Neuromagnetic correlates of temporal gap detection in human auditory cortex

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Abstract—In this study, spatiotemporal profiles of brain responses to gaps in tones were investigated using magnetoencephalography (MEG). Participants listened passively to diotically presented stimuli consisting of leading and trailing markers with gaps of 0, 30, or 80 ms in duration that were inserted between the two markers. The leading and trailing markers were 300-ms pure tones of either 800 or 3200 Hz in frequency. For the within-frequency condition, the leading and trailing markers were identical in frequency, whereas for the between-frequency condition, the leading marker and the trailing marker were presented at different frequencies from each other. Neuromagnetic brain activities were recorded from 6 participants. Auditory evoked fields (AEFs) were obtained from temporal areas in both hemispheres. Auditory MEG responses (N100m) appeared in response to the onset of the trailing markers as well as the leading markers. In the between-frequency conditions, N100m appeared for all trailing marker onsets regardless of the gap duration. In within-frequency conditions, the stimulus did not produce a clear N100m response when there was no gap. Even though N100m appeared with gap durations of 30 ms and 80 ms, the amplitudes were smaller than those observed in the between-frequency conditions. Minimum norm estimate (MNE) was applied to localize the activated areas for these conditions. The results indicated that the areas activated by an 800-Hz tone were distributed more posteriorly than those for a 3200-Hz tone.

I. INTRODUCTION

The human auditory system is quite sensitive to the temporal changes of sounds. We can detect 2- to 3-ms gaps within sound streams at the same frequency [1], [2]. One of the frequently used tasks employed in the behavioural measurement of auditory temporal resolution is gap detection. When leading and trailing markers share the same frequency, this task is referred to as a “within-channel” or “within-frequency” detection task. On the other hand, when the frequencies of the leading and trailing markers are different from each other, the task is referred to as a “between-channel” or “between-frequency” detection task. Gap detection becomes more difficult with increasing frequency separation between the leading and trailing markers [3], [4].

Compared with the large number of psychoacoustic studies on gap detection [3]–[7], its underlying neural mechanisms have not yet been well understood. Although several electroencephalogram (EEG) [8] and magnetoencephalogram (MEG) studies that examined the brain mechanisms of gap detection have been reported [9]–[11], these studies mainly dealt with within-frequency gap detection.

In this study, auditory evoked fields (AEFs) were measured during listening to silent gaps under between-frequency and within-frequency conditions to investigate spatiotemporal profiles of the neuromagnetic responses to gaps marked by tones of the same and different frequencies.

II. MATERIALS AND METHODS

A. Participants

Six healthy volunteers (three females and three males, aged 23-53 years) participated in the experiment. All participants reported no hearing deficits, and had no difficulty hearing all of the stimuli used in the experiment. Informed consent was obtained from each participant after an explanation of the purpose and procedures of the experiment, which were approved by the Ethics Committee of the Faculty of Information Science and Electrical Engineering, Kyushu University.

B. Stimuli and procedure

Stimuli were synthesized with J software (sampling frequency was 44.1 kHz) run on a personal computer (Dell Dimension 4500C). The leading and trailing markers were 300-ms pure tones of either 800 or 3200 Hz. The leading marker included 20-ms rise and 3-ms fall times, while the trailing marker contained a 3-ms rise/fall time (Figure 1).

For the within-frequency condition, the frequencies of the leading and trailing markers were identical to each other, that is, both markers were presented at either 800 Hz or 3200 Hz. We refer to these frequency combinations as 800/800 and 3200/3200, respectively. For the between-frequency condition, the frequencies of the two markers were different from each other: their frequency combinations were 800/3200 and 3200/800. The duration of the silent gaps inserted between the two markers of all frequency combinations was 0 (no gap), 30, or 80 ms. 1 For each frequency combination, these three gap durations were presented 40 times each in a pseudo-random order in two separate blocks; thus, a total of 80 measurements were made for each gap duration. The experiment consisted of 8 blocks of 120 trials (2 blocks for each frequency combination) per participant. Inter-stimulus intervals (ISIs) for successive presentations of pairs of leading and trailing markers were

1For the gap 0 ms stimuli, there were no rise/fall time in the middle of the tone. We used continuous 600-ms pure tone, which had 20-ms rise time and 3-ms fall time.
randomly varied from 1.5 to 1.8 seconds during a single block. The order of condition was counterbalanced among the participants.

Stimulus presentations were controlled by a personal computer with presentation software (Neuroscan, STIM2), and the stimuli were amplified by an amplifier (Marantz PS3001) and presented diotically to the participant via a pair of inserted earphones (Etymotic Research, ER-3A). The leading and trailing markers of all frequency combinations were presented at an intensity level of 82 dB SPL measured by a sound level meter with a 1/2-inch condenser microphone (Brüel and Kjær, models 2250 and 4192, respectively). The participants were instructed to listen passively to the stimuli, while staying alert with their eyes kept open throughout a block.

After recording, Maxfilter was applied to reduce the artifact signals arising from outside the sensor array [14]. A 1-30-Hz off-line bandpass filter was applied to highlight the AEFs. AEFs measured from approximately 80 responses for each frequency combination were averaged for each stimulus condition. Using the averaged data, we focused on the contralateral hemisphere, in which AEFs are usually larger than in the ipsilateral side [15]. The peak latencies and amplitudes of the AEFs were picked up from the gradiometer that showed the most salient activation in the AEFs for each frequency combination (Fig. 2).

Following the off-line signal processing, we applied the MEG source reconstruction. A distributed source model of the MEG signals, recorded from the entire head surface, was estimated using the minimum norm estimate (MNE) to obtain the current strength of cortical sources. This method offers high spatial resolution to detect simultaneous magnetic sources distributed across the entire cortical surface. The precise procedure for performing MNE has been described elsewhere [16]. Each participantfs cortical surface was reconstructed from high-resolution T1-weighted MR images using FreeSurfer software [14], [16]. An anatomical MRI image was co-registered with the MEG head coordinate system using headshape points obtained by Polhemus measurement.

