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Research Report

Temporal resolution properties of human auditory cortex: Reflections in the neuromagnetic auditory evoked M100 component

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ABSTRACT

Previous work has provided evidence for a brief, finite (~35 ms) temporal window of integration (TWI) in M100 formation, during which stimulus attributes are accumulated in processes leading to the M100 peak. Here, we investigate resolution within the TWI by recording responses to tones containing silent gaps (0–20 ms). Gaps were inserted in 1 kHz tones in 2 conditions: +10 ms post-onset (10 ms masker) wherein the masker and gap of longest duration (20 ms) were contained within the initial 35 ms of the stimulus and +40 ms (40 ms masker) wherein all gaps were inserted +40 ms post-onset. Tones were presented binaurally and responses sampled from both hemispheres in 12 adults using a twin 37-channel biomagnetometer (MAGNES-II™, BTi, San Diego, CA). *Results*—10 ms masker: M100 latency was prolonged and amplitude decreased as a function of gap duration, even with the shortest duration (2 ms) gap, indicating that integrative processes underlying M100 formation are sensitive to fine-grained discontinuities within a brief, finite TWI. *Results*—40 ms masker: M100 latency and amplitude were unaffected by gaps inserted at +40 ms, providing further evidence for an M100 TWI of <40 ms. *Conclusion*: within a brief integrative window in M100 formation, population-level responses are sensitive to discontinuities in sounds on a scale corresponding to psychophysical detection thresholds and minimum detectable gap thresholds in single unit recordings. Cumulatively, results provide evidence that M100 resolution for brief fluctuations in sounds reflects temporal acuity properties that are both intrinsic to the auditory system and critical to the accurate perception of speech.

1. Introduction

The temporal resolution of the auditory system is exquisite, with neural systems capable of submillisecond resolution in decoding features in the acoustic signal (Eggermont, 2001). The high level of resolution in auditory cortical systems provides the ability to resolve fine-grained, transient fluctuations in the temporal envelope of sounds, critical to the accurate perception of speech. Psychophysical investigations of auditory perceptual acuity frequently employ gap detection paradigms, where a silent gap is inserted in a tone or noise burst, and the minimum detectable gap is measured (Eddins et al., 1995; Moore, 1993). Lowest thresholds (<10 ms) are typically obtained for within-channel or isofrequency stimuli, where

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the spectral contents in the signal before and after the gap are identical (Formby et al., 1998; Phillips et al., 1997). Psychophysical measures of gap detection correlate with speech perception acuity (Naetaenen and Picton, 1987; Phillips and Smith, 2004), and thus, it may be that similar or overlapping neural processes are employed both in detecting brief silent gaps and in resolving the fine structure of the speech signal. Evidence in support of this notion is provided in clinical studies where poor performance on gap detection tasks is diagnostic in hearing disorders such as auditory neuropathy, where peripheral function is intact but speech perception is impaired (Zeng et al., 1999).

Non-invasive measures of human auditory function have been conducted using Magnetoencephalographic (MEG) recording. MEG, with millisecond temporal resolution, is well suited for recording neural responses to stimuli with fine-grained contrasts (Naetaenen and Picton, 1987; Sams and Hari, 1991). MEG studies have shed light on the spectrotemporal resolving properties of subcomponents in the auditory evoked field (AEF), such as the M100, occurring ∼100 ms post-stimulus onset with a modeled source that localizes to auditory cortex (Lutkenhoner and Steinstrater, 1998; Naetaenen and Picton, 1987; Sams and Hari, 1991). The M100 component is sensitive to stimulus properties at the onset of sounds within a brief (<40 ms) and finite temporal window of integration (Gage and Roberts, 2000). While the neural processes underlying the formation of the M100 are sensitive to stimulus features such as peak intensity and integrated energy within the temporal window of integration, it is stimulus *presence*, or on-time, that dominates the amplitude of the M100 (Gage and Roberts, 2000). The temporal resolution of neural processes to brief discontinuities—or the *absence* of a stimulus—within this window of integration has not been elucidated to date and forms the focus of the present investigation.

