Differences in Global Functional Connectivity During Sound Location Processing: An Auditory MMN Study

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Research Article

Keywords: sound localization, interaural time difference, auditory mismatch negativity, functional connectivity, theta band

Posted Date: March 2nd, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1365081/v1>

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Abstract

Our ability to localize low-frequency sounds relies on interaural time differences (ITD), the sensitivity to which underlies our ability to localize sound sources in azimuth and to segregate competing sound sources across a wide range of situations. However, the cortical representation of ITD has not been well characterized. To investigate differences in evoked cortical potentials and global functional connectivity during the unattended processing of sound localization on the horizontal plane, auditory mismatch negativity (MMN) was recorded and analyzed in adults using a deviant-standard oddball paradigm. A central sound source at the centerline of the horizontal plane (ITD = 0 μ s) was used as the standard stimulus and lateralized sounds with various ITDs were used as deviant stimuli. Characteristics of event-related potentials (ERP) and MMN obtained from young adults were compared between different deviant stimulus groups. The time-frequency (TF) power at each electrode associated with standard and deviant conditions were calculated. Distribution differences of electrode power between standard and deviant stimuli among oddball experiments were compared. Phase lag index (PLI) was also calculated to examine the dynamics of functional connectivity in various deviant stimulus groups. Network topological parameters were calculated to examine the global efficiency of information transfer in different deviant stimulus groups. Results of MMN analysis indicated that sounds with larger deviations from centerline elicited MMNs with greater amplitudes and shorter latencies and the MMN response was stronger in the hemisphere contralateral to the deviant stimulus. Results from the TF analysis showed a significant event-related synchronization (ERS) in the theta frequency band. Results of PLI functional connectivity suggested that the deviant stimulus resulted in a global increase in connectivity in theta band. Increased functional connectivity was found in frontal electrode pairs in sound stimuli towards the central rather than peripheral sound stimuli, and the peripheral sound stimuli revealed a higher global efficiency. This study suggests that the auditory system response in horizontal sound localization appeared to originate from the activity of the theta band. Sound sources with larger deviations from the centerline revealed higher brain network efficiency.

Introduction

Humans use spatial hearing to rapidly localize auditory events in the environment. "Horizontal localization" primarily refers to the localization of a sound source to the left or right, relative to the midline plane¹, i.e., sound lateralization. According to the duplex theory of directional hearing, horizontal localization relies on the neural processing of a variety of acoustical cues, particularly interaural time (ITD) and interaural level differences (ILD)². Specifically, ITD plays a major role in locating sound sources at frequencies below 1500 Hz, but becomes ambiguous at higher frequencies, while ILD only becomes reliable at high-frequencies (> 3000Hz)¹⁻⁴. This apparent cue dichotomy for horizontal localization has been supported by numerous psychoacoustic studies. Previous research found horizontal localization acuity to be best at frontal locations near the interaural midline (at 0° azimuth) with smaller minimum audible angles (MAAs), and deteriorates towards the periphery and the back⁵. It is suggested that a fundamental function of the sensory system is to alert the organism to environmental change. However,

the mechanism of horizontal sound localization is still unclear, with little known about the accuracy of automatic tracking of spatial changes in the human auditory cortex.

Spatial changes in sound location can be detected automatically through the auditory system. In humans, automatic change detection can be reflected by the mismatch negativity (MMN) event related brain potential^{4,6}. Several neuroimaging studies have revealed that deviations in the spatial location of stationary sound sources generated MMN responses, and the stimulus-specific adaptation (SSA) versus MMN generation potentially being able to clarify the issues of horizontal localization⁷⁻⁹. Auditory MMN is a widely used ERP component that reflects pre-attentive auditory processing at a latency of about 100–250ms¹⁰. The neural discriminative response, which is reflected by the MMN, has been used as a tool to study a variety of cognitive disorders in audition. Leon et al. reported that azimuthal spatial displacement is rapidly and automatically represented in auditory sensory memory in humans at the level of the auditory cortex, and humans beings are capable of discerning the locations of sounds as close as 1–10 degrees apart¹¹. Previous studies also suggested that MMN amplitudes may have a linear dependency on the magnitude of spatial deviance, the suspected mechanism being the population rate-based coding of opposing hemifield channels for ITD representation¹²⁻¹⁵. However, the majority of current MMN research focuses primarily on automatic change detection mechanisms being examined with time variables, with little research involving spectral variables and functional connectivity.

