Recording brain activities in unshielded Earth’s field with optically pumped atomic magnetometers

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Understanding the relationship between brain activity and specific mental function is important for medical diagnosis of brain symptoms, such as epilepsy. Magnetoencephalography (MEG), which uses an array of high-sensitivity magnetometers to record magnetic field signals generated from neural currents occurring naturally in the brain, is a noninvasive method for locating the brain activities. The MEG is normally performed in a magnetically shielded room. Here, we introduce an unshielded MEG system based on optically pumped atomic magnetometers. We build an atomic magnetic gradiometer, together with feedback methods, to reduce the environment magnetic field noise. We successfully observe the alpha rhythm signals related to closed eyes and clear auditory evoked field signals in unshielded Earth’s field. Combined with improvements in the miniaturization of the atomic magnetometer, our method is promising to realize a practical wearable and movable unshielded MEG system and bring new insights into medical diagnosis of brain symptoms.

INTRODUCTION

Magnetoencephalography (MEG) is a functional neuroimaging technique for mapping human brain activities using an array of magnetometers to detect magnetic fields produced by neural currents (1–3). Compared with its electric signal detection–based counterpart, i.e., scalp electroencephalography (EEG) (4, 5), MEG has a higher spatial resolution due to the nearly homogeneous magnetic permeability of biological tissues (6). MEG is a promising noninvasive method for locating brain activities compared with intracranial EEG, an invasive method using electrodes placed directly on the exposed surface of the brain to record electrical signals (7). MEG has various applications in neuroscience (8), cognitive science (9), and especially in the diagnosis of brain symptoms such as epilepsy presurgical evaluation (10), Alzheimer’s disease (11), Parkinson’s disease (12), traumatic brain injury (13), and multiple sclerosis (14).

The MEG system typically uses two different kinds of magnetometers as the magnetic sensors, the superconducting quantum interference devices (SQUIDs) (15–17) or the optically pumped atomic magnetometers (OPMs) (18–25). For the commercial MEG systems, it is the SQUID sensors that are widely used. Although the SQUID sensor has a sufficient sensitivity to detect the weak magnetic field signals originating from brain activities, the cryogenic operational condition demands that the sensor geometry has to be fixed in a liquid helium dewar, which makes the measuring helmet of the commercial MEG system costly and inflexible. The associated immovability of the measuring helmet limits the applications of MEG in cases where head motion is needed. A general tendency within the MEG community is replacing SQUID with noncryogenic high-sensitivity OPM as the magnetic sensor (18–25), considering that the sensitivity of the OPM sensor has been comparable with that of the most sensitive SQUID sensor and the miniaturization has become much improved (26, 27). A wearable MEG system based on an array of OPM sensors, which allows head movement and customization of the measuring helmet, has already shown similar performances in both the spatial resolution and sensitivity in comparison to a commercial MEG system based on SQUID (25).

There are several advantages of using OPM sensor in MEG, for example, noncryogenic, movable, custom-design friendly, and less expensive. These advantages make it possible to construct a wearable and movable MEG system for noninvasive long-term observations of the patients with brain symptoms, such as epilepsy, to capture the infrequent epileptiform events (28). Such a task is conventionally tackled by the scalp EEG, considering that the MEG system based on SQUID is not suitable for long-term observations (29). The performance of the EEG in locating the brain symptoms is limited by the nonuniform resistive properties of biological tissues. From this aspect, using OPM as the MEG sensor is important for some clinical applications, especially in the noninvasive surgical treatment of epilepsy that demands a precise localization of the epileptogenic focus.

