AUDITORY EVOKED MAGNETIC FIELDS IN RELATION TO THE FACTOR EXTRACTED FROM AUTOCORRELATION FUNCTION

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Abstract
Auditory evoked magnetic fields in relation to the factor extracted from autocorrelation function (ACF) were examined by magnetoencephalography (MEG). In the first experiment, bandwidth of bandpass noises (BNs) was varied to control the peak amplitude of the ACF. Auditory evoked fields (AEFs) were recorded using a neuromagnetometer in a magnetically-shielded room. The results showed that the peak amplitude of N1m, which was found above the left and right temporal lobes around 100 ms after the stimulus onset, decreased with increasing bandwidth of the BN. In the second experiment, iterated rippled noise (IRN) was used. The IRN was produced by a delay-and-add algorithm applied to BN that was filtered between 400-2200 Hz. Each delay-and-add cycle is called iteration; the delay-and-add process increases the peak amplitude of the ACF. The results showed that the peak amplitude of N1m increased with increasing the number of iteration. These results clearly indicate that the peak amplitude of N1m increased with increasing the peak amplitude of ACF of the stimulus. Therefore, sounds that have more temporal regularity could lead to more cortical activity, which would cause an increase in the strength of the N1m response.

INTRODUCTION

Pitch plays an important role in all aspects of hearing. It is the basis of recognition of speech and melody in music. Pitch phenomena can be explained in terms of the frequency composition or the time structure of the sound. Magnetoencephalography
(MEG) has been used to investigate how features of sound stimuli related to pitch are represented in the human brain. Focused on a spatial representation of pure tone in the auditory system according to their frequency, tonotopic organization of the human auditory cortex has been investigated (e.g., Elberling et al., 1982; Romani et al., 1982; Pantev et al., 1988; 1995). Focusing on the temporal structure of the sound, the periodicity pitch related cortical response has been investigated (e.g., Pantev et al., 1989; Langner et al., 1997; Seither-Preisler et al., 2003).

In temporal models of pitch perception, it is assumed that the pitch is extracted with autocorrelation (Licklider, 1952; Meddis and Hewitt, 1991; Cariani and Delgutte, 1996). Regarding the strength of pitch or pitch salience, psychophysical research has revealed that the strength of the pitch corresponds well to the peak amplitude of the autocorrelation function (ACF) of the auditory signal, which represents the degree of temporal regularity of the sound (Wightman, 1973; Yost et al., 1996; Yost, 1996; Ando et al., 1999).

The present study aimed to evaluate the magnetic activity of the auditory cortex against the peak amplitude of the ACF of the auditory signal. Bandpass filtered noise (BN) and iterated rippled noise (IRN) were used as the auditory signal. To evaluate responses related to temporal regularity of the sound in auditory cortex, the AEFs elicited by BNs with different bandwidths and IRNs with different iteration numbers were recorded in the present study.

MATERIAL AND METHODS

Ten normal-hearing subjects (22-31 years; all right-handed) took part in the 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, and all experimental procedures were conducted in accordance with the Declaration of Helsinki.

BNs with center frequencies of 500, 1000 or 2000 Hz were used as auditory signals. The white noises were repeatedly digitally filtered ten times by setting the magnitude of the Fourier coefficients to a cut-off slope of 200 dB/octave outside the desired bandwidth. The bandwidth of the BN was controlled. The IRN was produced by a delay-and-add algorithm applied to BN that was filtered using fourth-order Butterworth filters between 400-2200 Hz. The reciprocal of the delay determines the pitch and the number of iterations determines the pitch strength (Yost, 1996). The number of iterations of the delay-and-add process was set at 0, 1, 4 and 16. The delay was fixed at 1 ms, corresponding to a pitch of 1000 Hz. The stimulus duration used the experiment was 0.5 s, including rise and fall ramps of 10 ms. The auditory stimuli were binaurally delivered to subjects through plastic tubes and earpieces inserted into the ear canals at a comfortable listening level adjusted separately for each subject. Figure 1 shows the temporal waveforms, power spectra and ACFs of some of the sounds used in this study. The peak amplitude of the ACF, $\phi_1$, decreases as the bandwidth of the BN increases. The $\phi_1$ increases as the number of iterations increases.
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 (Hämäläinen et al., 1993). The magnetic data were sampled at 0.4 kHz after being bandpass filtered between 0.03 and 100 Hz, and then averaged approximately 50 times. 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, with an average prestimulus period of 0.2 s serving as the baseline. The Neuromag-122\textsuperscript{TM} has two pick-up coils in each position. To evaluate the amplitude and latency of the N1m peak, the root-mean-squares (RMS) of $\partial B_z/\partial x$ and $\partial B_z/\partial y$ were determined as the amplitude of the responses at each recording position. The N1m peak amplitude and latency were defined as the RMS peak and latency in the latency range from 70-130 ms over the right and left hemispheres. In each subject, we employed the N1m peak latency and amplitude with a channel that showed the maximum amplitude placed at each hemisphere.

