Unveiling Auditory Evoked Processing: Bridging MEG and EEG

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Abstract

Auditory perception is essential for human communication and development, influencing cognitive and social functions. Electroencephalography (EEG) has long been used to examine auditory evoked potentials (AEPs), while magnetoencephalography (MEG) has more recently enabled the investigation of auditory evoked fields (AEFs), providing complementary spatial detail. However, MEG's high costs and operational complexity limit its accessibility. In this study, we adapted analysis protocols originally developed for MEG to EEG in order to explore their applicability in a more accessible and cost-effective modality. We examined auditory evoked potentials in response to instrumental tones among adults (N=12) using EEG and compared the results with previously published MEG data. Our findings suggest that EEG can approximate MEG-based methodologies, demonstrating similar mean latencies and standard errors for P1, N1, and P2 components. Despite slight variations in standard errors, likely due to the smaller sample size, the results support EEG's continued value for broader application in auditory neuroscience. The accessibility of EEG opens opportunities for large-scale studies, enhancing our understanding of auditory perception across diverse populations. This approach may also contribute to the development of diagnostics and tailored interventions for auditory-related conditions, including ADHD and dyslexia.

Keywords: auditory-evoked potential, auditory perception, EEG

Introduction

Auditory perception plays a central role in human development and communication processes, contributing to cognitive and social functions. In previous research, we used a Neuromag-122 whole head MEG system to record auditory evoked fields (AEFs) in response to different instrumental tones. These stimuli evoke the primary auditory response (P1) within approximately 30-80 ms after tone onset, followed by secondary auditory responses (N1 and P2) that typically manifest at approximately 90-250 ms after tone onset (Schneider et al., 2005).

Musical stimuli affect auditory evoked potentials, particularly the P1, N1, and P2 components (Kühnis et al., 2014; Lee et al., 2024). Musical training enhances these components, reflecting improved auditory processing and sensory specialization. The P1 component is influenced by metrical context and musical training (Polat & Ataş, 2014), while the N1 component is shaped by musical expertise and spectral complexity (Shahin et al., 2005). These findings highlight the profound impact of musical experience on auditory processing capabilities.

Particularly the synchronization and asynchrony of auditory evoked responses play a key role in populations with neurodevelopmental conditions. Asynchrony in AEFs, for instance, has been linked to deficits in auditory processing, which may underlie challenges in language acquisition, attention, and literacy (Groß et al., 2022; Schneider et al., 2022; Seither-Preisler et al., 2014; Serrallach et al., 2016, 2022). Our previous research has identified significant asynchronies in auditory cortex activation and subtype-specific processing differences in individuals with ADHD (Seither-Preisler et al., 2014; Serrallach et al., 2016, 2022). These insights underline the importance of precise neurofunctional assessment tools. However, the use of MEG is confined to specialised facilities due to its high-cost, technical complexity, and the requirement for magnetically shielded environments to minimise external interference. In contrast, EEG provides a more practical and cost-efficient method for investigating auditory processing, particularly in paediatric and clinical populations. Building on this rationale, the present study aimed to evaluate whether analytical strategies developed for MEG could be effectively transferred to EEG.

Therefore, we developed a pilot study to adapt and validate MEG methodologies for EEG. This study aimed to determine whether EEG could reliably replicate the temporal and spatial characteristics of auditory responses observed in MEG, laying the groundwork for more accessible auditory neuroscience research, including research involving ADHD, dyslexia, and other auditory related conditions

Methods

Participants

Twelve healthy adults (3 male, 9 female) participated in the study. Participants' age ranged from 42 to 58 years (M = 48.9, SD = 4.7). None of them had history of neurological or psychiatric disorders. Written informed consent was obtained from all individuals prior to participation. The study was conducted in accordance with the guidelines of the Declaration of Helsinki, and approved by the Institutional Review Board of the Medical Association of Riga (Latvia) 2-PĒK-4/3/2022.

Measures

The study employed auditory stimuli consisting of seven instrumental tones (piano, guitar, flute, bass clarinet, trumpet, violin, and drums) and four synthetically generated harmonic complex tones. The aim was to compare EEG-derived auditory evoked potentials (AEPs) with published MEG data to evaluate consistency in temporal resolution (see Figure 1).