Almost all the MEG measurements based on OPM sensors are performed in magnetically shielded rooms (MSRs) for suppressing the ambient magnetic field noise and providing a nearly zero magnetic field circumstance therein. The application of MSR improves the signal-to-noise ratio (SNR) of the MEG signal, whereas it limits the potential advantages of using OPM-based MEG in clinical applications and for long-term observations (10, 28). For example, the crowded inner space of MSR makes the long-term observations less efficient. There are several important advantages to eliminating the MSR, e.g., reducing cost, ease of siting of OPM-based MEG systems, and a more naturalistic environment. The unshielded MEG system also makes it possible to be combined with the low-field magnetic resonance imaging system (16) and provides a convenient way for the coregistration in locating and imaging the brain activities. Thus, it is of great demand that the OPM-based MEG measurements can be performed in unshielded Earth’s field.
Here, we develop and test an OPM-based MEG system operating in unshielded Earth’s field. The OPM that we use is based on amplitude-modulated nonlinear magneto-optical rotation (AM-NMOR; section S1), which is different from the spin-exchange relaxation-free (SERF) magnetometer (30–32), a conventionally used OPM sensor for MEG. The SERF magnetometer has the advantages of high degree of miniaturization and portability and is one of the most sensitive magnetic sensors operating near-zero magnetic field. As a comparison, the AM-NMOR magnetometer operates in a much wider range of magnetic field and could cover the Earth’s field (33, 34). We use two AM-NMOR cesium magnetometers and perform gradiometric detection, together with feedback methods, to reduce the magnetic field noise. The atomic magnetic gradiometer has a magnetic field gradient noise floor (sensitivity) of ~4 fT/cm Hz^{1/2} (1 fT = 10^{-15} T) under the unshielded condition. On the basis of the atomic magnetic gradiometer, we successfully observe the alpha rhythm signal related to open and closed eyes and a clear auditory evoked magnetic field (AEF) signal. We also fully characterize the technical issues to be solved and the corresponding improvements to be implemented for realizing a practical wearable and movable MEG system. We recently learned that Limes et al. (35) also reported successful MEG measurements in unshielded Earth’s field. Compared with the AM-NMOR magnetometer that we use, the researchers demonstrate a configuration of atomic magnetometer operating in the pulsed mode. Through using microfabricated multipass vapor cells and custom electronics, they realize a compact system and reduce the power consuming to 5 W, making a quite notable step forward.

RESULTS

In this section, we describe the measurement results of our MEG system in unshielded Earth’s field. First, we give a brief description on the unshielded MEG system and the performance in suppressing the common-mode magnetic field noise. Second, we present two typical MEG measurements. One is for the spontaneous alpha rhythm signal related to open and closed eyes and the other one is for the AEF signal. All the experiments are performed under the approval of the local Institutional Review Board and with all the participants providing written informed consent.

MEG system in unshielded Earth’s field

The overall layout of the real system is shown in Fig. 1A. We use two sets of three orthogonal coils. The outer layer is for adjusting the bias magnetic field strength, while the inner layer is for compensating the magnetic field fluctuations. The OPM sensors are placed at the center of the coils. The person is lying on a wooden table with the head resting on the OPM sensors. Figure 1B and C shows the details of the alpha rhythm signal and AEF signal detection experiments, respectively. The horizontal components of the Earth’s field are compensated to be within ±10 nT (1 nT = 10^{-9} T) around zero so that the remaining magnetic field is along the vertical direction, which is the sensitive axis of the OPM sensor. It is important to have the large magnetic field along the sensitive axis of the sensor to reduce the dead-zone effect. Technical details of the OPM sensor are described in Materials and Methods (36). The field strength B_0 along the vertical direction can be set to any value (within ±10 nT) below 10^3 nT by adjusting the currents applied to the outer layer of the coils (the strength of the Earth’s field is ~54,500 nT in Beijing). Given that the bandwidth of our OPM sensor is determined by the spin precession frequency, which is proportional to the strength of the magnetic field, we set the minimum magnetic field to be around 5000 nT.

The distance between the top and bottom OPM sensors is 6 cm, and the two sensors are distant from the surrounding magnetic substances. The environment magnetic noise is taken as the common-mode noise for the two sensors. Furthermore, since the head of the participant is placed more closely to the top OPM sensor, the amplitude of the MEG signal detected by the top sensor is almost one order of magnitude larger than that of the bottom one (section S2). On the basis of this consideration, we use the two OPM sensors to realize an atomic magnetic gradiometer (37), through which the measured results of the two sensors are subtracted so as to enhance the SNR of the MEG signal.

