken to indicate statistical significance.

Results

AEF waveform

The standard AEF stimulus (/ne/vocal syllabic sound with a steady pitch contour) elicited obvious peaks during the time window of 40– 150 ms (i.e. P50m) for all participants in both hemispheres. Figure 3 shows the waveform and magnetic contour map of P50m in one representative subject. Predominant P50m peaks in both hemispheres were followed by sustained fields with opposite signs. Some participants showed bimodal waveforms. In cases with a trimodal waveform, the magnetic fields in the latter two peaks had the same sign.

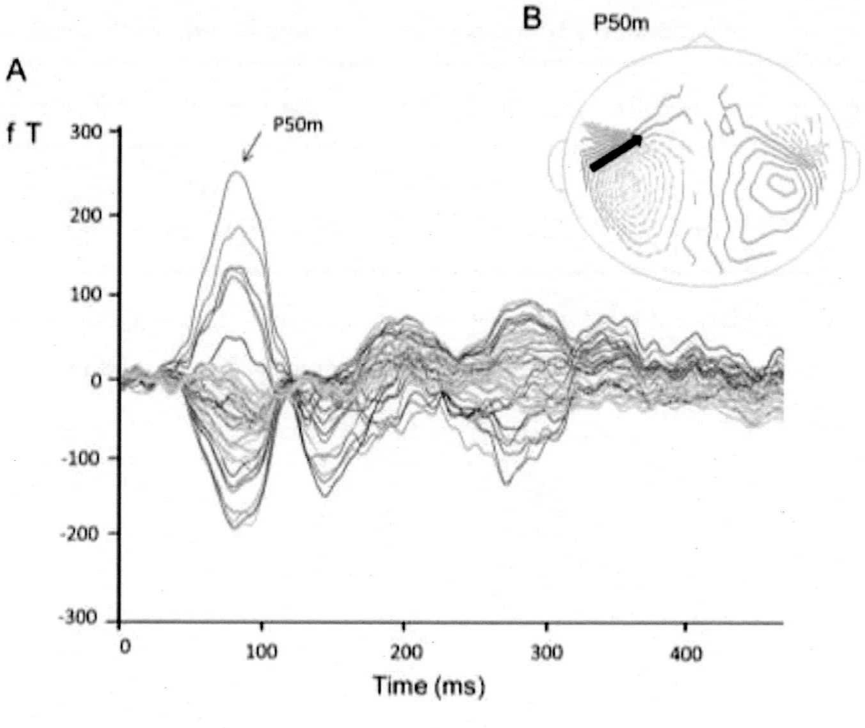
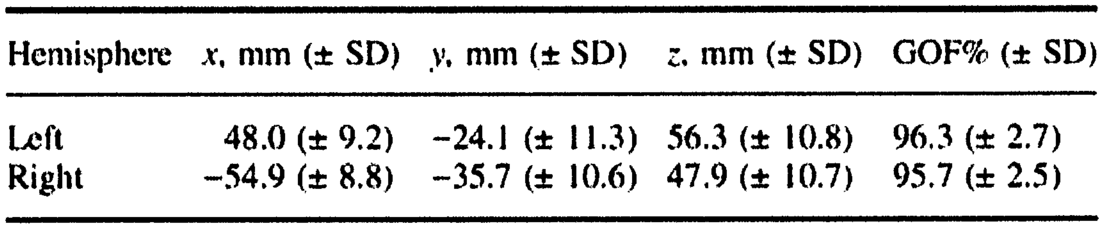


Fig.3. Source modelling of neuromagnetic responses evoked by the auditory stimuli. (A) The response showed an activity peak at 45–150ms. (B) Typical magnetic field patterns of the peak in the auditory cortex.