An inverse solution was calculated based on the forward solution that models the signal pattern generated by a unit dipole at each location on the cortical surface using a single homogeneous realistic head model and a boundary element method (BEM) [17], [18]. The activation at each cortical location was estimated at each time point of the activity, and was simultaneously estimated using a noise-normalized linear estimation approach (dynamic statistical parametric maps, dSPM). The noise covariance matrix was created using pre-trigger periods from -100 ms to 0 ms via trigger onset. The activation patterns derived from the analysis are mapped onto the cortical surface images of each participant to make visualization clear. All participants’ data were transformed into a standard brain (fsaverage; MNI305 [19]) in order to estimate the source activations across the subjects in the same scale [18].

The regions of interest (ROIs) on the cortical surface in the left temporal cortices were manually selected on the standard brain reference from the grand averaged dSPM values to demonstrate auditory evoked activities. The homologous area in the right temporal cortex was also marked as ROIs. To analyze the source level waveforms, the activation curves in each ROI for each stimulus condition were extracted (not shown).

### III. RESULTS

#### A. Auditory evoked neuromagnetic fields.

Figure 2 shows the averaged AEFs of one representative participant. The waveforms were derived from one selected MEG sensor with maximum detection in the left temporal area. AEFs appeared at around 100 ms (called N100m) after the leading and trailing markers.

The figure shows the neuromagnetic activities of between-frequency (800/3200 and 3200/800) and within-frequency (800/800 and 3200/3200) conditions. The average N100m response to the leading marker was easily identified across all conditions. In between-frequency conditions, N100m appeared for all trailing marker onsets regardless of gap duration. The amplitude was larger for the 800-Hz than the 3200-Hz trailing marker. In within-frequency conditions, the trailing marker did not generate clear N100m when there was no gap. Even
though N100m was observed for 30- and 80-ms gap durations, its amplitude was smaller than that for the comparable gap durations in the between-frequency condition.

B. Estimated cortical activity corresponding to the auditory N100m

Figure 3 shows the AEFs in response to a 3200/800 stimulus pattern with three gap durations (no gap, gap of 30 ms, and gap of 80 ms) and corresponding MNE results after transformation into the averaged brain from individual anatomical images. Compared with the source location activated by a 3200-Hz tone (Figure 3 (a)), the areas activated by a 800-Hz tone were distributed more posteriorly (Figure 3 (b)-(d)).

IV. DISCUSSION

N100m appeared in response to the onset of the trailing markers (Figure 2) as well as the leading markers, and the results clearly indicated that the reasonable location of N100m is estimated in the primary auditory cortex (Figure 3, bottom). The MNE results suggested that the areas activated by the tones of different frequencies were spatially separated in the auditory cortex. In the tonotopic organization of the human auditory cortex, the areas activated by high-frequency tones are located at more posterior and medial regions than those for low-frequency tones [20]. The sounds of different frequencies activated different areas at temporally closer timing in the auditory cortex. The auditory system would be required to process frequency changes as well as temporal changes in parallel. The spatial distribution in the auditory cortex might cause the difficulty in gap detection in the between-frequency condition.

The onset response to a trailing marker has been considered as an important cue for gap detection [6]. It has been suggested that within-frequency gap detection is relatively easy because it requires monitoring (dis)continuity in a single frequency. For between-frequency gap detection, the listener must make a decision regarding the relative timing between the offset of the leading marker in one frequency channel and the offset of the trailing marker in the other channel [6]. In the present results for the within-frequency condition, there was no trailing marker for a 0-msec gap and thus no corresponding N100m response appeared, whereas discriminable N100m was observed for 30- and 80-ms gap durations. The comparison between the presence and absence of a gap could be easy in the within-frequency condition because it would be realized by discriminating the “ON/OFF” of the neural activity (N100m). This is likely to be “discontinuity detection” as suggested by [3] and [4]. On the other hand, in the between-frequency condition, N100m appeared for all trailing marker onsets, even for a 0-msec gap (no gap), because N100m occurred in response to the change in frequency from the leading to the trailing marker. The comparison between the presence and absence of a gap could be less easy because of the robust N100m for the trailing marker with a 0-ms gap duration. This is likely to be “relative timing” discrimination, as suggested by [3] and [4]. The AEF patterns observed in this study are consistent with a previous EEG study [8] and the traditional explanation of gap detection [3], [4]. The above reasoning is a speculation and will require further investigation in order to relate the perceptual difficulty of between-frequency gap detection to neurophysiological responses to a silent gap in comparable situations.

ACKNOWLEDGMENT

The MEG measurement was conducted in the Brain Center in Kyushu University Hospital. The research was supported by a Research Grant from the Kawai Foundation for Sound Technology & Music and Grant-in-Aid from the Japan Society for the Promotion of Science for Scientific Research (A) 25240023 to S. M.

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Fig. 2. The averaged auditory evoked fields (AEFs) of one representative participant. The top two panels show AEFs for the between-frequency conditions, while the bottom two panels are for the within-frequency conditions. The colors of each line indicate gap duration (green = 0 ms (no gap), blue = gap of 30 ms, red = gap of 80 ms).

Fig. 3. Top: Auditory evoked fields (AEFs) recorded in the left hemisphere in one representative participant in response to a 3200/800 stimulus pattern with 0 ms (green), 30 ms (blue), and 80 ms (red). Bottom: Averaged MNE for the 6 participants that represent the cortical source of N100m corresponding to the onset of the leading and trailing markers.