The ability of suppressing the common-mode magnetic noise, or the common-mode noise rejection ratio (CMRR), plays a critical role in determining the performance of the magnetic gradiometer. To get a higher CMRR, the responses of the two OPMs with respect to the same magnetic field signal should be as closed as possible. Figure 1D and E shows that the measured frequency responses of the two OPMs are almost identical. Both of the two OPMs are working in the closed-loop mode, which provides a larger bandwidth and better performance in reducing the common-mode noise compared with the open-loop mode (37, 38). The 3-dB bandwidth of the two OPMs is both ~950 Hz, which is primarily determined by the parameter settings of the proportional integral derivative (PID) feedback system. To characterize the ability of rejecting the common-mode magnetic field noise and the CMRR of the gradiometer, we apply a sinusoidal magnetic field to each of the two OPM sensors and measure the residual signal amplitude after subtracting the measurement results from the two OPMs. The orange triangle in Fig. 1F shows the measured CMRR of the gradiometer at different frequencies. The CMRR is larger than 1000 for frequencies lower than 30 Hz and then decreases with the increased frequency while still larger than 400 for frequencies between 30 and 100 Hz. The decrease in the CMRR at higher frequencies is primarily due to the nonidentical frequency responses of the two OPMs. The CMRR could be improved by increasing the bandwidths of the two OPMs (section S1). Details of the procedures for measuring the frequency responses of the two OPMs and the CMRR of the atomic gradiometer are described in Materials and Methods.

The magnetic field noise for an unshielded magnetically noisy environment, which is surrounded with ferromagnetic substances, could be much larger than tens of pT/Hz^{1/2} for the range of frequencies where the MEG signals occur. Therefore, even using a magnetic gradiometer with a CMRR of 1000, the residual magnetic noise floor of the atomic gradiometer is still larger than most of the MEG signals. The conventional method for suppressing the environment magnetic noise is using passive shielding. In our system, instead, the environment magnetic noise is monitored with the bottom OPM sensor and then compensated by automatically controlling the current applied to the coils along the vertical direction (see Materials and Methods for details). Compared with magnetic field noise along the vertical direction, our OPM sensors are not sensitive to magnetic field noise along the horizontal directions as these field components add in quadrature to the dominant vertical magnetic field component. The blue square in Fig. 1F shows the result of CMRR using this noise compensation method, indicating that the magnetic noise is suppressed by ~800 times for frequencies below 10 Hz. The residual
noise is determined by the intrinsic noise level of the OPM sensor. For higher frequencies, the CMRR decreases due to the reduction of the gain of the error signal for field stabilization and can be improved by increasing the bandwidths of the two OPMs and optimizing the parameter settings of PID controller for field stabilization (section S3).

In general, the combination of the two methods, i.e., the atomic gradiometer and the active field stabilization, gives an expected overall magnetic noise suppression ratio up to $10^6$ for frequencies smaller than 10 Hz (see the green circles in Fig. 1F) and is comparable to a value expected from a passive MSR with seven mu-metal layers (39). These results indicate that our magnetic gradiometer, together with the field stabilization, is capable of measuring the weak MEG signals even in a noisy unshielded Earth’s field. It should be noted that the overall noise suppression ratio shown in Fig. 1F is a direct multiplication of the CMRRs of the two individual noise suppression mechanisms. This is valid for conditions where the ambient magnetic field noise is along the sensitive axis of the sensor and is large and identical for the two sensors, while the field generated inside the coils for field stabilization is homogeneous.

Spontaneous alpha rhythm signal
The alpha rhythm, or the alpha wave, is a pattern of slow brain wave with a typical frequency ranging from 7 to 13 Hz and arises from the synchronous and coherent electrical activity of thalamic pacemaker cells in humans (40). It is normally considered to represent the activity of the visual cortex in an idle state and/or the areas of the cortex not in use. For example, the alpha rhythm signal for a normal person is stronger with closed eyes and becomes suppressed with open eyes. The amplitude of the alpha rhythm signal is relative...
strong among all the signals detected with EEG and MEG (40). On the basis of these characteristics, at first, we measure the alpha rhythm signal of a normal person in unshielded Earth’s field to test the performance of our MEG system.