It was thought that auditory space was encoded by broadly tuned neurons within each hemisphere of the auditory cortex, activated primarily by sounds coming from the contralateral hemifield. Evidence of a population rate-based opponent process has been revealed from human neuroimaging studies for ITD coding¹⁶⁻¹⁸, however, how the representation of these cues is distributed within and across cortical regions remains controversial¹⁶. Lakatos' experiment with macaque monkeys has shown that the strongest intracortical correlate of the MMN is located in layer 1 of the A1, and was primarily involved in the reset and alignment of theta frequency band neuronal activity to the onset of deviant stimuli¹⁹. In humans, at the level of cortex, neuroimaging studies have indicated that non-primary regions of auditory cortex, in particular the planum temporal and posterior superior temporal gyrus (STG), are sensitive to sound localization stimuli²⁰⁻²³. At the level of the brainstem, the neurons within the inferior colliculus (IC) are sensitive to ITD with the sound location sensitivity of the IC neurons being dependent on the previous sound position²⁴; however, the nature of the underlying local circuitry remains undetermined.

The purpose of this study was to explore the nature of MMN evoked by acoustic stimuli with different ITDs through time variables, spectral variables, and functional connectivity.

Results

MMN Components

The latency and amplitude of MMN waveforms from Cz (Fig. 1A, B) were measured. It was found that larger deviations from center resulted in significantly shorter MMN latencies (L799 vs L450, 138.3 ±

12.5ms vs 158.5 ± 21.2 ms, $t = -3.3$, $P = 0.005$; R799 vs R450, 145.4 ± 13.1 ms vs 156.7 ± 13.8 ms, $t = -2.3$, $P = 0.03$) and significantly greater MMN amplitudes (L799 vs L450, $-3.3 \pm 0.94\mu\text{V}$ vs $-1.9 \pm 0.8\mu\text{V}$, $t = -3.9$, $P = 0.001$; R799 vs R450, $-2.9 \pm 1.2\mu\text{V}$ vs $-1.8 \pm 0.7\mu\text{V}$, $t = -3.6$, $P = 0.003$) for the same side sound stimulus. When a topographic map representing MMN amplitudes at latency ± 5 ms was plotted, a clear contralateral regulation mechanism was observed (Fig. 1C). Statistical analysis (Fig. 1D) revealed that the averaged MMN amplitude was significantly higher in the right hemisphere than the left hemisphere for left-deviant sound stimuli (L799, -1.3 ± 0.3 vs -0.7 ± 0.4 , $t = -2.2$, $P = 0.04$; L450, -1.0 ± 0.3 vs -0.4 ± 0.2 , $t = -3.4$, $P = 0.004$). Similarly, it was significantly higher in left hemisphere than right hemisphere for right-deviant sound stimuli (R799, -1.5 ± 0.3 vs -1.2 ± 0.3 , $t = -2.3$, $P = 0.04$; R450, -0.8 ± 0.4 vs -0.3 ± 0.2 , $t = -3.0$, $P = 0.01$).

Time–Frequency Characteristics

A time-frequency analysis of the EEG activity at Cz electrode suggested that both standard and deviant stimuli elicited increased evoked power in the theta band within 100–400ms after stimulus onset (Fig. 2A, B). Furthermore, the TFD-difference between the responses to standard and deviant stimuli was also significant in the theta band within the post-stimulus period of 100–400ms (Fig. 2C).

The TF-ROI was defined as theta band within 100–400ms. TF distributions were analyzed from all the electrodes. It was revealed that the power distribution of the deviant stimulus (Fig. 3B) was significantly higher than standard stimulus (Fig. 3A) in some regions. The contralateral regulation mechanism could also be observed in regions of differences (Fig. 3C). The EEG energy was mainly concentrated in the right brain area when the auditory system regulated MMN for the left sound source and was opposite for the sound source on the right.

