




RESEARCH ARTICLE

Brain responses to human-voice processing predict child development and intelligence

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Abstract

Children make rapid transitions in their neural and intellectual development. Compared to other brain regions, the auditory cortex slowly matures, and children show immature auditory brain activity. This auditory neural plasticity largely occurs as a response to human-voice stimuli, which are presented more often than other stimuli, and can even be observed in the brainstem. Early psychologists have proposed that sensory processing and intelligence are closely related to each other. In the present study, we identified brain activity related to human-voice processing and investigated a crucial neural correlate of child development and intelligence. We also examined the neurophysiological activity patterns during human-voice processing in young children aged 3 to 8 years. We investigated auditory evoked fields (AEFs) and oscillatory changes using child-customized magnetoencephalography within a short recording time (<6 min). We examined the P1m component of AEFs, which is a predominant component observed in young children. The amplitude of the left P1m was highly correlated with age, and the amplitude of the right P1m was highly correlated with the intelligence quotient. For auditory-related oscillatory changes, we found a positive correlation between the intelligence quotient and percent change of gamma increase relative to baseline in the right auditory cortex. We replicated the finding of age-related changes in auditory brain activity in young children, which is related to the slow maturation of the auditory cortex. In addition, these results suggest a close link between intelligence and auditory sensory processing, especially in the right hemisphere.

KEYWORDS

auditory system, child development, event-related fields, gamma oscillations, intelligence, magnetoencephalography

1 | INTRODUCTION

Understanding the neural and cognitive development of children is one of the most crucial missions in neuroscience, and there is

bountiful potential for discovery through further research. Intelligence is a construct to understand an individual's cognitive abilities as measured by a broad range of tests. For a long time, early psychologists have suggested that intelligence and sensory processing are closely

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related to each other through common neural processes (Galton, 1883; Spearman, 1904). Over the last three decades, a number of psychological studies have found a relationship between sensory processing and intellectual functions. A higher intelligence quotient was related to quicker sensory processing (Deary, 2012; Deary, McCrimmon, & Bradshaw, 1997; Sheppard & Vernon, 2008), higher sensory acuity (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994), and sensory discriminations (Acton & Schroeder, 2001; Melnick, Harrison, Park, Bennetto, & Tadin, 2013). A previous study demonstrated the role of both visual and auditory sensory processing in intelligence (Lindenberger & Baltes, 1994). This link between intelligence and sensory processing could be examined by investigating the relationship between the intelligence quotient and brain activities during sensory processing.

Among several sensory stimuli, auditory stimuli are less restrictive compared to other sensory stimuli for child participants. Although auditory processing was related to intelligence in previous behavioral studies (Acton & Schroeder, 2001; Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994), until now there has been no neurophysiological evidence for this relationship. Therefore, we investigated the relationship between brain activities during auditory processing and intelligence in this pediatric study.

In addition, the auditory cortex matures slowly compared to the visual and sensorimotor cortices (Kinney, Brody, Kroman, & Gilles, 1988; Pujol et al., 2006; Yakovlev, 1967), which would be suitable as a neurodevelopmental indicator in late childhood (e.g., 3–8 years old). With the slow maturation of the auditory cortex, children show immature brain responses to auditory stimulation. Children show an obvious P1 component of auditory-evoked brain activity, with the first positive component arising at approximately 100 ms after presentation of an auditory stimulus. P1 latency was negatively correlated with age in electroencephalography (EEG) (Ponton, Eggermont, Khosla, Kwong, & Don, 2002; Ponton, Eggermont, Kwong, & Don, 2000) and magnetoencephalography (MEG) (Yoshimura et al., 2016) studies.

Among auditory stimuli, the human-voice stimulus is the more frequently experienced stimulus in the real world than a click or tone stimulus. Therefore, the activity- and experience-dependent developmental plasticity related to human-voice sounds were higher than that from simple click sounds, even in the brainstem in young children (Johnson, Nicol, Zecker, & Kraus, 2008). Therefore, we hypothesized that brain responses to human-voice stimuli could more efficiently show neural development resulting from activity- and experience-dependent developmental plasticity in children.

In the present study, we measured auditory cortical activity in typically developing 3- to 8-year-old boys ($n = 49$) using child-customized MEG that provided high temporal and spatial resolution. For brain responses to human-voice processing, we examined the auditory evoked fields (AEFs) and oscillatory changes in the child participants. The intelligence of participants was assessed using the Kaufman Assessment Battery for Children (K-ABC) (Kaufman & Kaufman, 1983), which provided an intelligence quotient evaluating general cognitive performance.

Based on the psychological theory regarding common neural processing between sensory processing and intelligence, we hypothesized that brain activity during human-voice processing could be correlated with the intelligence quotient. In addition, we hypothesized that we could replicate the findings of developmental changes in brain activity during human-voice processing based on the slow maturation of the auditory cortex.