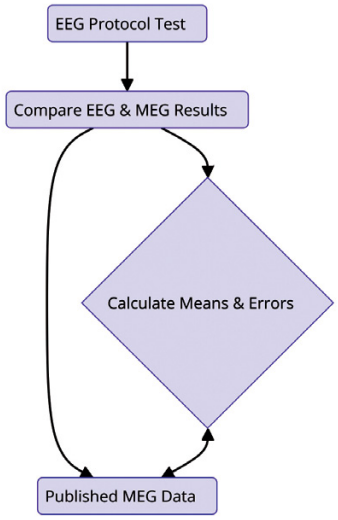

Figure 1. MEG-EEG workflow

The MEG protocols (Bücher et al., 2023; Christiner et al. 2022; Groß et al., 2022; Schneider et al., 2005; Seither-Preisler et al., 2014; Serrallach et al., 2016) used as a basis for this study were adapted to account for the technical and functional differences between MEG and EEG. MEG measures magnetic fields generated by neural activity using superconducting quantum interference devices (SQUIDs) and requires a magnetically shielded room to ensure accuracy. In contrast, EEG records electrical potentials at the scalp using electrodes, which are more susceptible to noise and artefacts from non-neural sources. To address these challenges, we implemented the following adaptations:

Electrode placement. EEG recordings were obtained using the Neuroelectrics Enobio 32 system, which provides 32 channels of data at a temporal resolution of 500 Hz. A standard gel-based 32-channel electrode cap was used, with electrodes positioned according to the extended international 10–20 system, ensuring comprehensive scalp coverage and comparability across studies in accordance with established electrophysiological guidelines (Klem et al., 1999; Oostenveld & Praamstra, 2001). Electrode positions included frontal (Fp1, Fp2, F3, F4, Fz), central (C3, C4, Cz), temporal (T7, T8), parietal (P3, P4, Pz), occipital (O1, O2), as well as intermediate sites (e.g., FC1, FC2, CP1, CP2, PO3, PO4) to enhance spatial resolution over auditory-relevant cortical areas. The system employed gel-based electrodes to ensure low impedance and high signal stability. Signals were amplified and digitised using a compact NECBOX amplifier unit attached to the back of the cap. EEG data were wirelessly transmitted to the Neuroelectrics Instrument Controller (NIC) software (version 2.0.11.1) on a recording computer. To improve signal quality and reduce preparation time, participants' skin was cleaned prior to electrode application, and electrode impedance was checked and maintained below standard thresholds. Electrode placement was designed to optimize coverage of the auditory cortex bilaterally, with particular attention to temporal and centro-parietal sites. This setup allowed for reliable capture of auditory evoked potentials (AEPs) while maintaining participant comfort and data integrity, particularly critical when working with developmental and clinical populations.

Signal processing. EEG data were recorded at a sampling rate of 1000 Hz using the Neuroelectrics Enobio 32 system. A hardware bandpass filter

from 0.0 Hz (DC) to 330 Hz was applied during acquisition using the Neuroelectrics Instrument Controller (NIC) software (v2.0.11.1), and raw data were stored for offline analysis. Further preprocessing and analysis were conducted using BESA Research (Version 7.1; BESA GmbH, Gräfelfing, Germany). EEG epochs were segmented from −100 ms to 400 ms relative to the auditory stimulus onset, and baseline-corrected using the −100 to 0 ms pre-stimulus interval. Artefact correction was performed using BESA's automatic artefact scan tool, which identified and excluded epochs containing eye blinks, saccades or muscle artefacts. On average, 5–10% of trials and 2–5 channels per participant were excluded and subsequently interpolated using spherical spline interpolation where necessary. Following artefact rejection, data were averaged per subject across all stimulus types to ensure a high signal-to-noise ratio. The components of interest (P1, N1, and P2) were identified based on grand-average waveforms across midline and lateral fronto-central electrodes (e.g., Cz, FCz, C3, C4, T7, T8). Peak latencies were extracted individually.