Time Courses of Average PLI

PLIs for all possible pairs of electrodes for delta (1–4 Hz), theta (4–8 Hz), alpha (8–13 Hz), beta (13–30 Hz) and gamma (30–45Hz) frequency band were analyzed. For each time point, PLIs of all pairs at each frequency range were averaged (Fig. 4). Our results suggested clear dynamic changes after stimulus onset only in the theta band for all conditions with higher phase synchronization within 100-400ms.

PLI Functional Connection

Based on the result of the average PLI, a PLI matrix of theta band within the 100-400ms was constructed for all conditions. An intragroup comparison between standard and deviant stimulus was carried out (Figs. 6A and B).

Results further suggested that in the left deviant conditions (ITD = $-799\mu\text{s}$), smaller angles from the centerline (ITD = $-450\mu\text{s}$) had a stronger functional connection, especially for several frontal electrode pairs (Fig. 5A), specifically, electrode pairs AF1–F4 ($P = 0.0005$, $T = 3.9$), PF1-F4($P = 0.003$, $T = 3.3$). Right deviant (ITD = $799\mu\text{s}$ and $450\mu\text{s}$) stimuli also showed a similar functional connection with the frontal electrode pairs (AF1–F4, $P = 0.002$, $T = 3.5$; C1-FP2, $P = 0.001$, $T = 3.6$; C2-FP2, $P = 0.0047$, $T = 3.1$, Fig. 5B).

Global Efficiency

To assess sound location differences in brain network properties during the task, the AUC of global efficiency (Eg) was analyzed (Fig. 6). Findings suggest that the Eg of larger deviations from the center angle was higher than that of smaller deviations from the center angle (ITD = -799 μ s vs ITD = -450 μ s, 0.187 ± 0.006 vs 0.183 ± 0.007 , $t = 2.4$, $P = 0.01$; ITD = 799 μ s vs ITD = 450 μ s, 0.186 ± 0.005 vs 0.180 ± 0.008 , $t = 2.3$, $P = 0.02$).

Discussion

It has previously been shown that spatial MMN depends on the deviance magnitude, which increases monotonically in amplitude and decreases in latency when the difference between the standard and the deviant increases³². However, how cortical activities reflect ITD cues in the auditory space was not clear. In the present study, auditory MMN using frequently occurring stationary midline standards and with infrequent deviant sounds on the horizontal plane was recorded. The MMN components, TF and functional connection analyses were conducted in this study.

Recent studies have shown that the cortex is sensitive to positions of sound sources and MMN amplitudes reflect the spatial separation between standard and deviant sounds^{12,32}. Our results confirmed and reiterated such findings. Our analysis found that the larger deviation from the center angle, the greater amplitude of the MMN and the shorter latency of MMN for the same side sound stimulus (Fig. 1A, B). The topographic maps (Fig. 1C) and the statistics for left and right hemispheres (Fig. 1D) exhibited clear contralateral regulation mechanisms. There are two hypotheses regarding the processing of spatial auditory information: contralateral hemisphere dominance and right-hemispheric dominance, but recent research supports the contralateral dominance hypothesis with the contralateral advantage of the MMN amplitudes not being influenced by the direction of sound motion³³. Our results confirmed the contralateral regulation mechanism. The statistical analysis of MMN amplitude and latency, as well as the comparison with previous results, confirm the reliability of the experimental data.