2 | MATERIALS AND METHODS

2.1 | Participants

Forty-nine young children (3–8 years old, all male) participated in this study. To reduce confounding factors (e.g., sex and handedness), we recruited only right-handed boys based on the Edinburgh Handedness Inventory (Oldfield, 1971). We used the data from 16 children from Yoshimura et al. (2016) and recorded data from an additional 33 children to equate the number of participants at each age. We selected participants without known developmental and neurological disorders, hearing loss, or premature birth. The experimental procedures were approved by the Ethics Committee of Kanazawa University Hospital. Written informed consent was obtained from the parents of all children prior to enrolment in the study.

2.2 | Assessment of intelligence

The Japanese version of the K-ABC was used to assess the intelligence of all participants. K-ABC has typically been used to assess the cognitive skills of children aged 30 to 155 months (Kaufman & Kaufman, 1983). K-ABC consists of two global scales: a mental processing composite scale with 9 subtests and an achievement scale with 5 subtests. Raw scores on all subtests were converted to scaled scores based on norms for the child's own age group. The sums of the scaled scores for each global scale were transformed into standard scores with a mean of 100 and a *SD* of 15.

The mental processing composite scale assessed fluid intelligence, which measures the ability to solve novel problems by reasoning (Kaufman & Kaufman, 1983). The mental processing composite scale was intended to measure general cognitive performance. The achievement scale assessed crystallized intelligence, which measures knowledge-based abilities acquired by applying the mental processing ability (Kaufman & Kaufman, 1983). Acquired knowledge is highly influenced by variables other than intellectual ability, such as opportunities for education, environmental background, and motivation of the children. To measure the child's intellectual ability using K-ABC, it is recommended to use only the mental processing composite scale and not the achievement scale (Kaufman & Kaufman, 1983). Therefore, we used the score of the mental processing scale as the intelligence quotient of the participants in the present study.

2.3 | Human-voice stimulation and experimental paradigm

We used human-voice stimuli, which we reported in our previous studies (Yoshimura et al., 2014; Yoshimura et al., 2016). The human-voice stimuli consisted of the single Japanese syllable /ne/, which was recorded by a female native Japanese speaker using a condenser microphone (NT1-A; Rode, Silverwater, Australia). The stimuli comprised standard stimuli with a steady pitch contour and deviant stimuli with a falling pitch of 342 ms duration. The waveforms and spectra of the human-voice stimuli are represented in Figure 1. We delivered 228 standard stimuli (83%) and 45 deviant stimuli (17%) in the typical oddball sequence. All stimuli were presented with a 1,160-ms inter-stimulus interval.

The stimuli were presented via speakers placed outside the magnetically shielded room. The stimulus was delivered to the participants binaurally through a hole in the magnetic shield room. At the head position, the intensity level of each stimulus was approximately 65 dB (A-weighted) against a background noise of 43 dB, measured using an integrating sound-level meter (LY20; Yokogawa, Tokyo, Japan).

2.4 | Magnetoencephalography recording

Before the experiment, the participants took the time to become familiar with the experimental paradigm and surroundings. MEG

recording conditions were similar to those in previous studies (An et al., 2018; Yoshimura et al., 2014). Whole-head MEG data were recorded using a child-customized MEG system (PQ 1151 R, Yokogawa/KIT, Kanazawa, Japan) installed at the MEG Center of Ricoh (Kanazawa, Japan). MEG data were measured at a sampling rate of 2000 Hz and filtered with a 200 Hz low-pass filter.

We determined the head location of the participants in the MEG helmet using four head-positioning coils attached on their head's surface (i.e., Cz, 5 cm superior from the nasion and 5 cm superior from the left and right pre-auricular points). The locations of the head-positioning coils were measured before the MEG recordings.

Participants were comfortably placed in a supine position on a bed during the MEG recording. The MEG data were recorded while they watched a silent video projected on the screen to encourage remaining still and awake. An experimenter was seated next to the participants to encourage them during the MEG recording. The participants were monitored through a video monitoring system to assess their attention level and notable artifacts from head motion. The recording was approximately 6 min long.

Because it is difficult to obtain individual magnetic resonance images from young children, we used a child brain template using a modified version of the estimation algorithm reported in previous studies (Hayashi et al., 2012; Yoshimura et al., 2017). The algorithm determined an optimal brain structure image from 98 young children's brain images based on the individual head surface.

2.5 | Data analysis

The child MEG data were analyzed using the Brainstorm toolbox (Tadel, Baillet, Mosher, Pantazis, & Leahy, 2011) and MATLAB (Mathworks, Natick, MA). The continuous MEG data were bandpass filtered from 0.2 to 200 Hz and notch filtered at 60 Hz.

To eliminate artifacts caused by heartbeats, eye blinks, and eye movements, we applied an independent component analysis method ("RunICA" of EEGLAB [Delorme & Makeig, 2004]). The independent components representing cardiac and ocular activity were identified by visual inspection based on their waveform and topography. The artifact-rejected independent components were back-projected into the signal space. We applied a low-pass filter at 40 Hz to the data for event-related field analysis but not to the data for the time-frequency analysis. Thereafter, we segmented the continuous MEG data from -2000 to 2000 ms relative to the onset of a human-voice stimulus.