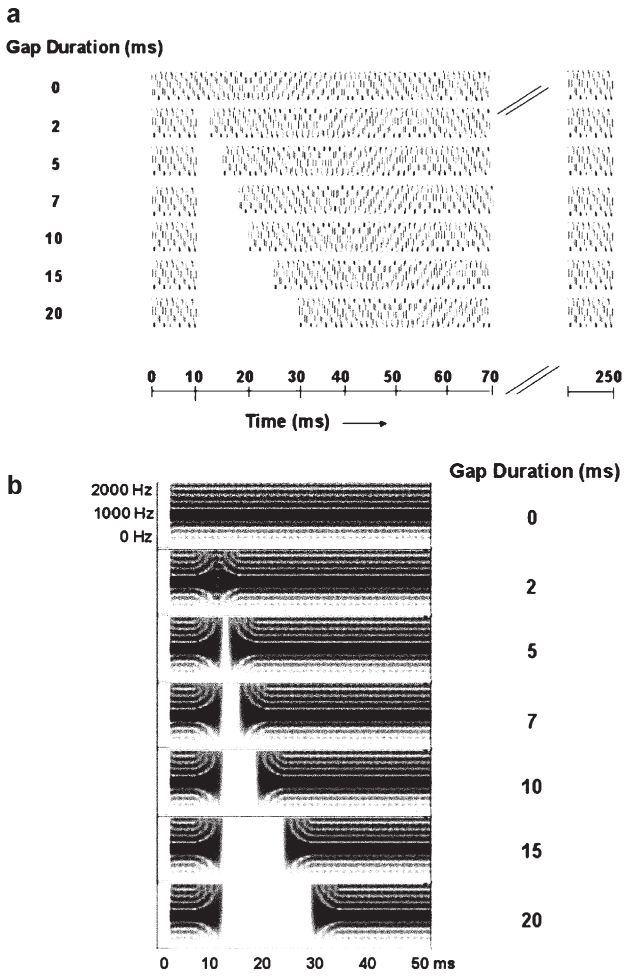

Fig. 1 – Sinusoidal 1 kHz tone stimuli of 250-ms duration presented in the experimental (10 ms masker) condition. All tones were generated at constant amplitude, equivalent to 70 dB SPL. Silent gaps of 2-, 5-, 7-, 10-, 15-, and 20-ms duration were inserted at a point +10 ms post-stimulus onset. Waveforms of the initial 70 ms of the tonal stimuli are presented in the upper panel (a), with *y*-axis representing the amplitude of the sinusoids and *x*-axis representing time in units milliseconds; spectra of the initial 50 ms of the stimuli are presented in the lower panel (b), with *y*-axis representing the frequency of the tones in units Hertz and *x*-axis representing time in units milliseconds.

Here, we investigated the sensitivity of the integrative processes leading to M100 formation by inserting brief gaps of silence in tones. Stimuli consisted of 1 kHz sinusoidal tones containing gaps of silence of varying duration [2,5,7,10,15,20 ms] in two experimental conditions. In the first condition, gaps were inserted at a point +10 ms from stimulus onset (the 10 ms masker condition, see Fig. 1). In this condition, the initial 10 ms masker as well as the gap of longest duration (20 ms) lie within the ∼35 ms temporal window of integration for the M100. Our prediction in this condition was that the insertion of silent gaps would modulate the latency and amplitude of the M100 component. In the second condition, gaps were inserted at a point +40 ms post-onset (the 40 ms masker condition). In this condition, the gaps lie beyond the M100 temporal window of integration, and our prediction was that they would not affect M100 latency or amplitude, providing further evidence for a ∼35 ms temporal window of integration for the M100.

2. Results

All stimuli reliably elicited an M100 evoked field response in each hemisphere, with an underlying modeled source in auditory cortex. Data from 3 subjects did not meet the dipole fit correlation criterion and were excluded from further analysis. Data for the remaining 9 subjects were analyzed using repeated measures analysis of variance (ANOVA) with an alpha level of 0.05. Four of the subjects also participated in the control condition, where the gaps were inserted at +40 ms post-tone onset. Results for this condition are presented separately, below, in the 40 ms Masker section. See Fig. 2 for characteristic AEFs in the left hemisphere for the 10 ms masker (upper panels) and the 40 ms masker (lower panels) conditions.