P50m component

In the left hemisphere, 75% (44 of 59) of the participants showed detectable P50m (i.e. met the criteria for ECD) at 93 ms on average (± 24 ms) after the onset of the vowel (Table 2). Mean dipole intensity of detectable P50m was 19.6 nA on average (± 7.6 nA). In the right hemisphere, 78% (46 of 59) of the participants showed detectable P50m at about 84 ms on average (± 23 ms) after onset of the vowel. The mean dipole intensity of detectable P50m was 14.1 nA on average (± 7.0 nA). The locations of these estimated P50m dipole sources are shown in Table 2.

Table 2. Coordination of estimated P50m dipole source strengths and GOF (goodness of fit).



Hemisphere	x, mm (± SD)	y, mm (± SD)	z, mm (± SD)	GOF% (± SD)
Left	48.0 (± 9.2)	-24.1 (± 11.3)	56.3 (± 10.8)	96.3 (± 2.7)
Right	-54.9 (± 8.8)	-35.7 (± 10.6)	47.9 (± 10.7)	95.7 (± 2.5)

The midpoint of the bilateral mastoid processes is the origin. Positive values on the x-, y- and z-axes indicate the leftward direction, the occipital direction and the vertex, respectively. GOF, good of fit.

N100m component

Only 24% (14 of 59) of the participants showed detectable N100m (i.e. met the criteria for ECD) in the left hemisphere at 169 ms on average (± 28 ms) after the onset of the vowel (Table 3). The mean dipole intensity of detectable N100m was 13.1 nA on average (± 7.8 nA). In the right hemisphere, 19% (11 of 59) of the participants showed detectable N100m at 162 ms on average (± 28 ms) after the onset of the vowel. The mean dipole intensity of detectable N100m was 14.8 nA on average (± 7.0 nA).

Table 3. Detectable rates of P50m and N100m ECD source and their estimated intensity and latency over participants' right and left hemispheres.

	Hemisphere	Detectable rate (number)	Intensity nA (± SD)	Latency ms (± SD)
P50m	Left	75% (44/59)	19.6 (± 7.6)	93 (± 24.3)
	Right	78% (46/59)	14.1 (± 7.0)	84 (± 23.0)
N100m	Left	24% (14/59)	13.1 (± 7.8)	169 (± 28.3)
	Right	19% (11/59)	14.8 (± 7.0)	162 (± 27.8)

Correlation between P50m and cognitive and language performances

Pearson's tests showed a significant positive correlation between P50m intensity in the left hemisphere and performance of the K-ABC language subtest 'riddles' (n = 44, r = 0.33, P = 0.02; Fig. 4; Table 4), whereas this correlation was not significant with other K-ABC language subtests [i.e. 'number recall' (n = 44, r = 0.08, P = 0.59) and 'expressive vocabulary' (n = 44, r = 0.06, P = 0.67). P50m latency of either hemisphere was not related to K-ABC subtests related to language performance. Next, a hierarchical regression analysis examining the relationship between P50m intensity in the left hemisphere and performance of the K-ABC language subtest 'riddles' was conducted. As shown in Table 4, the hierarchical multiple regression model revealed that the K-ABC 'riddle' language subtest performance was significantly and independently associated with P50m dipole intensity in the left hemisphere at the final step (Table 4; step 3, $\triangle R^2$ = 0.187, F1,40 = 9.270, P = 0.004), whereas other variables (i.e. age and nonverbal performance) did not reach statistical significance at any step (Table 4). Among these variables we found correlation coefficients of 0.503, 0.385 and 0.575 between the 'riddle' sub-score and age, the 'riddle' sub-score and non-verbal performance, and age and nonverbal performance, respectively. As a complementary analysis, we compared the performances of three language-related K-ABC subtests between the P50m detectable group (n = 44) and undetectable group (n = 15), but no significant differences were observed.