To remove trials with muscle artifacts from further analysis, we automatically excluded trials that exceeded 2000 ft/cm for MEG gradiometer channels and rejected those that included small amplitudes of muscle artifacts by visual inspection. For standard stimuli, a mean of 55 ± 30 trials were excluded from 228 trials, and a mean of 172 ± 30 trials were used for further analysis. For deviant stimuli, a mean of 18 ± 7 trials were excluded from 45 trials, and a mean of 27 ± 6 trials remained. The number of remaining trials with deviant stimuli was not sufficient for further analysis, and we used only the trials with standard stimuli in this study.

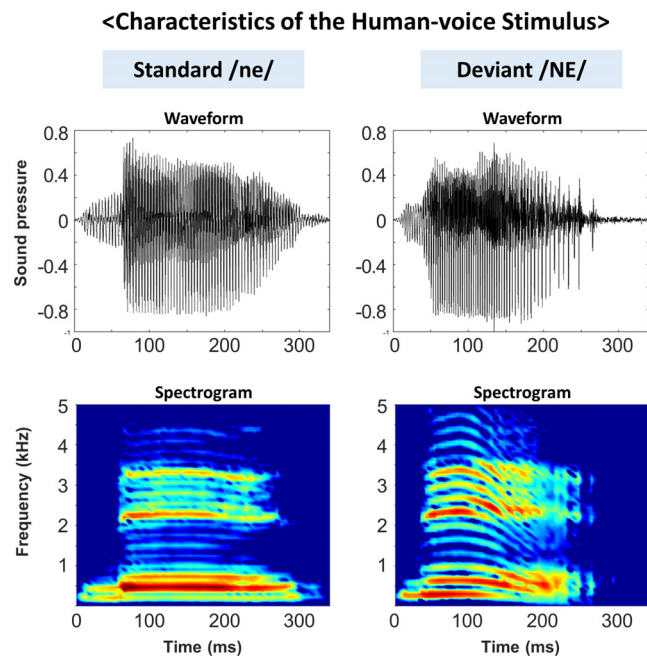


FIGURE 1 Characteristics of the human-voice stimuli. The left panel is the waveform and spectrogram of standard human-voice stimuli. The right panel is the waveform and spectrogram of deviant human-voice stimuli. While the waveform for the consonant 'n' has a small amplitude, the waveform for the vowel 'e' has a large amplitude. The spectrogram shows that human-voice stimuli contain a broad range of frequencies and larger sustained periodic signals during the vowel sound than during the consonant sound

For source analysis, we performed the weighted minimum norm estimates (wMNE) (Hamalainen & Ilmoniemi, 1994; Hauk, 2004; Lin et al., 2006) implemented in the Brainstorm toolbox. We built an overlapping-sphere conductor model using the child template anatomy, which was individually determined according to each participant's individual head surface measured by using a 3D digitizer (Fastrak; Polhemus, Colchester, VT). We computed the noise-covariance matrix for each participant during the baseline period (−210 to −10 ms). The wMNE source analysis was estimated using the overlapping-sphere head model with a Tikhonov regularization ($\lambda = 0.1$) (Tikhonov & Arsenin, 1977).

To obtain individual AEFs, we averaged segmented trials within each participant. The individual AEFs were corrected by subtracting the mean over the baseline period (−210 to −10 ms pre-stimulus onset). The P1m component from the individual AEFs was selected based on the topography representing the anterior and superior direction of the current source. The cortical sources of P1m were projected on the ICBM152 template anatomy in Montreal Neurological Institute coordinates. We grand-averaged the cortical sources of P1m and source waveform at the individual P1m cortical source across all participants.

For the time-frequency analysis, we selected the individual P1m source and calculated the time-frequency representations (TFRs) at 2–60 Hz using a 7-cycle Morlet wavelet for the source data of every single trial, as in previous studies (Cheyne, Jobst, Tesan, Crain, & Johnson, 2014; Gaetz, Macdonald, Cheyne, & Snead, 2010). We converted the TFRs to percent power changes relative to the mean over the baseline (−210 to −10 ms pre-stimulus onset), and we averaged within each subject and grand-averaged across all participants. Our baseline period (−210 to −10 ms pre-stimulus onset) was not long enough to estimate the oscillatory changes in the theta, alpha, and beta frequency bands. Therefore, we focused on the oscillatory power changes only in the gamma frequency band. We observed statistically significant oscillatory changes in the gamma frequency band (30–40 Hz) from 100 to 600 ms after stimulus onset ($p < .05$, FDR-corrected). We calculated the gamma power changes in these time and frequency windows.

2.6 | Statistical analyses

We performed statistical analyses using SPSS (version 24.0; IBM, Armonk, NY). For the statistical analysis of AEFs, we employed the latencies and amplitudes of the P1m source in the bilateral hemisphere. For the statistical analysis of TFRs, we used parametric *t* tests (two-tailed) against zero to select statistically significant oscillatory changes for further analysis. False discovery rate (FDR) correction was applied to control for type I error in the *t* tests of the TFRs. According to the results from this exploratory analysis, we employed power changes of gamma oscillations (30–40 Hz) from 100 to 600 ms in the bilateral auditory sources.