For the alpha rhythm signal measurements, the person is asked to put his head, typically, his inion, right on top of the OPM sensor (see Fig. 1B) to have the strongest signal measured. The cesium vapor cell is kept at room temperature and has no heating issue for the person. Details of the measurement procedures are described in Materials and Methods. With no person present, the green line (region) in Fig. 2A shows that the noise floor of the atomic gradiometer is 20 fT/Hz$^{1/2}$ for frequencies between 1 and 30 Hz (magnetic field gradient noise level of ~4 fT/cm Hz$^{1/2}$ with a 6-cm baseline). The noise of the atomic gradiometer for frequencies larger than 40 Hz (not shown in Fig. 2A) comes from the intrinsic noise of the OPM sensors and is not reduced with the gradiometric detection. Compared with the sensor operating in the open-loop mode, the sensor operating in the closed-loop is known to have enhanced bandwidth, however, have no improved SNR, and results in an increase in the sensor noise outside the original magnetic resonance line width (section S3). The noise level slightly increases when the person is present, which may come from the mechanical vibrations. The person is asked to keep his eyes closed and open, both for 180 s. The blue region in Fig. 2A shows the recorded spectrum when the person closes his eyes. As a comparison, the spectrum obtained with open eyes is also plotted, shown as the yellow region in Fig. 2A. We could observe an alpha rhythm signal around 10 Hz when the person keeps his eyes closed, including a suppression in the signal amplitude when the eyes are open. Besides the dominant alpha rhythm signal around 10 Hz, there is also a small peak around 20 Hz, which is possibly due to the second harmonic of the alpha rhythm signal (41).

The person is also asked to repeat closing and opening his eyes every 30 s, and the magnetic field signal is recorded in time domain, shown in Fig. 2B. There is a clear change in the amplitude of the magnetic field signal every 30 s. When the eyes open, the peak-to-peak variation of the magnetic field signal is ~0.5 pT and increases

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**Fig. 2. Spontaneous alpha rhythm signal.** (A) The green region shows the measured spectral density of the atomic gradiometer with no person present and indicates a noise floor of 20 fT/Hz$^{1/2}$ for frequencies between 5 and 30 Hz. When the person is present and asked to keep his eyes open, the measured result is shown in the yellow region. When the person closes his eyes, a clear alpha rhythm signal around 10 Hz is observed, see the blue region. (B) The time domain signal acquired when the person is asked to repeat closing and opening his eyes every 30 s. (C) The spectrogram for the acquired 300-s data shown in (B).
to \(~1\) pT with closed eyes. Figure 2C shows the spectrogram of the acquired 300-s data, of which the frequency range is 5 to 20 Hz. All the measurements are performed in unshielded Earth’s field, with a bias field of \(~20,000\) nT. The same measurements are also performed under a bias field of \(~50,000\) nT, under which the recorded signal is almost the same as in Fig. 2 (section S6). For even larger magnetic field, the nonlinear Zeeman effect tends to broaden the line width of the OPM magnetic resonance signal and degrades the performance of the OPM sensor. We can replace cesium with potassium to construct the OPM sensor for large magnetic field. Potassium has a much larger nonlinear Zeeman effect than cesium and, thus, makes the different peaks of the magnetic resonance signal well separated for larger magnetic field. One of these separated peaks can be used for magnetic field measurement.

Auditory evoked signal

The AEF signal is also measured in unshielded Earth’s field. The AEF signal originates from the auditory evoked electric potential generated within the brain while an auditory stimulus is presented (42). The AEF signal has characteristics such as latency and positive and negative peaks, with an amplitude much smaller than that of the spontaneous MEG signal, such as the alpha waves. Measuring the AEF signal is of great importance in understanding, examining, and determining the auditory ability level of an individual, especially, for predicting and diagnosing the hearing loss in newborns, infants, and multiple handicaps.

We measure the AEF signals for three healthy male individuals aged between 22 and 25 years old (see details of the measurement procedures in Materials and Methods). During the measurement, each person is lying on his right side so as to place the temporal lobe right above the OPM sensor (see Fig. 1C). To prevent the heating on the sensor from the face and drifts in the OPM signal amplitude for long-term measurements, we place a silicone pad with a thickness of 2 mm between the head and the sensor. For each person, we apply 480 auditory stimuli. The time interval between each stimulus is randomly distributed between 0.7 and 1.7 s to prevent the person from being adapted to the stimulus. Each stimulus lasts for 100 ms and is applied automatically to the left ear of the person via plastic tubes and a nonmagnetic earpiece (see the red component in Fig. 1C). For all the 480 auditory stimuli, the frequency of the tune is standard and is 440 Hz. Figure 3A shows the measured AEF signals in the time domain for the three individuals. Each line is averaged from the 480 measured results of all the stimuli with a standard frequency. An AEF signal occurs and can be seen \(~100\) ms after the stimulus. Such a signal is called M100 and is the most prominent magnetic signature of the cerebral auditory response. Although the AEF signal waveforms of the three persons are similar, the signal strengths are quite different. This is because, for different person, the source of the AEF signal has different depth relative to the scalp (sensor). Figure 3B shows the map of all the 480 measured results for person no. 2. It is shown that for all the measurements, our system is capable of measuring the AEF signal in a stable state.