2.1. *10 ms masker results*

2.1.1. *M100 latency*

An effect of gap duration was statistically significant ($F_{6,48} = 20.58$, $P < 0.0001$): M100 latency was prolonged in a

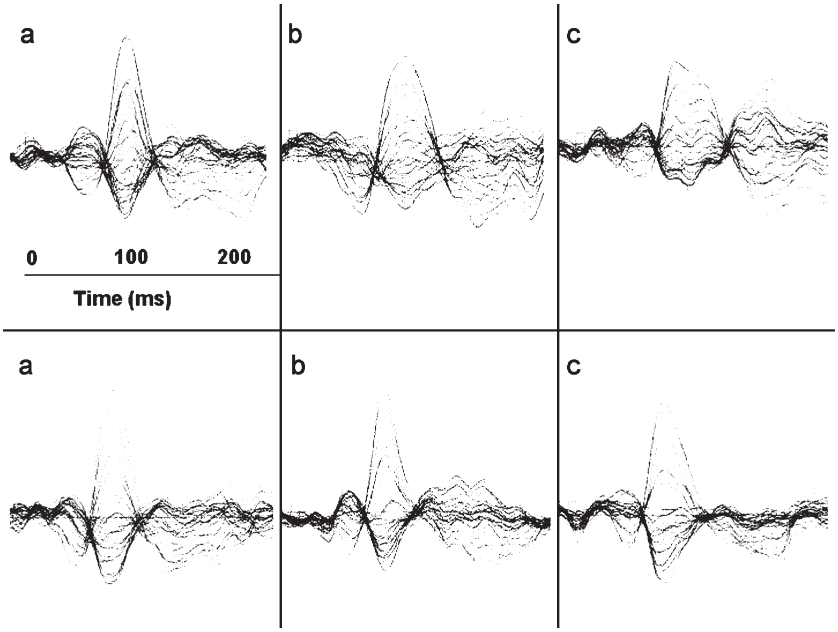

Fig. 2 – Auditory evoked neuromagnetic fields recorded in the left hemisphere in one representative subject in response to a 1 kHz tone with (a) no gap, (b) a gap of 10 ms, and (c) a gap of 20 ms. The upper panel depicts auditory evoked fields in the experimental (10 ms masker) condition. The lower panel depicts auditory evoked fields in the control (40 ms masker) condition.

nearly linear manner as a function of gap duration in both the left (r^2 = 0.93) and the right (r^2 = 0.99) hemispheres (see Fig. 3a). M100 latencies in the left hemisphere were slightly longer (*M* = 121.1, SEM = 2.8) than those in the right (*M* = 119.2, SEM = 3.0), however, this effect was not statistically significant ($F_{1,8}$ = 0.58, *P* = 0.47). The hemisphere × gap interaction was not statistically significant ($F_{1,6}$ = 0.39, *P* = 0.88).