We used the Pearson's correlation coefficient to test correlations between brain activity in the bilateral auditory cortex and age in months or K-ABC scores. FDR correction was applied to control for type I error in correlation tests for AEFs (i.e., amplitude and latency, age and intelligence, left and right hemisphere) and gamma oscillations

(i.e., gamma power, age and intelligence, left and right). The alpha level was set to .05 for all statistical analyses in this study.

3 | RESULTS

3.1 | Auditory-evoked brain activity during human-voice processing

We examined AEFs during human-voice processing and explored the relationship with age and intelligence. First, we ensured that there was no statistically significant correlation between age and intelligence quotient ($r = .000$, $p = .997$).

We observed an obvious P1m component of AEFs during human-voice processing in individual child participants. P1m is the earliest cortical component of AEFs and is observed at approximately 100 ms after the stimulus onset in 1- to 10-year-old children (Ponton et al., 2000; Ponton et al., 2002; Yoshimura et al., 2016). Figure 2a shows the P1m component of the AEFs and its topography in representative subjects. The Pearson's correlation coefficient revealed that P1m latencies in both hemispheres were correlated with age ($r = -.339$, $n = 49$, $p = .017$ for left; $r = -.349$, $n = 49$, $p = .014$ for right) (Figure 2b) but not with intelligence ($p > .05$). We observed the cortical sources of grand-averaged P1m in the bilateral auditory cortices at 137 ms after human-voice stimulation (Figure 3). The individual cortical sources of P1m were located in the bilateral superior temporal cortex (Figure 4a).

We found that age was correlated with the left cortical P1m amplitude ($r = .436$, $n = 49$, $p = .002$) but not with the right P1m amplitude ($p > .05$) (Figure 4b). Intriguingly, however, intelligence was correlated with the right P1m amplitude ($r = .442$, $n = 49$, $p = .001$) but not with the left P1m amplitude ($p < .05$) (Figure 4b). We present the individual source locations, latency, and amplitude for the P1m component in Table 1.

3.2 | Gamma oscillatory changes during human-voice processing

We examined the oscillatory changes in the gamma band during human-voice processing and explored the relationship with age and intelligence. The oscillatory changes in the theta and gamma band were increased, and those in the alpha and beta bands were decreased during human-voice processing (Figure 5a). Due to the low baseline in our paradigm, however, we focused on only gamma power changes for further analysis. Significant gamma power changes were observed from 100 to 600 ms after the onset of stimuli ($p < .05$).

The gamma power increases in the bilateral auditory cortices were not correlated with age ($p > .05$). The gamma power increases in the right hemisphere were positively correlated with intelligence ($r = .373$, $n = 49$, $p = .008$), but those in the left hemisphere were not ($p > .05$) (Figure 5b).

There were no significant correlations between the P1m amplitude and gamma power changes ($r = .114$, $p = .434$ for left; $r = .162$, $p = .265$ for right).

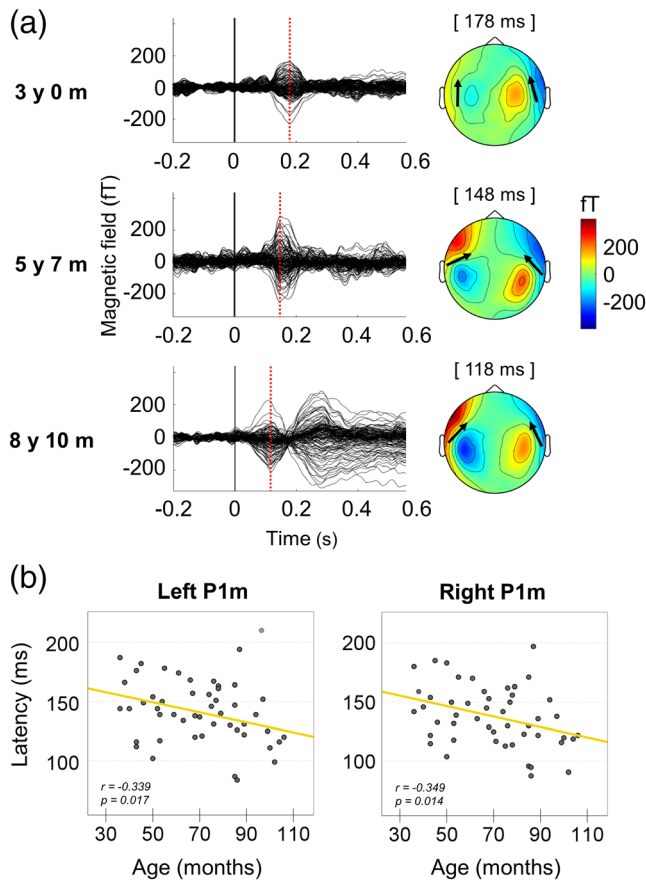


FIGURE 2 P1m components in three representative subjects and the correlations between age and P1m latencies. (a) Child participants show an obvious P1m component of the auditory evoked fields (AEFs). The topography of P1m presents anterior and superior current directions. Younger children show longer latencies than older children. (b) P1m latencies in both hemispheres negatively correlate with age in months ($r = -0.339$, $p = .017$ for left; $r = -0.349$, $p = .014$ for right)