Previous studies have demonstrated that low-frequency EEG oscillations are influenced by temporal modulations of sensory input³⁴. To measure event-related desynchronization (ERD) and synchronization (ERS), single-trial electrocortical responses in the time domain are usually transformed in TFD. Results of TFD analysis from this study showed the theta band had an obvious ERS to the auditory stimuli between 100 and 400ms (Fig. 2), potentially affecting the parametric track of both externally-presented and internally-generated stimulus-specific information represented within the cortex^{35,36}. The association of theta band activity with sound localization can also be found in animal experiments. Previous research findings in animal models showed that the dominant spectral signature of the monkey MMN made a deviant-related time frequency intertrial coherence (ITC) properties increase focused in the theta band. The strongest intracortical correlate of the MMN located in layer 1 of the A1, and mostly involved in the reset and alignment of theta frequency band neuronal activity to the onset of deviant stimuli¹⁹. In our study, we analyzed the TF-ROI distributions of the entire cap with over 60 electrodes. Our results showed

that the power distribution maxima of the responses to the deviant stimuli with ITDs of $\pm 799\mu\text{s}$ and $\pm 450\mu\text{s}$, were higher than that of the standard stimulus with ITD of $0\mu\text{s}$ (Fig. 3). A clear contralateral regulation mechanism was also observed with the MMN response being stronger in the hemisphere contralateral to the deviant stimulus. These results suggest that theta power might contribute in decoding the spatial characteristics of the sound location in an auditory scene.

The oscillatory phenomena in the EEG frequency band plays a major role in functional communication during cognitive processes³⁶. The present study analyzed ITD-related oscillatory functional connectivity during sound location. Our results suggested that the deviant stimulus condition revealed global increase in connectivity in the theta frequency band (supplementary material). Further, larger deviations from the centerline on the horizontal plane showed a decreased functional connectivity in the frontal electrode pairs (Fig. 5). According to the SSA, the deviant stimulus could elicit a stronger group response from neurons⁷. Our results suggested that the functional communication between cortical areas could be enhanced under deviant stimulus. Furthermore, the theta band has been suggested to involve in the top-down control and coordination of interregional communications^{37,38}. Specifically, theta activity plays a role in directing attention to information of motivational significance^{39,40}. Considering the differences of the functional connectivity between the employed deviant stimuli, the current findings seem to imply that smaller deviation from the center angle engages more top-down modulation of attention to salient features, which is then matched with relevant memory templates to comprehend the affiliative context⁴¹. Speculations can be made that humans require higher attention capacity to distinguish smaller deviations from center line, however, further studies are needed before firm conclusions can be drawn on this particular observation.

The graph theory may explain the neural activity in the brain from the perspective of network and information processing⁴². Our results indicated that a larger deviation from the centerline on the horizontal plane had a higher E_g . The higher E_g of the network typically suggests a faster rate of information transfer between network nodes³⁰. Imaging evidence shows that the activation of brain regions caused by the peripheral sound source is significantly stronger than that of the sound source towards the central^{25,43}. Taken together, these results may suggest that larger deviation from the center line may have higher-order representation of auditory space in the human cortex. It may be that larger deviations may be easier to distinguish, thus, requiring less effort for the brain to complete the cognition process when it perceives the peripheral sound source, which in turn results in a higher global efficiency.

In conclusion, this study examined the characteristics of cortical responses with different ITD cues in an auditory scene. The main contribution was to clarify the characteristics of the global functional connectivity guided by the theta band of the EEG during the sound localization task. These results may have future clinical implications in identifying stimulus parameters that are relevant to spatial discrimination, laying foundational groundwork for novel sound localization algorithms in hearing devices.

Materials And Methods

Participants

Seventeen healthy participants (10 males and 7 females, aged between 22 and 31) were recruited in the experiment. One subject was excluded due to poor data quality. The inclusion criteria for participation included: no history of otological pathologies, noise exposure, family history of otological pathologies, or chronic diseases. Subjects had normal outer and middle ear function and normal hearing, indicated by pure tone air conduction thresholds ≤ 20 dB HL at octave bands between 250 and 8000 Hz. Audiological assessments were performed by experienced clinical audiologists with best practice guidelines. All participants were provided with written informed consent on the details of the study and were compensated for their time in participation. The Medical Research Ethics Committee of Capital Medical University (Beijing, China) approved the study protocol in accordance with the recommendations of the declaration of Helsinki for investigation of human participants.