To estimate the location and strength of the underlying neural activity of the N1m wave, a single equivalent current dipole (ECD) was assumed as the source of the magnetic field of the N1m wave in a head-based coordinate system. The ECDs that best described the measured magnetic field at the N1m peak latencies were found by least-squares fitting in a spherical volume conductor (Kaukoranta et al., 1986). A one-dipole model was used separately for the left and right hemispheres, with a subset of channels over each hemisphere.

Figure 2—Typical waveforms of auditory evoked magnetic fields from 122 channels in a subject.
RESULTS

Clear N1m responses were observed in both the right and left temporal regions in all subjects (Fig. 2). The N1m latencies were not systematically affected by the bandwidth of the BN or the number of iterations of the IRN. A narrower bandwidth of BN produced a larger N1m peak amplitude. A two-way ANOVA (bandwidth \times hemisphere) revealed a significant main effect of the bandwidth on the N1m peak amplitude (P < 0.05). A greater number of iterations of IRN produced a larger N1m peak amplitude. A two-way ANOVA (number of iterations \times hemisphere) revealed a significant main effect of the number of iterations on the N1m peak amplitude (P < 0.005).

For the dipole strength, similar results to those for the N1m peak amplitude were obtained. Figure 3 depicts the mean ECD moment as a function of the bandwidth of the BN or the number of iterations of the IRN. A narrower bandwidth of BN produced a larger N1m ECD moment. A two-way ANOVA (bandwidth \times hemisphere) revealed a significant main effect of the bandwidth on the ECD moments (P < 0.05). A greater number of iterations of IRN produced a larger N1m ECD moment. A two-way ANOVA (number of iterations \times hemisphere) revealed a significant main effect of the number of iterations of IRN on the ECD moments (P < 0.01). The ECD locations did not show any systematic variation across the subjects as a function of the bandwidth of the BN or the number of iterations of the IRN.

Figure 3 – Mean ECD moment of the N1m (± SEMs) as a function of the (a) bandwidth of BN and (b) number of iterations of IRN from the right (■, ◻): and left (□, ○): hemispheres. The asterisks indicate statistical significance (*P<0.05, **P<0.01; Post hoc Bonferroni test).
DISCUSSION

Using AEFs, the brain activities corresponding to the peak amplitude of the ACF, \( \phi_1 \), of the auditory signal were analyzed in the present study. As for BN, a broader bandwidth produced a smaller N1m amplitude, that is larger \( \phi_1 \) of the stimulus produced a larger N1m response. Reite et al. (1982) found that AEF amplitudes to pure tones were significantly larger than those to white noises for both the right and left hemispheres. Sams and Salmelin (1994) investigated the effects on the human auditory cortex of masking pure tones of 1000 and 2000 Hz using continuous white-noise maskers with frequency notches around the tone frequencies, and revealed that the N1m amplitude becomes larger with larger notches. These results are consistent with the present findings. A larger notch passes through less noise, that is, tones with a larger notched noise are narrower bandwidth sounds. As for IRN, a greater number of iterations produced a larger N1m amplitude, that is larger \( \phi_1 \) of the stimulus produced a larger N1m response. The amplitude of the AEF component in response to periodic stimuli was compared with simulated peripheral activity patterns of the AN (Seither-Preisler et al., 2003). The results showed that the amplitude of the N1m is correlated with the pitch strength estimated on the basis of AN activity. This result is consistent with the present findings. Figure 4 shows the relationship between \( \phi_1 \) of the stimulus and ECD moment of the N1m response. Psychophysical studies have indicated that first peak of the ACF, \( \phi_1 \), could account for the pitch strength of the stimulus (Wightman, 1973; Yost et al., 1996; Ando et al., 1999) and pitch strength of IRN was an exponential function of \( \phi_1 \) (Yost, 1996). Note that the ECD moment derived in the current study could also be described in the form \( a + 10^{b \phi_1} \), where \( a = 6.6 \) and \( b = 0.9 \), as shown in Fig. 4.