4 | DISCUSSION

Our results show that brain activity during auditory sensory processing could reflect the age and intelligence quotient in young children. We investigated the P1m component of AEFs and brain oscillatory changes during human-voice processing. We observed that age was reflected in the latency of the P1m component in the bilateral hemisphere and the amplitude of the left P1m component. In addition, we found that the intelligence quotient was reflected in the amplitude of the right P1m and right gamma oscillations.

4.1 | Auditory brain activity and child development

We found that age was negatively correlated with the P1m latency in the bilateral hemisphere and positively correlated with the left P1m amplitude. The age-related changes in the P1m latency and amplitude were consistent with those of previous studies.

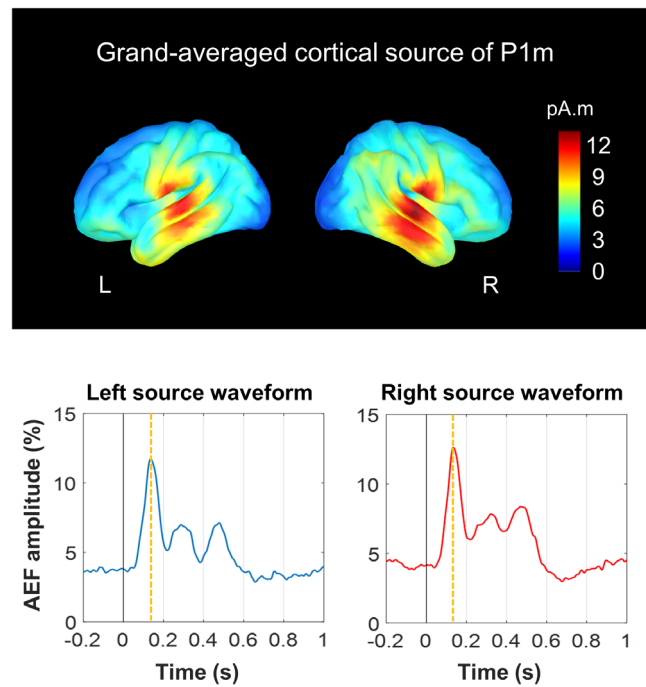


FIGURE 3 Grand-averaged cortical sources of the P1m component during human-voice processing. The cortical sources of P1m are shown in the bilateral superior cortices. Source waveforms show an obvious P1m component at approximately 137 ms in both hemispheres

Previous neurophysiological studies have reported decreasing bilateral P1m latencies with age. Previous EEG studies have revealed that the latency of the P1 component evoked by an acoustic stimulus consisting of 10 click sounds was negatively correlated with age (Ponton et al., 2000; Ponton et al., 2002). Our previous MEG studies have reported a strong negative correlation between age and P1m latencies using dipole source analysis (Yoshimura et al., 2016). We replicated the finding that age was negatively related to the latencies of the P1m component, consistent with previous studies.

For the P1m amplitude, we found a positive correlation with age only in the left hemisphere and not in the right. This finding is consistent with our previous study, which reported that 2- to 10-year-old children showed an inverted U-shaped growth curve of P1m dipole intensity only in the left hemisphere (Yoshimura et al., 2016). Given the growth curve in the age range of the present study (3–8 years old), our positive age-related changes in the left P1m amplitude were congruent with our previous study.

The age-related changes in the P1m component might have been related to the slow maturation of myelination and axonal filaments in the auditory cortex. Whereas maturation of myelination is achieved at approximately 4 months of age for the visual cortex (Kinney et al., 1988; Yakovlev, 1967) and at approximately 8 months of age for the sensorimotor cortex (Pujol et al., 2006), the auditory cortex begins to mature at approximately 1 year of age (Kinney et al., 1988; Yakovlev