Spatial resolution and source localization. Source localization was performed using current density reconstruction (CDR) within BESA Research 7.1, based on a four-shell spherical head model. Dipole fitting procedures were used to extract source waveforms from bilateral auditory cortices. Regional sources were placed bilaterally in the auditory cortex and fitted around the P1, N1, P2 peak using BESA's dipole fitting procedures. Dipole orientations were optimized to maximize field strength toward the vertex. For each participant, source waveforms were extracted from the left and right auditory cortices, and the peak latency of the P1-N1-P2 complex was determined. To ensure consistency with previous MEG studies used for reference comparisons (Christiner et al., 2022; Serrallach et al., 2016, 2022), the analysis focused exclusively on latency parameters, as amplitude values were not reported systematically across all datasets.

Stimulus presentation. Auditory stimuli consisted of a total of eleven samples: seven instrumental tones (piano, trumpet, flute, plucked violin, bass, clarinet, and timpani) and four synthetically generated harmonic complex tones. Each stimulus had a duration of 500 ms and was presented in a pseudo-randomized order with interstimulus intervals ranging from 400 to 500 ms. Every tone was presented 100 times, resulting in a total duration of approximately 15 minutes per session. Stimuli were delivered binaurally via calibrated headphones at a comfortable listening level. Participants were instructed to listen passively to the stimuli while remaining as still as possible. This paradigm was chosen to ensure comparability with MEG protocols previously published by the group (e.g., Seither-Preisler et al., 2014; Serrallach et al., 2016), where auditory evoked responses were likewise elicited under passive listening conditions with matching stimulus parameters. The high number of stimulus repetitions was selected to ensure a high signal-to-noise ratio, which is essential for robust component identification and waveform averaging in both MEG and EEG. For the present pilot analysis, responses across all tone types were merged for averaging, focusing on the extraction of the most prominent auditory components (P1, N1, P2). This strategy allowed direct comparison of temporal response characteristics with existing MEG data.

To ensure comparability with previous MEG studies, the auditory stimulation protocol was implemented using a custom MATLAB-based application designed to ensure millisecond-accurate presentation and trigger synchronization with the EEG system. The presentation software was re-coded to ensure consistent stimulus onset, interstimulus intervals, and synchronization with EEG triggers. Originally optimized for magnetically shielded MEG environments, the output was converted for EEG-compatible delivery via calibrated in-ear headphones using a USB interface. These modifications ensured that the temporal properties of the stimulus protocol—previously validated in MEG contexts—could be reliably transferred to the EEG recording environment.

The pilot study replicated key elements of the MEG experimental design, including the temporal structure and intensity of auditory stimuli. AEPs corresponding to the P1, N1, and P2 components were recorded and analysed. Latency values derived from EEG were then compared to MEG findings reported in previously published studies. Reference means for P1 (6 means), and for N1 and P2 (5 means each), were established by aggregating data from three MEG studies (Bücher et al. 2022; Christiner et al. 2022; Serrallach et al. 2022) with similar methodologies. The overall mean served as a reference for comparison with our EEG-derived latencies using a one-sample *t*-test.

Results

The analysis of EEG-derived AEPs revealed mean latency values for the P1, N1, and P2 components that closely aligned with those observed in previous MEG studies. Figure 2 illustrates the latency mean values with standard errors derived from EEG for P1, N1, P2.

The mean P1 latency in our sample (M = 63.3 ms [right], SE = 2.2) did not differ significantly from the calculated reference value (M = 64.5 ms [right]). The one-sample t-test yielded $t(11) = -0.54$, $p = 0.60$. The mean P1 latency in our sample (M = 65.2 ms [left], SE = 3.2) did not differ significantly from the calculated reference value (M = 64.6 ms [left]). The one-sample t-test yielded $t(11) = 0.18$, $p = 0.86$.

The mean N1 latency in our sample (M = 118.6 ms [right], SE = 2.8) did not differ significantly from the calculated reference value (M = 113.4 ms [right]). The one-sample t-test yielded $t(11) = 1.86$, $p = 0.09$. However, the mean N1 latency in our sample (M = 121.5 ms [left], SE = 3.2) differed significantly from the calculated reference value (M = 112.8 ms [left]). The one-sample t-test yielded $t(11) = 2.67$, $p = 0.02$.