Figure 4 – Relationship between peak amplitude of the ACF, \( \phi_1 \), and ECD moment of the N1m.
There is an ongoing, shifting debate over the respective roles of place and temporal representations in the perception of pitch and other auditory forms. In the temporal-place model of hearing, it is assumed that the pitch is extracted with the ACF, in which the neural pattern is correlated with a delayed version of itself (Patterson et al., 1996; Yost, 1996). The ACF model, which computes autocorrelograms from the intervals in the spike train, is one of the purely temporal models (Licklider, 1951; Meddis and Hewitt, 1991; Cariani and Delgutte, 1996). Psychophysical research has revealed that the strength of the pitch corresponds well to the $\phi_1$ of the auditory signal (Wightman, 1973; Yost, 1996; Ando et al., 1999). To locate the mechanism for the detection of temporal regularity in humans, positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) experiments have been performed using an IRN (Griffiths et al., 1998; 2001). The results showed that the activity of the primary auditory cortex, cochlear nuclei and inferior colliculi increased with the regularity, namely $\phi_1$, of the sound. Such a demonstration indicates the presence of a mechanism that converts the temporal regularity into a local neuronal activity level to one at the cortical level. By comparing the N1m responses elicited by a vowel, a pseudo-vowel and a wide-band noise burst, it was found that noise markedly reduces the amplitude of N1m (Alku et al., 2002; Palomäki et al., 2002). The $\phi_1$ of a pseudo-vowel is smaller than that of a vowel because a pseudo-vowel is produced using random noise. In the present study, the $\phi_1$ was varied, that is, the temporal regularity of auditory signals was controlled. Therefore, sounds that have more temporal regularity could lead to more cortical activity, which would cause an increase in the strength of the N1m response.

The pitch onset response (POR) was introduced to circumvent the energy onset response (EOR), such as N1m, and thereby isolate the response of those neural elements specifically in pitch processing (Krumbholz et al., 2003). The POR is a negative component of the AEF, which can be elicited by the transition from a noise to a tone even when there is no concurrent change in sound energy. The results showed that the amplitude of the POR is correlated with the pitch strength, that is to say, the number of iterations of the IRN, suggesting that the underlying generators are part of a pitch-processing network. This is consistent with the present results. The results also show that the source of the POR lies somewhat anterior and inferior to that of the N1m. Then, whether the POR originates from the same generator as the EOR was examined (Seither-Preisler et al., 2004). The results suggest an interaction between the POR and the EOR, which may be based on common generators. Given this, the N1m responses derived in our study are considered to include both the EOR and POR responses. However the stimulus used in the present study had the same sound pressure level and the same stimulus onset as shown in Fig. 1. Consequently, the effect of the number of iterations of the IRN on N1m is contributed mainly by a pitch-processing network.

CONCLUSIONS

In the present study, the amplitudes, latencies, source strengths and coordinates of the N1m wave of AEFs in response to the peak amplitude of the ACF, $\phi_1$, obtained. In
summary, the results demonstrate that the larger $\phi_1$ of the stimulus produced a larger N1m response. The latency and source location of N1m in the cortex do not reveal any systematic change relating to $\phi_1$.

REFERENCES