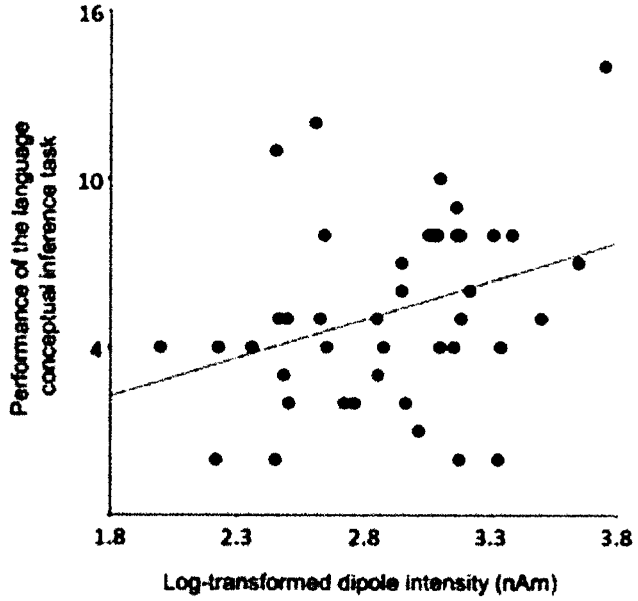
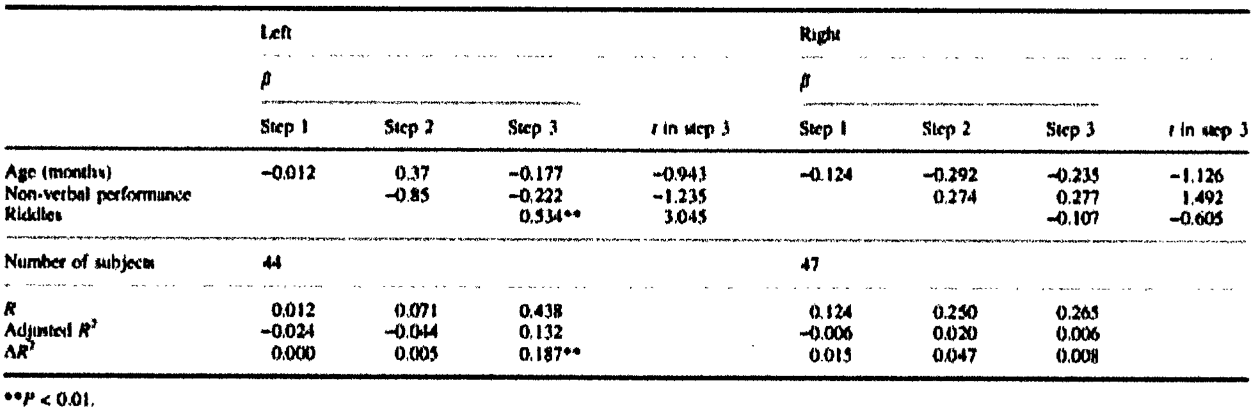


Fig.4. Scatterplot for the log-transformed P50m intensity in the left hemisphere (x-axis) and performance of 'language conceptual inference' (y-axis)

Table 4. Hierarchical regression analysis summary for P50m intensity, on age, non-verbal performance and a language-related K-ABC subtest "riddles".



	Left				Right			
	β				β			
	Step 1	Step 2	Step 3	t in step 3	Step 1	Step 2	Step 3	t in step 3
Age (months)	−0.012	0.37	−0.177	−0.943	−0.124	−0.292	−0.235	−1.126
Non-verbal performance		−0.85	−0.222	−1.235		0.274	0.277	1.492
Riddles			0.534**	3.045			−0.107	−0.605
Number of subjects	44				47			
R	0.012	0.071	0.438		0.124	0.250	0.265	
Adjusted R^2	−0.024	−0.044	0.132		−0.006	0.020	0.006	
ΔR^2	0.000	0.005	0.187**		0.015	0.047	0.008	

**$P < 0.01$.

Correlation between N100m and cognitive and language performance

Pearson's tests showed no significant correlation between N100m components in both hemisphere and performance of any K-ABC subtests related to language performance.