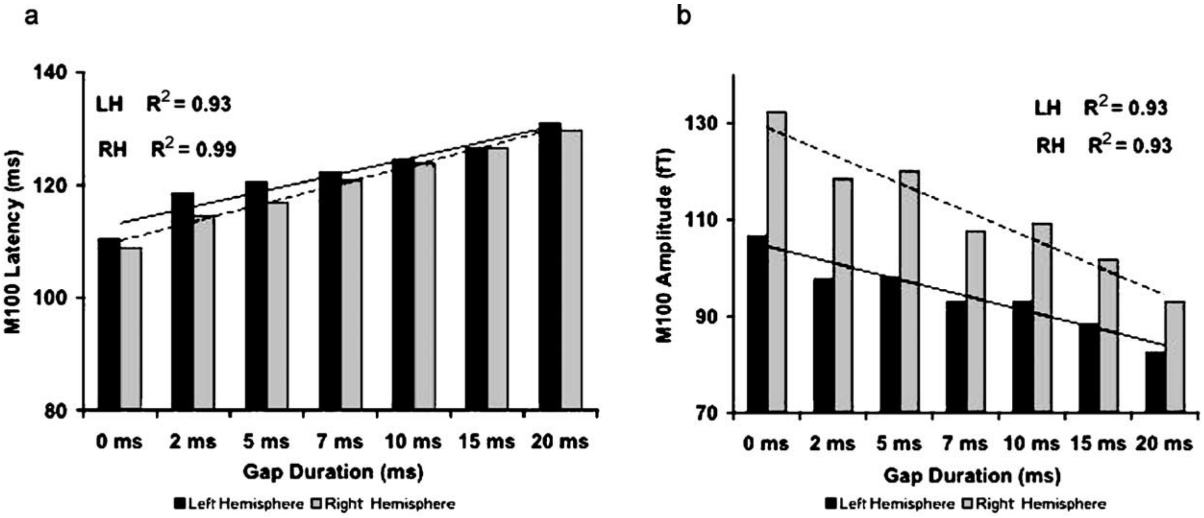

Fig. 3 – (a) Mean M100 latency in the left and right hemispheres for 9 subjects in response to 1 kHz tones in the 10 ms masker condition. The latency (in ms) of the M100 peak is represented on the vertical axis, tones with gaps of varying duration are represented on the horizontal axis. Solid black columns represent M100 latency for the left hemisphere, shaded grey columns represent M100 latency for the right hemisphere. Curves reflect fits (r^2) to a linear function (Left Hemisphere curves are represented by a solid line, Right Hemisphere curves are represented by a dashed line). (b) Mean M100 amplitude in the left and right hemispheres for 9 subjects in response to 1 kHz tones in the 10 ms masker condition. The amplitude (in fT) of the M100 peak is represented on the vertical axis, tones with gaps of varying duration are represented on the horizontal axis. Solid black columns represent M100 latency for the left hemisphere, shaded grey columns represent M100 latency for the right hemisphere. Curves reflect fits (r^2) to a linear function (Left Hemisphere curves are represented by a solid line, Right Hemisphere curves are represented by a dashed line).

2.1.2. *M100 amplitude*

An effect of gap duration was statistically significant ($F_{6,48}$ = 6.80, P < 0.0001): M100 amplitude decreased in a nearly linear manner as a function of gap duration in both the left (r^2 = 0.93) and the right (r^2 = 0.93) hemispheres (see Fig. 3b). M100 amplitude in the right hemisphere was slightly higher (M = 115.1, SEM = 11.9) than in the left (M = 97.7, SEM = 12.5), however, this effect was not statistically significant ($F_{1,8}$ = 1.74, P = 0.22). The hemisphere × gap interaction was not statistically significant ($F_{1,6}$ = 1.08, P = 0.39).

2.2. *40 ms masker results*

2.2.1. *M100 latency*

In the 40 ms masker control condition, M100 latency was not modulated by gap duration in either hemisphere ($F_{6,18}$ = 0.91, P = 0.49, see Fig. 4a). The effect of hemisphere was statistically significant ($F_{1,3}$ = 4.21, P = 0.04): M100 latencies in the left hemisphere were longer (M = 110.6, SEM = 3.8) than those in the right (M = 107.4, SEM = 2.7), however, the hemisphere × gap interaction was not statistically significant ($F_{1,6}$ = 0.41, P = 0.87).

2.2.2. *M100 amplitude*

In the 40 ms masker control condition, M100 amplitude was not modulated by gap duration in either hemisphere ($F_{6,18}$ = 0.06, P = 0.99, see Fig. 4b). M100 amplitude was slightly higher in the right hemisphere (M = 131.8, SEM = 7.40) than in the left (M = 118.0, SEM = 9.57), however, this effect was not statistically significant ($F_{1,3}$ = 1.04, P = 0.31). The hemisphere × gap interaction was not statistically significant ($F_{1,6}$ = 0.08, P = 0.99).

3. Discussion

In this investigation, we assessed the resolution of the integrative processes underlying the auditory M100 component for detecting brief discontinuities in sounds. In the 10 ms masker condition, both latency and amplitude of the M100 component were modulated in a nearly linear manner as a function of gap duration (see Fig. 3). Our results provide evidence that the integrative processes underlying the M100 are highly sensitive to fine-grained temporal discontinuities in sounds: M100 latency in both hemispheres was prolonged, and peak amplitude was reduced by even the briefest (2 ms) gap. In the control (40 ms masker) condition, the lack of M100 modulation by gaps inserted at a point +40 ms post-stimulus onset (see Fig. 4) provided further evidence for a finite temporal window of integration in the neural processes leading to the formation of the M100. Together with the results in the 10 ms masker condition, these data provide evidence that the neural processes underlying the M100 are highly sensitive to discontinuities in signals within a brief (~35) and finite integrative window.

The M100 component is also highly sensitive to brief discontinuities in the temporal envelope of speech sounds that mark voice onset time (VOT) contrasts (Simos et al., 1998). These results combine with our findings reported here to provide evidence that the M100 component has a high level of sensitivity to discontinuities in the sound signal, whether they occur as brief silent gaps in sinusoidal tones or in temporal fluctuations in the envelope of complex speech. The selective activation of the M100 for some stimulus features, such as periodicity and formant transitions, and not others, such as absolute sound level within a normal listening range, has led