DISCUSSION

In this work, we report the MEG results in unshielded Earth’s field with a prototype atomic gradiometer. We show that our unshielded MEG system is capable of measuring the spontaneous alpha rhythm signal and the AEF signal for normal persons. The results prove that the unshielded MEG system based on OPM sensor has sufficient sensitivity for various MEG applications. This is promising to realize a wearable and movable MEG system, which is important for normal clinical applications and for long-term observations and medical diagnosis of brain symptoms. To achieve this goal, several technical issues and challenges need to be considered and solved. These include, but may be not limited to, the suppression of the magnetic...
gradient, the miniaturization of the magnetic sensors for multichannel operation, and the calibrations of the systematic errors from movement of the person.

For the first issue, the atomic gradiometer that we use can suppress the common-mode magnetic field noise, while it has no effect on suppressing the variations of the magnetic gradient between the two sensors. Thus, the variation of the magnetic gradient is mixed into the detected signal and distorts the MEG signal. This issue can be solved with using more reference magnetometers to actively stabilize the magnetic gradient and to form a higher-order magnetic gradiometer (sections S2 and S4).

Since one of the potential applications of the MEG is to localize the neuronal activity, an array of OPM sensors is needed. The AM-NMOR OPM is suitable for constructing an array given that there is no cross-talk effect between the sensors. Currently, a dominant issue limiting the possibility of a whole-head array is the size of the device. To reduce the size of the device, we need to use a miniaturized vapor cell, with a typical size smaller than 10 mm. Although the relaxation rate of a paraffin-coated cesium cell with a diameter of 3 mm is comparable to that used in our experiment (43), decreasing the size of the vapor cell would markedly decrease the number of atoms that involves in the magnetic sensing, which, in turn, degrades the sensitivity of the magnetometer. This issue can be tackled by heating the vapor cell to increase the atomic number density. Heating paraffin-coated cell with a normal size from 20° to 95°C is experimentally shown to be achievable and is expected to increase the atomic number density by 400 times (44). This is possible to make the magnetic sensitivity of the OPM sensor on the order of femtotesla, which is sufficient for the MEG measurements.

The third issue comes from the movement of the person, which could bring systematic errors in the measured results. First, the movement of the person changes the relative direction between the MEG signal and the bias geomagnetic field and, in turn, affects the performance of source location, since it is the projection of the MEG signal along the direction of the bias geomagnetic field to be measured. Second, the change in the relative direction between the sensitive axis of the magnetometer and the geomagnetic field also generates heading error in the magnetometer (45). For example, the heading error is on the order of nanotesla when the cesium atomic magnetometer is rotating. To solve these issues, the head movement of the person should be constantly monitored and taken as input parameters for data after processing (46). Besides, the heading error of the atomic magnetometer can be suppressed by either modulating the polarization of the pump beam between left and right circularly polarized at the Larmor frequency (47) or using linearly polarized laser beams or even using other atomic elements, e.g., potassium to construct the OPM sensor.

**MATERIALS AND METHODS**

**Optically pumped atomic magnetometer**

The magnetometer is based on a pump-probe scheme to polarize the cesium atomic spins and monitor the Larmor precession. The pump laser is circularly polarized and has a 1/e² diameter of ~2.7 mm. The central frequency of the pump laser is locked to the D1 transition line (from 6 ⁵S₁/₂ F = 3 to 6 ⁵P₁/₂ F = 4, where F and F' are the total angular momentum numbers) with dichroic atomic vapor laser lock. The amplitude of the pump beam is modulated with an acoustic-optical modulator at the Larmor frequency. The modulation duty cycle is 20%. The averaged power of the pump laser is ~50 μW. The probe laser is linearly polarized and has a 1/e² diameter of ~1.1 mm. The power of the probe laser is ~50 μW. The central frequency of the probe laser is positively detuned by ~400 MHz from the D2 transition line (from 6 ⁵S₁/₂ F = 4 to 6 ⁵P₃/₂ F' = 5). The cesium vapor cell is antirelaxation-coated and is kept at room temperature, with a typical magnetic resonance line width of ~5 Hz. The diameter and the length of the cylinder vapor cell are both 25 mm. The vapor cell, including all the optical components, such as the polarizers, wave plates, mirrors, and the Wollaston prism, is mounted in a three-dimensional printed structure, which has a size of 5 cm by 24 cm by 27 cm. The pump and probe laser beams are coupled into the magnetic sensor with optical fibers. The transmitted probe laser from the vapor cell is fiber-coupled to the sensor and then detected with a balanced photodetector. The output signal from the balanced photodetector is demodulated with a lock-in amplifier (Stanford Research Systems, SR865A, LIA), from which the in-phase component amplitude is proportional to the difference between the Larmor frequency and the modulation frequency of the pump laser.