The mean P2 latency in our sample (M = 210.2 ms [right], SE = 7.3) did not differ significantly from the calculated reference value (M = 199.8 ms [right]). The one-sample t-test yielded $t(11) = 1,41$, $p = 0.19$. The mean P2 latency in our sample (M = 204.77 ms [left], SE = 17.77) did not differ significantly from the calculated reference value (M = 204.61 ms [left]). The one-sample t-test yielded $t(11) = 0.01$, $p = 0.99$.

While P1 and P2 latencies showed no significant differences compared to MEG-derived methods, N1 left latencies differed significantly, potentially due to our small sample size (n = 12) and the variability of aggregated N1 reference values from multiple publications (range: 107.8–121.5 ms). Notably, the highest reference value (121.5 ms) closely aligns with our observed value, suggesting methodological consistency despite the left-lateralized discrepancy.

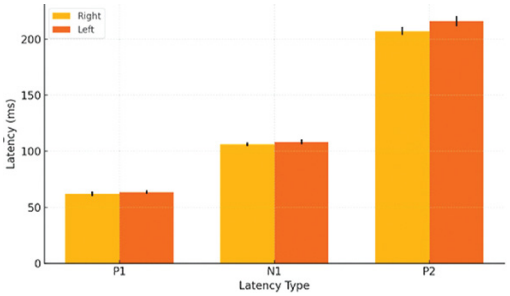

Figure 2. P1, N1, P2 Latency mean values with standard errors derived from EEG

Discussion

The present pilot study explored whether EEG protocols, adapted from MEG paradigms, can yield robust auditory evoked potentials (AEPs) with comparable temporal characteristics. The observed latencies for P1, N1, and P2 components were largely consistent with established MEG findings, suggesting that EEG may serve as a feasible and more accessible method for investigating auditory processing. This approach could be particularly relevant for studies in populations where MEG use is limited due to accessibility, cost, or participant compliance.

While the current sample size limits generalizability, this study demonstrates the technical feasibility of transferring MEG-derived stimulus and analysis protocols into EEG frameworks. These adaptations could enable broader adoption of temporally precise auditory neurophysiological testing across research and clinical settings.

Future research should aim to expand the methodology to neurodivergent populations such as individuals with ADHD and dyslexia, in whom atypical auditory asymmetries have previously been reported (Seither-Preisler et al., 2014; Serrallach et al., 2016, 2022). Longitudinal applications may further support the use of AEPs in tracking developmental or treatment-related changes. In addition, combining EEG with imaging modalities such as fMRI or structural MRI may enhance spatial interpretability.

Although the present results do not directly evaluate the use of AEPs in therapeutic settings, the protocol's non-invasive nature, passive task demands, and temporal specificity suggest potential for clinical and educational use. For example, identifying atypical auditory timing profiles may inform early screening and automated tools or guide individualized interventions (Holt & Özdamar, 2014; Manta et al., 2022). In this regard, music therapy training programs could benefit from integrating fundamental neurophysiological concepts—such as temporal synchrony, hemispheric asymmetry, and neural response plasticity—into their curricula (Bosse et al., 2013; Jackson, 2003; Neuhaus, 2020; Rickson, 2006; Rothmann et al., 2014; Sanju & Kumar, 2016; Timmermann & Oberegelsbacher, 2008). Such translational bridges between auditory neuroscience and clinical practice require further empirical work but represent a promising direction for interdisciplinary collaboration.

Conclusion

To the best of our knowledge, this study represents one of the first systematic attempts to apply EEG methodology in a direct replication of MEG-based auditory paradigms. Our findings suggest that key elements of MEG protocols—particularly in the elicitation and analysis of auditory evoked responses—can be effectively transferred to EEG, yielding temporally reliable results for the P1, N1, and P2 components.

The main advantage of this approach lies in the accessibility and cost-efficiency of EEG, which enables its application in larger and more diverse samples. This, in turn, increases statistical power and allows for the investigation of individual differences in auditory processing. Moreover, the feasibility of source localization within EEG supports its potential as a tool for capturing interhemispheric timing asymmetries and functional dynamics of the auditory system.

By expanding neurofunctional research beyond the constraints of specialized MEG laboratories, EEG can contribute to a more nuanced understanding of auditory perception across different populations. In the long term, this may support the development of targeted assessments and personalized interventions for conditions involving auditory processing deficits, such as ADHD or dyslexia. While further validation in clinical groups is required, the present findings provide a methodological foundation for such translational research.

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