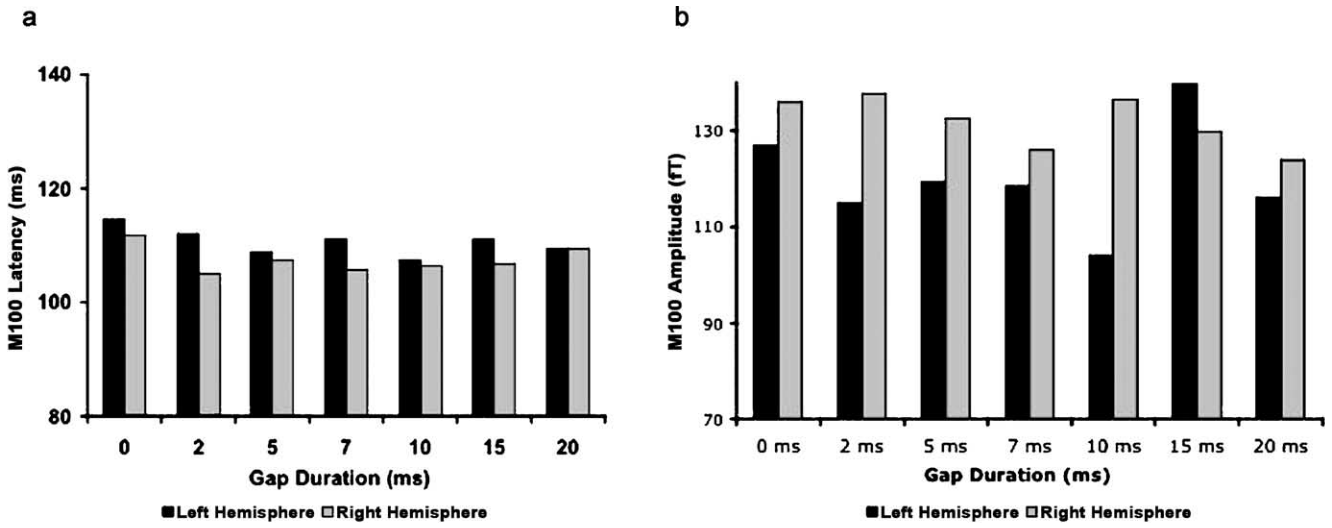

Fig. 4 – (a) Mean M100 latency in the left and right hemispheres for 4 subjects in response to 1 kHz tones in the control (40 ms masker) condition. The latency (in ms) of the M100 peak is represented on the vertical axis, tones with gaps of varying duration are represented on the horizontal axis. Solid black columns represent M100 latency for the left hemisphere, shaded grey columns represent M100 latency for the right hemisphere. (b) Mean M100 amplitude in the left and right hemispheres for the same 4 subjects in response to 1 kHz tones in the 40 ms masker condition. The amplitude (in fT) of the M100 is represented on the vertical axis, tones with gaps of varying duration are represented on the horizontal axis. Solid black columns represent M100 latency for the left hemisphere, shaded grey columns represent M100 latency for the right hemisphere.

to its description as an intermediate processing stage between sensory (acoustic) and perceptual (representational) processing (Diesch et al., 1996). Thus, it may be the case that the neural processes underlying M100 formation reflect feature extraction mechanisms that are invoked for detecting discontinuities both in simple (such as tones) and complex (such as speech) signals. While future work is needed to elucidate the neural networks underlying gap detection and speech perception, our findings indicate that the M100 reflects underlying auditory temporal processing mechanisms employed both in gap detection in simple sounds and VOT encoding in speech.

Our findings of M100 modulation by the shortest (2 ms) gap in the 10 ms masker condition are in good accord with psychophysical measures of gap detection thresholds (at 2–10 ms) for similar within-channel stimuli (Formby et al., 1998; Phillips and Smith, 2004; Phillips et al., 1997). Psychophysical measures of gap detection are in wide use as an objective method with which to evaluate auditory temporal acuity in both healthy and clinical populations (Moore, 1993; Zeng et al., 1999). A key reason for their widespread use is the relationship between performance on a gap detection task and speech perceptual acuity, with poor performance on gap tasks corresponding to impaired speech perception. While gap detection paradigms typically use tones or noise bursts as stimuli, rather than complex speech sounds, performance on these tasks relates nevertheless in a straightforward manner to speech perception abilities both for healthy listeners and for listeners with hearing impairment (Moore, 1993; Phillips, 1999). In clinical populations, for example, elevated gap detection thresholds provide important information about possible deterioration of, or damage to, auditory temporal processes leading to speech perception impairment in aging (Snell and Frisina, 2000) and in diseases affecting myelination, such as auditory neuropathy (Zeng et al., 1999) and multiple sclerosis (Rappaport et al., 1994). Cumulatively, these findings provide evidence that the neural mechanisms underlying gap detection performance and those for speech perception have at least some overlap in auditory cortical processing.

