AUDITORY EVOKED MAGNETIC FIELDS AND LOUDNESS IN RELATION TO BANDPASS NOISES

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ABSTRACT
Auditory evoked magnetic fields (AEFs) and loudness in relation to bandpass noises with different center frequencies and bandwidths were examined. All stimuli had duration of 500-ms with 10 ms rise and fall times. Stimuli at 60 dB sound pressure level (SPL) were presented diotically to the left and right ears. AEFs were recorded using a 122-channel whole-head DC superconducting quantum interference device magnetometer. The latencies and amplitudes of the N1m wave, which was found above the left and right temporal lobes around 100 ms after the stimulus onset, were analyzed. Loudness was measured using an adaptive two-interval, two-alternative forced choice procedure, with a simple up-down stepping rule tracking the 50% point on the psychometric function. The results demonstrated that the middle frequency range (0.5-2 kHz) had shorter N1m latencies and larger N1m amplitudes, and that the lower (< 0.25 kHz) and higher (> 4 kHz) frequency stimuli had relatively delayed N1m latencies and decreased N1m amplitudes. The lower (< 0.5 kHz) and higher (> 12 kHz) frequency stimuli had relatively decreased loudness. The N1m amplitudes correlated well to the loudness except for the frequency ranges between 2 and 8 kHz.

INTRODUCTION
The effect of sound intensity in the auditory cortex has been previously investigated by magnetoencephalography (MEG), and auditory evoked magnetic field (AEF) in response to stimulus intensity has been examined [1-4]. These results indicate that the N1m amplitude of the AEFs increases up to a stimulus intensity of 50-60 dB SPL, but then remains more or less constant or even decreases for higher intensities. The intensity dependence of the equivalent current dipole (ECD) location in space has also been examined. Pantev et al. [3] examined the influence of stimulus intensity on the depth of the ECD of wave N1m. They reported that the higher the stimulus intensity is, the more superficial is the locus of cortical excitation. Vasama et al. [4], however, failed to find any systematic variation of the N1m source locations as a function of intensity.

The subjective aspect of sound intensity is loudness. Loudness is the attribute of auditory sensation in terms of which sounds may be ordered on a scale extending from quiet to loud. Loudness is what we experience in daily life. The mechanisms underlying the perception of loudness are not fully understood. The idea that loudness is simply proportional to the total number of action potentials fired by all auditory nerve neurons (the spike count hypothesis) have been investigated in animal studies. The spike count hypothesis was tested and justified that the rate-of-growth of both loudness and the auditory nerve spike count agreed over a wide range of tone intensity [5-7]. However, disagreement also exists [8, 9].

Changes in sound intensity are highly correlated with loudness changes, however, the relationship is not perfect. That is, changes in the frequency and bandwidth also affect the perceived loudness [10]. Therefore, the present study aimed to evaluate the idea that loudness is simply proportional to the response magnitude of the auditory cortex elicited by sounds with different frequencies and bandwidths.
METHODS
Ten normal-hearing subjects (22-35 years old) took part in each experiment. They all had normal audiological status and no history of neurological diseases. Informed consent was obtained from each subject after the nature of the study was explained. The study has been approved by the ethics committee of the National Institute of Advanced Industrial Science and Technology.

Pure tone, 1/6 octave band noise, and 1/3 octave band noise with center frequencies of 0.063, 0.125, 0.25, 0.5, 1, 2, 4, 8, 12 and 16 kHz were used. For center frequencies of 8 to 16 kHz, the 1/12 octave band noises were used. The stimulus duration was 500 ms, including rise and fall ramps of 10 ms. Stimuli were presented binaurally to the left and right ears through plastic tubes and earpieces inserted into the ear canals. All signals were presented at 60 dB SPL.

The AEFs were recorded using a 122-channel whole-head DC superconducting quantum interference device (DC-SQUID) magnetometer (Neuromag-122™; Neuromag Ltd., Helsinki, Finland) in a magnetically-shielded room. Three experimental sessions, each with different center frequencies; low (0.063–0.25 kHz), middle (0.5–4 kHz), and high (8–16 kHz), were carried out. In each session, stimuli were presented in randomized order with a constant interstimulus interval of 1.5 s. To maintain a constant vigilance level, the subjects were instructed to concentrate on a self-selected silent movie that was being projected on a screen in front of them and to ignore the stimuli. The magnetic data were sampled at 400 Hz after being bandpass filtered between 0.03 and 100 Hz, and then averaged approximately 100 times. Responses were rejected if the magnetic field exceeded 3000 ft/cm in any channel. The averaged responses were digitally filtered between 1.0 and 30.0 Hz. The analysis time was 0.7 s from 0.2 s prior to the stimulus onset. The average of the 0.2 s prestimulus period served as the baseline. Figure 1 shows representative examples of the AEF. To evaluate the latency and amplitude of the N1m peak, the root-mean-squares (RMSs) of 18 channels over left and right temporal areas determined as the amplitude of the responses. The peak amplitude and latency of the RMS in the latency range from 70 to 130 ms over each left and right hemisphere was defined as the N1m amplitude and latency in each subject.