Stimulus and Presentation

For spatial sound stimulation from different azimuths on the horizontal plane, different ITDs were applied to 500 Hz tone bursts. ITDs used in this study included $-799\mu\text{s}$, $-450\mu\text{s}$, $0\mu\text{s}$, $450\mu\text{s}$ and $799\mu\text{s}$, for five azimuthal positions^{4,25}. Auditory stimuli were generated in MATLAB with a sampling rate of 48.828 kHz and a duration of 800 ms.

An odd-ball stimulation paradigm was used in this study (Fig. 7). Stimuli were delivered via Presentation 0.76 (Neurobehavioral Systems, San Francisco, CA) and through two Sensimetrics S14 insert headphones (Sensimetrics, Malden, MA, USA) at 65 dB SPL. In this study, sound source condition 0° azimuth (ITD = $0\mu\text{s}$) was used for the standard stimulus, whereas conditions with ITD = $\pm 799\mu\text{s}$ and $\pm 450\mu\text{s}$ were used as deviant stimuli, resulting in a total of four oddball sequences, each with a different deviant stimulus. The odd-ball paradigms consisted of 80% standard stimuli and 20% deviant, both presented in random order. The inter-stimulus interval was set at 700 ms. Each recording session consisted of 200 standard and 50 deviant stimuli, which resulted in a total duration of approximately 26.5 minutes.

EEG Acquisition and Analyses

During the experiment, participants sat in a comfortable chair and were instructed to watch a silent movie in an electrically shielded and acoustically attenuated room. They were asked to avoid excessive eye and body movements, and were allowed a short break after each recording session (250 stimuli). EEG data was collected simultaneously using a 64-channel EEG cap connected to a NeuroScan Synamps amplifier (Compumedics, Charlotte, NC, US). A cap based on the 10/20 system with 64 ring-type sintered nonmagnetic Ag/AgCl electrodes was placed on the scalp. Vertical and horizontal electrooculography (EOG) was recorded from an electrode placed 1.5 cm above the outer canthus of the right eye. Sampling rate was 1000 Hz and electrode impedances were kept at or below $5\text{k}\Omega$ for all electrodes. The NeuroScan Curry7 software (Compumedics, Charlotte, NC, US) was used to record and monitor online EEG signals to

ensure data reliability. Segments where differences between maximum and minimum values of each of the 64 channels exceeded 100 μ V was excluded from the analysis.

EEG data was processed using EEGLAB V2021.1 Toolbox in MATLAB (R2020a, MathWorks, Natick, MA, US) and custom MATLAB scripts. First, data was resampled with a sampling rate of 250 Hz and filtered from 1 to 45 Hz using a short, nonlinear, infinite impulse response filter. Recordings were re-referenced to M1/M2 electrodes and extracted to epochs from – 400ms to 700ms relative to the onset of each stimulus. Any epoch with a peak magnitude greater than 90 μ V was rejected. Artifact related to eye blinks and lateral eye movements were cleared from the data using independent components analysis (ICA)²⁶. A principal component analysis was conducted to reduce the dimensionality of the EEG data to 60 independent components (ICs), using the extended infomax algorithm implemented in EEGLAB²⁷. ICs reflecting eye blinks, lateral eye movements, and cardiovascular activity were removed. On average, 3 to 4 components in each recording session were removed by the ICA-based artifact removal.

MMN Analysis

Epochs from each stimulus condition were averaged for each participant. Waveform differences between standard and target stimuli were calculated to obtain the MMN component. If a region of negativity was visibly confirmed on the MMN (deviant minus standard) waveform and its peak was consistent with an MMN topography (frontocentral negativity with reversals in lower temporal-posterior channels), then the peak in 100–200ms was measured as the MMN peak amplitude¹⁴. In addition, we analyzed the amplitude average of the MMN of the left and right hemisphere electrodes and performed statistical analysis to verify contralateral regulation mechanism.

Time–Frequency Analysis

The time–frequency distributions (TFD) of the EEG time course was obtained using a windowed Fourier transform with a fixed 400ms Hanning window²⁸, which provide both sufficient time resolution and frequency resolution within the explored range of frequencies. A time-frequency analysis of the Cz electrode was performed with a baseline correction at 400ms. The main response frequency band and time period during the sound source localization process was used as the region of interest from time–frequency distributions (TF-ROI). The time-frequency distributions were then obtained from all the electrodes to characterize the differences between the standard and deviant stimulus.