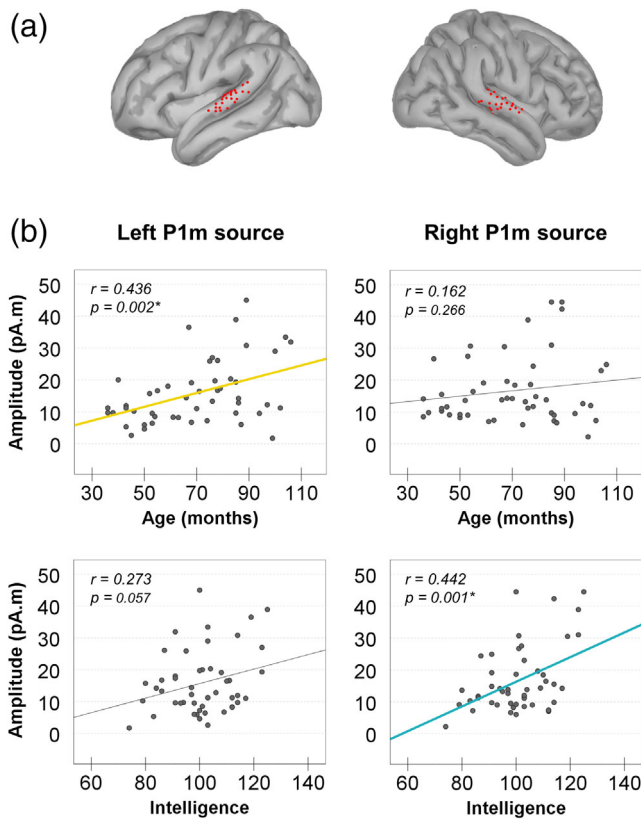


FIGURE 4 Individual P1m peak source locations and the correlations of P1m amplitudes with age and intelligence. (a) The individual peak sources of P1m are presented in the bilateral superior temporal cortices. (b) The amplitude of the left P1m source positively correlates with age in months ($r = .436$, $p = .002$). The amplitude of the right P1m source positively correlates with the scale of intelligence ($r = .442$, $p = .001$)

and Lecours, 1967; Moore and Linthicum 2007) reported that maturation of axonal neurofilaments in the auditory cortex occurs until 12 years of age. These axonal changes might be related to age-related changes in the P1 component of AEFs. The slow maturation of the auditory cortex might be a suitable phenomenon to make AEFs a kind of neurodevelopmental indicator in this age range (3–8 years old).

4.2 | Auditory brain activity and intelligence

We found that the intelligence quotient was correlated with the P1m amplitude and gamma oscillatory power changes during human-voice stimulation. Therefore, we demonstrated that brain activity during auditory processing is related to intelligence in children with typical development. Our neurophysiological findings are consistent with previous behavioral studies, which reported that intelligence is related to auditory discriminations (Acton & Schroeder, 2001) and auditory acuity (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994).

Various sensory processing including auditory information have also reported to be related to intelligence in previous behavioral studies (Acton & Schroeder, 2001; Baltes & Lindenberger, 1997; Deary, 2012; Deary et al., 1997; Lindenberger & Baltes, 1994; Melnick et al., 2013; Sheppard & Vernon, 2008). However, there is no neurophysiological evidence which supports these relationships. This is the first study to provide a possible neurophysiological evidence to support the early psychological theory from Galton and Spearman, which proposed a direct relation between sensory perception and intelligence (Galton, 1883; Spearman, 1904). Although we could not demonstrate whether common neural systems exist among these different sensory modalities (e.g., visual, tactile, and auditory), which would contribute to intelligence, their early psychological theory seems to be feasible for the relationship between auditory processing and intelligence.

4.3 | Right hemisphere and intelligence

Intriguingly, intelligence was correlated with the P1m amplitude and gamma oscillatory power changes only in the right hemisphere. These right-dominant findings are consistent with the right lateralization of brain functions for attentional control (Corbetta & Shulman, 2002). Although a key brain region involved in attention and working memory is the prefrontal cortex (Aine, Stephen, Christner, Hudson, & Best, 2003; Jensen & Tesche, 2002), some previous studies have clarified that the right superior temporal gyrus is responsible for spatial attention and perception (Ellison, Schindler, Pattison, & Milner, 2004; Karnath, 2001) and working memory maintenance (Park et al., 2011). Additionally, previous brain structural studies have reported that the intelligence quotient is associated with the temporal region (Shaw et al., 2006; Wilke, Sohn, Byars, & Holland, 2003). In particular, it has been reported that the intelligence quotient pattern is related to the gray matter volumes of the right superior temporal gyrus and adjacent regions, including the middle temporal gyrus (Yokota et al., 2015).

According to this view, the right superior temporal cortex might be involved in higher cognitive functions and intelligence.

4.4 | Gamma oscillations and intelligence

In addition, we found that the gamma oscillations in the right hemisphere were correlated with intelligence. Gamma-band activity is predominant in the upper layers of the cortical column, which is densely connected to the higher-order areas (Lakatos et al., 2005; Maier, Aura, & Leopold, 2011; Thomson & Bannister, 2003). Gamma activity is involved in neuronal communication (Fries, Nikolic, & Singer, 2007; Jensen, Kaiser, & Lachaux, 2007) and cognitive mechanisms such as attention (Busch, Schadow, Frund, & Herrmann, 2006; Tallon-Baudry, Bertrand, Henaff, Isnard, & Fischer, 2005; Tiitinen et al., 1993) as well as short- and long-term memory processing (Herrmann, Munk, & Engel, 2004; Lutzenberger, Ripper, Busse, Birbaumer, & Kaiser, 2002; Park

TABLE 1 Individual source locations, latencies, and magnitudes of the P1m component in both hemispheres