Figure 1. Typical waveforms of AEFs from 122 channels in one subject.
Loudness matches were obtained using a two-interval, two-alternative forced-choice paradigm. In each trial, the listeners heard two sounds, the reference and the test sound, each of 500 ms duration, which were separated by a 500-ms silence interval. The reference stimulus was the 1-kHz tone. Test and reference sounds were presented in random order with equal a priori probability. The listeners indicated which sound was louder by pressing the corresponding key on a keyboard. A simple up–down procedure was used, which converges at the 50 % point of the psychometric function [11]. If the listener indicated that the reference sound was the louder one, its level was reduced, otherwise it was increased. The step size was 5 dB up to the first four reversals, and 2 dB thereafter. Twelve reversals were obtained and loudness level was estimated as the mean level at the last four reversals.

RESULTS

Figure 2 show the N1m latency and amplitude in the low frequency range (0.063–0.25 kHz). The N1m latency was prolonged with decreasing the center frequency up to 0.125 kHz in left and right hemispheres. Large variation in latency was seen at 0.063 kHz. The N1m amplitude increased with increasing the center frequency in left and right hemispheres.

Figure 2. Mean (a) latency and (b) amplitude of the N1m (±SEMs) as a function of the center frequency for (○, ●) pure tone, (△, ▲) 1/6 octave band, and (□, ■) 1/3 octave band stimuli. Empty symbols indicate results from left hemisphere and filled symbols indicate results from right hemisphere.

Figure 3. Mean (a) latency and (b) amplitude of the N1m (±SEMs) as a function of the center frequency for (○, ●) pure tone, (△, ▲) 1/6 octave band, and (□, ■) 1/3 octave band stimuli. Empty symbols indicate results from left hemisphere and filled symbols indicate results from right hemisphere.
Figure 3 show the N1m latency and amplitude in the middle frequency range (0.5–4 kHz). N1m latencies were approximately 90-110 ms. The N1m amplitude peaked around 0.5 and 1 kHz in left and right hemispheres.

Figure 4 show the N1m latency and amplitude in the high frequency range (8–16 kHz). The variation of the N1m latency increased with increasing the center frequency. The N1m amplitude decreased with increasing the center frequency in left and right hemispheres.

Figure 4. Mean (a) latency and (b) amplitude of the N1m (±SEMs) as a function of the center frequency for (○, ●) pure tone, (◇, ●) 1/12 octave band, (Δ, ▲) 1/6 octave band, and (□, ■) 1/3 octave band stimuli. Empty symbols indicate results from left hemisphere and filled symbols indicate results from right hemisphere.

Figure 5 show the SPL that was required for the 1-kHz pure tone to balance the loudness to the stimuli used in the study. Loudness of the stimuli were more or less constant for frequencies between 0.5 and 8 kHz. In the low frequency range (< 0.25 kHz), loudness increased with increasing center frequency. In the high frequency range (> 16 kHz), loudness decreased with increasing center frequency.

Figure 5 Mean loudness (±SEMs) as a function of the center frequency for (○) pure tone, (◇) 1/12 octave band, (▲) 1/6 octave band, and (■) 1/3 octave band stimuli.
DISCUSSION

Figure 6 shows the relative N1m latencies and amplitudes in all frequency range (0.063–16 kHz). Middle frequency range sounds (0.5–4kHz) appear to be associated with shorter N1m latencies. Lower and higher frequency stimuli give rise to relatively delayed N1m responses. This result is consistent with the results of studies using pure tones [12, 13] and bandpass noises [14]. The N1m amplitude peaked at around 0.5-1 kHz. The N1m amplitude decreased with decreasing center frequency and decreased with increasing center frequency in the high frequency range (> 4 kHz). This tendency is consistent with the results of studies using pure tones [15] and bandpass noises [14].

The relationship between N1m amplitude and loudness was investigated. In the lower frequency range (< 2 kHz), the N1m amplitude and loudness increased up to a stimulus frequency of 0.5 kHz, then remained more or less constant or decreases up to a stimulus frequency of 2 kHz. The correlation coefficient between N1m amplitudes and loudness values were 0.95 and 0.98 in left and right hemisphere, respectively. In the frequency range between 2 and 8 kHz, the N1m amplitude decreased with increasing center frequency, however, the loudness did not vary as a function of center frequency. The correlation coefficient between N1m amplitudes and loudness values were -0.07 and -0.31 in left and right hemisphere, respectively. In the high frequency range (> 8 kHz), the N1m amplitude and loudness decreased with increasing center frequency. The correlation coefficient between N1m amplitudes and loudness values were 0.96 and 0.94 in left and right hemisphere, respectively. The phase locking might be important for the perception of loudness [16]. The precision of phase locking decreases with increasing frequency above 1–2 kHz and the upper limit lies at about 4-5 kHz. Therefore, the weak correlation between N1m
amplitudes and loudness values in the frequency range between 2 and 8 kHz might be due to the variation of phase locking activities.

Figure 7. Scatter-plot of loudness value as a function of the N1m amplitude in the center frequency range of (a) 0.063-2 kHz and (b) 8-16 kHz for (○, ■) pure tone, (◇, △) 1/12 octave band, (△, ▪) 1/6 octave band, and (□, ■) 1/3 octave band stimuli. Empty symbols indicate results from left hemisphere and filled symbols indicate results from right hemisphere.

CONCLUSIONS

The hypothesis that loudness is simply proportional to the response amplitude of the auditory cortex elicited by sounds with different frequencies and bandwidths was tested. The N1m amplitudes correlated well to the loudness except for frequency ranges between 2 and 8 kHz.

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