PLI Function Connection Analysis

PLIs in the delta (1–4 Hz), theta (4–8 Hz), alpha (8–13 Hz), beta (13–30 Hz) and gamma (30–45 Hz) frequency band were analyzed between 100 and 400ms. The PLI determines functional connectivity by calculating the consistency in the distribution of instantaneous phase differences $\Delta \phi_{i,k}(n)$, defined as:

$$PLI = \left| \frac{1}{S} \sum_{s=1}^S \text{sign}(\Delta \phi(n_s)) \right|$$

1

It examines the consistency of phase difference of S segments, which is defined as:

$$\Delta \phi_{i,k}(n) = \phi_i(n) - \phi_k(n)$$

2

where $\phi_i(n), \phi_k(n)$ indicate phase values of electrode and electrode at time .

PLI ranges between 0 and 1: A PLI of 0 suggests that the two signals are either not coupled or are coupled with a phase difference centered at approximately $0 \bmod \pi$. The PLI of 1 suggests that the two signals are perfectly phase locked at a value of $\Delta \phi$, which is different from $0 \bmod \pi$ ²⁹.

Graph of Theoretical Analysis of Dynamic Network Topologies

Functional connectivity among sensors was measured by computing the PLI for every possible pair during the time window. The resulting non-linear correlation matrices were converted to weighted graphs. To characterize the task-dependent weighted network dynamics, a network G (60×60) for each trial was constructed. Frequency and subject were analyzed with Graph Theoretical Network Analysis (GRETNA) by using the time window identified in the above analysis. Global efficiency (Eg) was calculated to examine the global topological characteristic variations. Each attribute was compared with 100 random networks. A sparsity threshold ($0.068 < S < 0.398$) was applied, which normalized the networks to examine the relative network organization. In addition, task-dependent areas under the curve (AUCs) of global efficiency were calculated to provide a scalar that did not depend on the specific threshold selection³⁰.

Statistical Analysis

The statistical analyses were performed with Statistical Product and Service Solutions (SPSS) 22.0 and GRETNA 2.0.0. The MMN and the global efficiency characteristics (including amplitude and latency) was tested with paired two-sample t-tests. Repeated-measure ANOVAs were carried out separately for the time–frequency (TF) power and TF-ROI (Theta band, 100ms-400ms) power. We carried out the false discovery rate (FDR) correction to correct for the effect of multiple comparisons in neural oscillations. A statistical significance level of 0.05 was used. The functional connection analysis between groups used the two-sample t-test under GRETNA³¹. Family wise error (FWE) correction was used in the comparison between the standard stimulus and the deviant within each group. The comparison between groups was not corrected, and $P < 0.005$ was considered a significant difference.

Limitations And Future Directions

According to the duplex theory of directional hearing, the ITD and ILD provide information on the spatial position of a sound source in the horizontal plane. Specifically, ITD are considered most relevant for localization of low frequency sounds (< 1.5 kHz) and ILD for localization of high frequency sounds (> 3.0 kHz)⁵. In this study, we only considered the ITD in the 500hz band as the acoustic cue. In addition, the

stimulus sequences in the current study could be further improved. Although subjects had enough time to rest between sessions and our pattern of MMN waveforms were similar to previous studies, without the randomization of stimuli presentation sequence, it was still possible that some adverse effects may have happened. In the future, we plan to expand our studies to include sound with higher frequencies and ILD, and optimize the experimental design.

Declarations

Acknowledgements

This work was supported by the National Natural Science Foundation of China [No. 81771909, 81870715].

Competing interests

All authors gave their final approval and agree to be accountable for all aspects of the work. The authors declare that they have no competing interests.