Subject	Age (months)	Left auditory P1m source					Right auditory P1m source				
		Latency (ms)	MNI coordinates			Magnitude (pA m)	Latency (ms)	MNI coordinates			Magnitude (pA m)
			X	Y	Z			X	Y	Z	
032	53	139	-65.0	-7.3	0.1	9.5	132	72.2	-23.4	3.4	9.0
038	43	112	-66.5	-15.6	1.3	11.9	122	69.8	-17.1	4.5	15.5
052	40	144	-68.0	-20.7	11.2	20.0	146	69.9	-26.7	4.1	26.7
055	55	178	-66.3	-20.0	4.8	16.6	171	72.2	-23.4	3.4	16.4
067	36	187	-66.1	-17.0	6.8	9.7	180	69.8	-17.1	4.5	14.1
072	38	166	-65.2	-17.4	11.1	9.7	159	69.8	-17.1	4.5	9.8
077	45	182	-68.5	-22.5	14.7	2.6	185	64.4	-8.8	4.7	11.6
078	50	154	-69.6	-21.2	12.1	5.9	183	68.3	-23.6	12.4	8.2
085	50	102	-69.7	-34.5	11.7	4.6	104	69.6	-25.2	9.2	9.2
088	43	176	-66.5	-15.6	1.3	5.3	154	69.9	-26.7	4.1	10.3
089	43	116	-68.1	-15.8	11.0	11.2	115	68.2	-18.1	4.4	11.1
090	46	149	-65.6	-7.5	-3.7	10.2	133	71.4	-14.4	3.5	9.1
093	36	144	-70.0	-15.5	5.4	11.2	142	68.5	-22.9	1.2	8.5
106	59	139	-69.3	-23.7	14.0	18.0	149	68.0	-14.7	-8.4	19.1
125	85	164	-71.7	-24.4	1.2	38.9	171	69.1	-11.5	-3.1	44.5
136	78	163	-69.7	-18.3	-0.8	16.7	114	68.5	-22.9	1.2	11.7
144	74	156	-72.0	-13.7	1.0	7.2	142	71.5	-19.4	6.0	6.0
152	52	144	-69.4	-22.3	13.2	15.7	150	64.8	-5.5	-7.1	13.6
154	76	167	-72.0	-27.8	5.0	13.3	162	69.1	-13.8	-11.2	11.2
155	77	151	-67.1	-38.9	10.1	19.7	150	70.6	-16.8	10.2	18.6
156	67	157	-71.8	-17.0	-9.1	36.5	145	72.4	-22.8	4.3	30.5
157	61	174	-72.6	-38.1	10.7	8.3	170	67.5	-2.7	0.4	7.0
159	70	137	-71.0	-27.4	3.5	11.0	125	71.8	-7.7	-3.4	14.2
172	66	168	-69.6	-21.2	12.1	14.4	159	68.0	-14.7	-8.4	13.8
174	78	161	-69.6	-21.2	12.1	26.1	156	68.1	-12.9	-3.5	24.4
180	75	146	-70.0	-15.5	5.4	25.9	113	68.2	-18.1	4.4	13.2
195	94	139	-70.6	-18.0	5.1	9.5	152	69.9	-23.5	14.8	9.5
196	83	130	-72.4	-22.4	12.0	20.3	123	69.1	-13.3	7.5	13.8
197	79	140	-71.4	-18.0	12.3	17.3	163	69.0	-5.6	-5.0	14.8
199	89	131	-71.7	-30.2	2.2	45.0	136	72.3	-17.2	10.5	44.5
202	85	147	-69.9	-15.7	1.5	19.3	130	70.3	-21.4	4.6	31.0
203	87	194	-71.4	-32.4	13.9	6.0	197	72.3	-32.0	9.0	6.6
205	97	152	-71.4	-21.0	14.2	12.2	138	74.6	-20.8	10.8	12.6
232	63	134	-71.2	-32.2	8.2	8.2	136	70.0	-29.6	-3.8	7.4
264	71	121	-69.4	-22.3	13.2	16.4	117	64.4	-1.6	-5.0	18.4
266	53	117	-72.3	-21.7	10.7	6.4	118	69.1	-20.1	1.2	27.5
273	89	122	-70.8	-23.7	-1.9	30.8	122	70.3	-15.6	-2.1	42.3
275	104	116	-69.3	-17.2	1.8	33.4	119	70.4	-20.7	-3.2	23.0
279	86	84	-69.0	-13.1	0.1	12.8	95	70.5	-17.6	1.4	9.0
281	86	126	-68.3	-25.2	16.1	14.2	88	69.3	-19.9	8.6	7.2
283	99	125	-67.0	-28.5	20.6	1.71	116	55.3	-16.3	9.4	2.2
286	102	99	-68.7	-25.7	12.6	11.2	91	67.7	-16.7	5.2	7.3
287	100	111	-70.5	-31.8	12.1	29.0	120	73.0	-13.1	9.8	12.0

(Continues)

TABLE 1 (Continued)