Discussion

In terms of brain functional development associated with language ability in 2- to 5-year-old children, this is the first report demonstrating the significance of left-hemispheric responsiveness of the auditory system using a method with high spatiotemporal resolution (i.e. MEG). The present study also provides new evidence to address the missing link of AEF dipole source analysis in infants aged 2–5 years, which is a challenging age for brain-imaging methods. Furthermore, for this research, we employed a child-customised MEG in which the sensors were as close to the whole head as possible for optimal recording. In the present study, we demonstrated that P50m dipole intensity in the left hemisphere is a significant predictor of language performance in preschool children. The results also showed that P50m was morphologically the most prominent component. This is consistent with previous study indicating prominent P50 instead of N100 in young children (Ponton et al., 2002; Oram Cardy et al., 2004; Gilley et al., 2005), and a previous study demonstrating that only 20% of 3- to 4-year-old children showed a detectable N100 - P200 complex with short ISI conditions of < 1 s (Gilley et al., 2005). Accordingly, P50m seems to be an easily detectable component for assessment of auditory processing in real-world environments (i.e. auditory information at rapid rates) in young children. Although amplitudes of P50m have been reported to decrease as a function of age especially after 10 years old (Ponton et al., 2000, 2002; Gilley et al., 2005), the present results did not show significant correlations between chronological age and amplitude or latency of P50m. The relatively small age range of the children (33–64 months) in our experiment may have contributed to a reduction in amplitude or latency variation due to age differences. P50m components in the present study may have been markedly influenced by the longer neuronal refractory period for stimulation because of the short ISI. Although long ISIs would enhance the amplitude of auditory evoked responses and improve the signal-to-noise ratio, we specifically employed this short ISI. Most of the sound information encountered in daily life, such as speech signals, occurs at rapid rates. To investigate childhood auditory functions in real-world environments, we employed speech stimuli with a short ISI despite the considerable refractoriness that this causes. As age related changes in myelination, synaptic refinement and cortical fibre density (Salamy, 1978; Huttenlocher & Dabholkar, 1997; Moore & Guan, 2001; Brauer et al., 2011) underlie the age-related changes in amplitude and refractoriness of P50m components, it is possible that a lower P50m amplitude indicates immaturity of the central auditory system. If this is the case, the observed positive correlation between P50m amplitude in the left hemisphere and the preschoolers' performance on the 'riddles' task (i.e. language conceptual inference) in the present study may reflect the maturation of synaptic organisation that forms the basis of linguistic acquisition in preschool children.

The dipole source of P50m is located in the primary auditory cortex and is an earlier component in the processing stream recorded by MEG (Pelizzone et al., 1987; Reite et al., 1988; Makela et al., 1994; Yoshiura et al., 1995; Onitsuka et al., 2000). Thus, P50m itself is thought to be a suitable candidate for the role of auditory input change detector for speech-like signals (Hertrich et al., 2000; Chait et al., 2004). In fact, a recent study provided evidence that P50m is sensitive to place-of-articulation features of speech and their co-articulatory processes (Tavabi et al., 2007). Furthermore, P50m evoked in the left hemisphere may already be involved in a long range brain network that contributes to language performance, because previous physiological studies indicated that the link between auditory perception and vocal production is quite rapid and connects within quite short periods. For example, Howard, Brugge and co-workers used depth electrode stimulation and electrophysiological recording in neurosurgical patients to explore the evoked responses and connectivity in a circuit involving primary auditory cortex, posterior lateral superior temporal, inferior frontal gyrus and orofacial motor cortex (Howard et al., 2000; Brugge et al., 2003; Greenlee et al., 2004). Their studies suggested that, within 40 ms after stimulus onset, a sound already has an impact on neural activity in orofacial motor cortex through the posterior lateral superior temporal and inferior frontal gyrus (Patterson & Johnsrude, 2008). These rapid linkages among language-related brain areas are consistent with previous anatomical studies indicating the intimate connections among these areas (Pandya & Seltzer, 1982; Seltzer & Pandya, 1991; Yeterian & Pandya, 1998; Petrides & Pandya, 2002; Patterson & Johnsrude, 2008). The suggestion that the P50m component may be involved in a long-range brain network modulating language performance is further supported by a recent study demonstrating that the P50m amplitude was enhanced after a phonological intervention program on the brain function of 6- to 7- year-old children diagnosed with specific language impairment (Pihko et al., 2007). These observations suggest that the P50m amplitude reflects plastic changes in the brain activities underlying the basis of the language system. In addition, it is worth noting that the synaptic density in the auditory cortex reaches a plateau at about age 10 years, followed by a rapid decrease (Huttenlocher & Dabholkar, 1997), and the same developmental trajectory was reported in P50 amplitudes (Ponton et al., 2000; Gilley et al., 2005), which would be strongly dependent on the number of pyramidal cell synapses contributing postsynaptic potentials.