**Frequency response of the atomic magnetometer**

To measure the frequency responses of the magnetometers, we use a pair of Helmholtz coils, which has a diameter of 30 cm and is connected in series with a resistance of 500 ohm and is driven with a signal generator (Keysight, 53230A), to generate a sinusoidal magnetic field with an amplitude of 3.7 nT. The readouts of the two magnetometers, together with the sinusoidal signal from the signal generator, are recorded simultaneously with a data acquisition card (National Instruments, USB6363) at a sampling rate of 40 kSa/s. The readouts are demodulated at the frequency of the applied sinusoidal signal to extract the amplitude and phase shift relative to the sinusoidal signal. The frequency responses of the two magnetometers are thus obtained by scanning the modulation frequency from 1 to 2010 Hz and repeating the above measurement procedures. Similarly, we get the amplitude-frequency characteristics of the gradiometer by demodulating the difference of the two OPM sensors’ readouts at the frequency of the applied sinusoidal signal. The frequency dependence of the CMRR of the gradiometer is thus obtained by dividing the amplitude-frequency characteristic of OPM1 by that of the gradiometer.

**Magnetic field stabilization**

The magnetic noise is compensated using OPM2 and a pair of vertical coils. We use OPM2 as a reference magnetometer to monitor the magnetic field fluctuations. The measured signal from OPM2 is fed into a PID controller (Stanford Research Systems, SIM960), from which the output signal is used to control the current added into the coils. To characterize the ability of rejecting the common-mode magnetic field noise of the field stabilization, we monitor the residual magnetic noise with OPM1. We use the same coils as those for measuring the frequency response to add a white magnetic field noise with a bandwidth of 200 Hz and an amplitude of 58 pT/Hz¹/₂ to both of the two OPMs and record the readout of OPM1 at a sampling rate of 40 kSa/s. We divide the noise spectrum density of OPM1 obtained under two different conditions, i.e., without and with field stabilization, to derive the CMRR of the field stabilization.

**Measurement of the spontaneous alpha rhythm signal**

Each measurement takes 180 s. To avoid the problem of synchronization, the person is asked to open (close) his eyes before recording
the data and keep his eyes open (closed) until the recording is finished. The multifunction input/output device US86363 (National Instruments) is used for data acquisition and is controlled with a LabVIEW program. To further confirm that the peak in Fig. 2A around 10 Hz is related to closing eyes, the participant is required to repeat closing and opening his eyes every 30 s to modulate the alpha rhythm signal. We set a 30-s timer around the unshielded MEG system and generate a ticking sound every 30 s. The person then opens or closes his eyes once hearing this sound.

**Measurement of the AEF signal**

For the AEF signal measurement, we need to know the precise time duration between the AEF signal and the auditory stimulus. To do so, we use the MATLAB program to generate auditory stimuli signals in advance and save the sound file to the computer. The time interval between each stimulus is randomly distributed between 0.7 and 1.7 s, and each stimulus is a 440-Hz sinusoidal wave with a time duration of 100 ms. Then, we use the LabVIEW program to play the generated sound file and record the measured magnetic field data at the same time. For each measurement, the time uncertainty between playing the sound and recording the data is less than 1 ms, which has negligible effects for the AEF signal measurement. The transmission of the sound between the loudspeaker and the person makes playing the sound and recording the data is less than 1 ms, which can be compensated with proper data processing. The measured data are filtered with a 0.5- to ~30-Hz band-pass filter.

**Supplementary Materials**

Supplementary materials for this report include 1. Methods of the sound generation and recording, 2. Relationship between the sound and the MEG measurement, 3. MEG signal analysis, 4. Details of the auditory stimulus generation, 5. Details of the MEG measurement setup, and 6. Details of the data analysis.

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