Subject	Age (months)	Left auditory P1m source					Right auditory P1m source				
		Latency (ms)	MNI coordinates			Magnitude (pA m)	Latency (ms)	MNI coordinates			Magnitude (pA m)
			X	Y	Z			X	Y	Z	
292	106	120	-69.4	-22.3	13.2	31.9	122	67.7	-16.7	5.2	24.9
297	85	87	-69.4	-22.3	13.2	9.6	96	67.7	-16.7	5.2	9.7
298	68	138	-71.4	-32.4	13.9	19.1	153	71.4	-17.5	0.8	19.6
300	68	120	-72.4	-19.2	2.9	6.7	129	72.4	-15.7	4.6	14.3
302	76	131	-71.4	-16.9	6.8	27.0	130	68.9	-9.8	1.8	38.9
308	54	150	-72.4	-19.2	2.9	8.5	139	72.4	-10.2	6.7	30.7

Abbreviation: MNI, Montreal Neurological Institute.

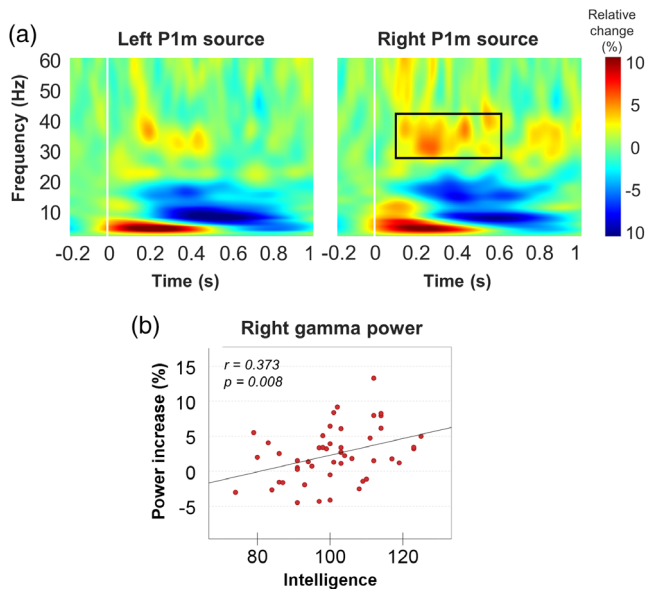


FIGURE 5 Grand-averaged time-frequency representations during human-voice processing and correlations between gamma power and intelligence. (a) Grand-averaged time-frequency representations show that the oscillatory power changes in the theta (4–7 Hz), alpha (7–12 Hz), beta (14–20 Hz), and gamma (30–40 Hz) bands. The alpha- and beta-band power decreased, and the theta- and gamma-band power increased. Due to the short baseline period, we focused on the oscillatory changes in the gamma band from 100 to 600 ms ($p < .05$, false discovery rate [FDR] corrected). (b) Changes in oscillatory power in the right gamma power positively correlate with the intelligence quotient measured by the K-ABC ($r = .373$, $p = .008$)

et al., 2011). Given this evidence, gamma oscillations could be associated with higher cognitive functions, such as intelligence.

5 | CONCLUSIONS

In this study, we evaluated AEFs and brain oscillatory changes during human-voice processing using a child-customized MEG system. We

observed the P1m component of the AEFs and oscillatory changes during human-voice processing in young children and demonstrated the neural correlates of age and intelligence quotient. Ages were correlated with the latencies of P1m in the bilateral hemisphere and amplitude of the left P1m. We speculate that age-related changes in the P1m component are associated with the maturation of the auditory cortex during child development. Intelligence quotient scores were correlated with the right amplitude of P1m and gamma power changes during human-voice processing. From this, we suggest that auditory brain activity could reflect high cognitive functions such as intelligence. Our neurophysiological findings support the early psychological theory that sensory processing and intelligence are closely related through common neural processes. Therefore, our study emphasizes the possibility that brain activity patterns during human-voice processing predict child development as well as intelligence.

In the present study, we found the relationships between age and intelligence with brain responses to a single-syllable human-voice stimulus. However, we cannot be sure whether these relationships are specific to the single-syllable human-voice stimulus. Future studies are required to demonstrate that age and intelligence relationships with particular brain responses exist in response to other auditory stimuli and/or other sensory stimuli as well. Furthermore, our data are only from males to exclude potential sex effects. Future studies are required to obtain data from females to increase the generalizability of our results and to observe any differential development tendencies between male and female children. Since our baseline period was too short to estimate lower frequency bands (i.e., theta, alpha, and beta frequency bands), we investigated only gamma oscillations in the present study. A longer inter-stimulus interval would be required to observe oscillatory changes in lower frequency bands during the presentation of human voice stimuli in future studies.

Our study is meaningful and fills a gap in the developmental neuroscience literature. Because of the difficulties in obtaining data from young children, few neuroscience studies have been conducted in this age range. We hope that the present study will be applicable to future studies on children with developmental and learning disorders, the prevalence of which has increased in recent years.

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CONFLICT OF INTEREST

The authors declare no competing financial interests.

DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are available on request from the corresponding authors, K.A. and Y.Y. The data are not publicly available as they contain information that could compromise the privacy of research participants.

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