Authors' contributions

S.W. contributed to study conception, design, data analysis and interpretation, statistical analyses, and manuscript writing. C. L. led the designing the research and proofreading the article. M. L. & Z. L. & M. W. & Q. S. contributed to data acquisition and interpretation. J. H. & E. P. contributed in the preparation and revision of the manuscript. The corresponding author S. W. & X. Z. were in charge of designing the research and correcting the article. All authors read and approved the final manuscript.

Data Availability

The datasets generated and/or analyzed during the current study are not publicly available to protect participants confidentiality but are available from the corresponding author on reasonable request.

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Figures

Figure 1

Grand averaged MMN waveform characteristics. Panel A represents grand average MMN waveforms of Cz electrode. Panel B represents the statistical analysis of the amplitude and latency of the Cz-recorded MMN for each ITD. Panel C represents the topographic map of MMN (latency $\pm$ 5ms). Panel D represents the comparison of the averaged MMN amplitudes for the left and right hemisphere electrodes, respectively. L_H represents the left hemisphere and R_H represents the right hemisphere.

Figure 2

Characteristics of time-frequency analysis at Cz electrode. Panels A and B represent the group-level average of the time–frequency distributions (TFD) of the baseline-corrected EEG power (μV^2) at Cz. The color scale represents the average increase (ERS) of oscillation power relative to the pre-stimulus baseline interval. Panel C represents point-by-point statistical tests on TFD, which assess the differential time–frequency characteristics between the standard and deviant stimuli. The color scale represents the statistical p-value (FDR-corrected). Groups were represented by the deviant stimulus condition used in the session (e.g., L799 represents the deviant stimuli with a ITD of -799 μs).

Figure 3

Power distribution characteristics. Panels A and B represent the group-level average of the time–frequency distributions (TFD) obtained from the whole brain electrodes (expressed in μV^2). Color scales represent theta band power of the MMN. Panel C represents results of the statistical analyses of the theta band power difference between the responses evoked by standard and deviant stimuli across all EEG channels and in the 100ms-400ms temporal ROI. Color scale represents the statistical p-value (FDR-corrected). Groups were represented by the deviant stimulus condition used in the session (e.g., L799 represents the deviant stimuli with a ITD of -799 μs).

Figure 4

Time courses of average PLI in the four bands. PLI of each time point (including 100ms before stimulus onset and 400ms after stimulus onset) in the delta\theta\alpha\beta\gamma band. Groups were represented by the deviant stimulus condition used in the session (e.g., L799 represents the deviant stimuli with a ITD of -799 μ s).

Figure 5

Functional connection comparisons between stimuli with different sound source angles. Panel A presents the PLI matrix with deviant stimulus from the left side (ITD = $-799\mu\text{s}$ and $-450\mu\text{s}$). Panel B presents the PLI matrix with deviant stimulus from the right side (ITD = $799\mu\text{s}$ and $-450\mu\text{s}$). Brown lines show larger PLI values in the condition of MMN-L450 (or MMN-R450) than the condition of MMN-L799 (or MMN-R799), $P < 0.005$ uncorrected.

Figure 6

Global efficiency (Eg) of sparsity (Panel A) and the comparison of the area under the curve (AUC) of each group (Panel B). Error bars denote means and standard deviations for Eg. Red dots in the violin chart indicates the average AUC of Eg for each group and * denotes $p < 0.05$.

Figure 7

Schematics of the odd-ball stimuli pattern and the stimuli used in this study. The experiment consisted of four groups with each group using the front sound source (ITD=0us) as the standard stimuli, and the remaining four sounds with non-zero ITDs (ITD=-799us, ITD=-450us, ITD=450us, ITD=799us) used as the deviant stimuli for each group. The figure shows the number of deviant stimuli for each group of experiments, as well as the total number of stimuli and the duration of the experiment. The figure describes the initial 4 stimulus events in each group of the experiment in the green frame. L799 represents deviant stimuli with a ITD of -799 μ s, L450 represents deviant stimuli with a ITD of -450 μ s, R450 represented deviant stimuli with a ITD of -450 μ s, L799 represented deviant stimuli with a ITD of -799 μ s and C0 represented deviant stimuli with a ITD of 0 μ s.

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