In the present study, we employed 'number recall', 'expressive vocabulary' and 'riddles' subtests in K-ABC to assess the language abilities of 2- to 5-year-old children (Kaufman & Kaufman, 1983). However, only the 'riddles' subtest was a significant predictor of P50m dipole intensity in the left hemisphere (Table 4; Fig. 4). This result suggested that P50m dipole intensity in the left hemisphere was not sufficient to explain the correlation with general language ability as we initially mentioned as our hypothesis. On the other hand, this was also an intriguing result, because this 'riddle' subtest requires higher brain functions compared with the other two language-related subtests, i.e. simple repetition or simple naming tasks. In this 'riddle' subtest, children were required to retrieve a target word according to suggested words that were conceptually associated with the target word. Correct answers must be represented in long-term memory as a network of associations among concepts and can be retrieved by spreading activation through the network structure (Anderson, 1983; Roelofs, 1992). In general, this subtest evaluates the development of conceptual formation and conceptual inference as well as word retrieval ability. In this context, this 'riddle' subtest requires efficient brain networks among regions that contribute to the representation of conceptual knowledge. Recent neuroimaging studies in adult subjects also support the importance of efficient brain networks for these types of ability. With regard to conceptual formation, a modality-specific account of conceptual knowledge organization was recently reported (Martin, 2007; Kiefer et al., 2008; Marques et al., 2008), which suggested that an efficient brain network among widely distributed areas involved in conceptual knowledge is crucial to infer correct answers that must be found in one of the modality-specific brain regions. With regard to word retrieval, a recent study demonstrated the importance of brain connectivity between the left ventrolateral prefrontal cortex and the posterior temporal and perhaps other cortical areas (Martin, 2007). Accordingly, it is reasonable to assume that the brain maturation processes involving myelination, synaptic refinement and cortical fibre density contribute to language ability – especially to conceptual inference, which requires higher brain function – in young children. The present study had the general limitation that we investigated P50m with only one short ISI (818 ms). Therefore, we cannot conclude whether P50m generation or refractoriness crucially reflects neuronal maturation.

Further studies with longer ISIs are therefore necessary to reduce the effects of refractoriness. However, even our short ISI resulted in the total MEG recording time being too long (12 min) for some children. Recent advances in head position calculation and correction of head movement (Uutela et al., 2001), however, may resolve this issue. Another limitation arises from the ECD criteria set for reliable ECD detection. In cases where estimated ECDs were rejected based on these criteria, we could not conclude whether it is because of truly lower neural response or higher noise. In this study, participants were monitored with a video camera that allowed us to detect obvious body movement. The examiner who accompanied children in the shielded room also instructed participants to keep the position of their head constant throughout the experiment. However, the influence of the fine movement of the head and variability in the head shape could not be taken into account in the present study.

Despite these limitations, this is the first study to demonstrate a correlation between detectable P50m dipole intensity with short ISI (818 ms) and language conceptual inference performance in preschool children.

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Abbreviations

AEF, auditory evoked magnetic field; ECD, equivalent current dipole; EEG, electroencephalography; ISI, interstimulus interval; K-ABC, Kaufman Assessment Battery for Children; MEG, magnetoencephalography.

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