Our findings of M100 modulation by the shortest gap (2 ms) tested are also in good accord with animal studies of auditory cortical temporal acuity, where gap detection thresholds have been measured using electrophysiological methods to record activity in single or cluster units. A key result of those studies is that the firing patterns of neurons in auditory cortex reflect minimum detectable gap thresholds that are similar in scale (at 2–10 ms) to thresholds measured psychophysically in human (Eggermont, 1999, 2000; Phillips et al., 1997). Our MEG findings reported here provide evidence for a similar level of temporal resolution to brief (2 ms) discontinuities in sounds in the synchronized neural response of tens of thousands of neurons in secondary auditory cortical fields (Naetaenen and Picton, 1987), reflecting neural response properties at the population level in auditory cortex.

4. Conclusions

We report a brief and finite integrative window in the neural processes underlying M100 formation. Within this brief window, population-level neural responses are highly sensitive to discontinuities in sounds on a scale that corresponds to gap detection thresholds measured psychophysically as well as minimum detectable gap thresholds measured in single units using electrophysiological methods. Cumulatively, these results provide evidence for a high level of temporal resolution for brief fluctuations in the envelope of sounds that reflects temporal acuity properties that are both intrinsic to the auditory system and critical to the accurate perception of speech.

5. Experimental procedures

5.1. *Subjects*

Twelve right-handed healthy adult native English speakers (7 male, 28–46 years) volunteered to participate in the experiment. Stimulus presentation and MEG recording were performed with the approval of the institutional committees on human research at UC Irvine and at UC San Francisco. Informed written consent was obtained from each subject. All 12 subjects participated in the main experiment, 4 (2 male) subjects participated in a second Control condition.

5.2. *Stimuli and procedure*

Stimuli were 1 kHz sinusoidal tones of 250-ms duration generated using SoundEdit™16 (Macromedia Inc.). Gaps of varying duration (0,2,5,7,10,15,20 ms, see Fig. 1) were inserted in the tones in two experimental conditions: (1) at a point +10 ms post-stimulus onset (the 10 ms masker condition), and (2) in the Control condition, at a point +40 ms post-stimulus onset (the 40 ms masker condition). Stimuli were presented using a Mac Quadra 800 computer with an Audiomedia II soundcard (DigiDesign, Palo Alto, CA) and Psyscope stimulus presentation software at 40 dB SL (sensation level, i.e., 40 dB above the perceptual detection threshold, which was individually determined for each subject). Stimuli were presented binaurally using Etymotic™ ER-3A earphones and air tubes designed for use with the MEG system (Etymotic, Oak Brook, IL). Tones were presented 100 times in a pseudorandom order in a passive listening paradigm.

5.3. *Magnetic field measurements and procedure*

Neuromagnetic fields were recorded bilaterally for each subject using a twin 37-channel biomagnetometer system (MAGNES-II™, Bti, San Diego, CA) in a magnetically shielded room. Sensor arrays were placed over the right and left superior temporal lobes. Evoked responses to a 1000 Hz pure tone were evaluated to determine if the sensor arrays were positioned to effectively record the auditory evoked M100 field. Epochs of 900-ms duration (100 ms pre-stimulus onset and 800 ms post-stimulus onset) were acquired around each stimulus at a sampling rate of 2083 Hz with a bandwidth of 800 Hz and a 1.0 Hz high-pass filter.

5.4. *Data analysis*

The data were inspected and individual epochs that contained motion-related artifacts (>2.5 pT, pT = 10^{-12} Tesla) were removed. Data were then selectively averaged by stimulus condition for each hemisphere. Averaged waveforms were band-pass filtered using a low cut-off frequency of 1 Hz and a high cut-off frequency of 40 Hz. The root mean square (RMS) magnetic field response was calculated using field values for the 37 channels defining the left hemisphere and the 37 channels defining the right hemisphere for each sampled point. The M100 peak was determined as the peak in

RMS value across 37 channels in the interval 80–140 ms, subject to a single equivalent current dipole (ECD) model/data correlation $r > 0.97$, with $Q < 50.0$ nAm, and a signal-to-noise ratio that met or exceeded a factor of 6:1. The latency and amplitude of the M100 component served as the dependent measure.

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