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Magnetoencephalographic responses correspond to individual annoyance of bandpass noise

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Abstract

The relation between human brain responses to an individual's annoyance of bandpass noise was investigated using magnetoencephalography (MEG) measurements and analysis by autocorrelation function (ACF) and cross-correlation function (CCF). Pure tone and bandpass noises with a centre frequency of 1000 Hz were used as source signals. The sound pressure level was constant at 74 dBA and the duration of the stimulus was 2.0 s. The scale values of annoyance for each subject were obtained by paired-comparison tests. In MEG measurements, the combination of a reference stimulus (pure tone) and test stimuli (bandpass noise) was alternately presented 30 times at a constant 2 s interstimulus interval. The results show that the effective duration of the ACF, τ_e, of MEG in the 8–13 Hz range, which represent repetitive features within the signal itself, became shorter during the presentation of an annoying stimulus. Also, the maximum value of the CCF, $|\phi(\tau)|_{\max}$, became smaller. The shorter τ_e and smaller $|\phi(\tau)|_{\max}$ indicate that a wider area of the brain is unstable for longer with annoying auditory stimuli.

1. Introduction

Industrial development has substantially increased environmental noise. Some research has investigated the effects of noise on mental work, human placental lactogen (HPL), and sleep [1–7].

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This study investigates the relationship between brain activity and individual annoyance to a noise. Environmental noise has been related to annoyance in several studies (e.g. [8–12]). In most studies loudness has been identified as the most influential determinator for annoyance, and can be predicted by the sound pressure level (SPL). Previous studies have concluded that perceived loudness remains constant with increasing noise bandwidth until the bandwidth reaches the critical band. Loudness then increases with increasing bandwidth at the same sound pressure level [13–16]. However, the loudness of a sharply filtered noise increases as the effective duration of the autocorrelation function (ACF), τ_e, increases, even when the bandwidth of the signal is within the critical band [17,18]. The τ_e represents repetitive features within the signal itself and increases as the filter bandwidth decreases. In addition, a sound is perceived to be annoying although the sound pressure level was only about 35 dBA in a given situation [19]. This demonstrates that annoyance cannot be predicted by sound intensity alone.

To investigate the relationship between the human brain and the environment, studies were made using electroencephalography (EEG) and magnetoencephalography (MEG). EEG measures electric potential differences on the scalp while MEG measures the weak magnetic fields produced by electric currents in cortical neurons. In both methods, the recorded signals are generated by the same synchronized neuronal activity [20]. To investigate the relationship between the EEG responses and subjective preferences for a sound field, a method was developed using the ACF of EEG [21–23]. The effective duration of the envelope of the normalized ACF, τ_e, was analysed with variation in the time delay of the single echo, Δt_1, reverberation time, T_{sub}, and magnitude of interaural cross-correlation (IACC), of sound fields. The results showed that the τ_e is significantly longer in preferred conditions for the factors, Δt_1, T_{sub}, and IACC. It has recently found that the τ_e and the maximum amplitude of the cross-correlation function (CCF), $|\phi(\tau)|_{\max}$, of MEG between 8 and 13 Hz is correlated with subjective preference for Δt_1 of speech [24,25].

In this study, the responses of the human brain that correspond to noise annoyance were investigated. The scale values of annoyance for each subject were obtained by paired-comparison tests. MEG measurements and analyses by the ACF and CCF were made. The relationship between the scale value of annoyance to bandpass noise and the factors extracted from the ACF and CCF of MEG in the brain's magnetic responses were investigated.

2. Method

2.1. Subjective annoyance test

Pure tone and bandpass noises with a centre frequency of 1000 Hz were used as source signals. The bandwidth of the source signal was to 0,40,80,160 or 320 Hz with a 2000 dB/octave sharp filter, obtained by a digital FFT filter, to control the ACF of the source signal [18]. The filter bandwidth of 0 Hz was the only slope component. The auditory stimuli were binaurally delivered through plastic tubes and earpieces inserted into the ear canals. The sound pressure was measured with an ear simulator, including a microphone and a preamplifier, and an adaptor connected to the earpiece. All stimuli were fixed at the same sound pressure level (74 dB(A)) by measuring the ACF at the zero delay, $\Phi(0)$. The source signals were characterized by ACF factors, τ_e, which is defined by the delay time at which the envelope of the normalized ACF becomes 0.1, the delay time of the first maximum peak, τ_1, and its amplitude, ϕ_1. The measured τ_1 of all signals were 1.0 ms, which correspond to the centre frequency of bandpass noise. The measured ϕ_1 and τ_e increased as the filter bandwidth decreased with a certain degree of coherence between ϕ_1 and τ_e.

Seven subjects participated in the experiment, 22–28 year old with normal hearing. They were seated in a dark soundproof room, with a comfortable thermal environment, and were presented the sound stimuli. A paired-comparison tests were performed for all combinations of the pairs of pure tone and bandpass noise, i.e., 15 pairs ($N(N-1)/2$, $N = 6$) of stimuli with interchange of the order of each pair per session, and random presentation of the pairs. Ten sessions was conducted for each subject. The duration of the stimuli was 2.0 s, the rise and fall times were 10 ms, the silent interval between the stimuli was 1.0 s, and the interval between pairs was 4.0 s, which was the allowed time for the subjects to respond by pushing one of two buttons. They were asked to judge which of the two sound stimuli was more annoying. The scale values of the annoyance were calculated according to Case V of Thurstone's theory [26,27] and the model of Case V for all data was confirmed by the goodness of fit test [28].

2.2. Measurement of magnetic response

The same subjects used in the annoyance tests participated in the recording of MEG responses. The magnetic responses were measured in a magnetically shielded room and recorded (pass-band 0.03–100 Hz, sampling rate 400 Hz) with a 122 channel whole-head magnetometer (Neuromag-122$^{\mathrm{TM}}$, Neuromag Ltd., Finland). In this system, 122 channels are located at 61 sites, and each site has two channels: one measures $\partial B_z/\partial x$ orthogonal tangential derivatives of the magnetic field B_z normal to the surface of the head along the latitude, and the other measures $\partial B_z/\partial y$ along the longitude, as shown in Fig. 1. For the measurements, the subjects were seated in a dark soundproof room, with a comfortable thermal environment and were asked to close their eyes and fully concentrate on the sound stimulus. The paired-auditory stimuli were presented in the same way as in the subjective annoyance test. Combinations of a reference stimulus (pure tone) and test stimuli (bandpass noise) were presented alternately 30 times at a constant 2.0 s interstimulus interval and MEGs recorded. Eighteen channels that were located around the temporal area in each hemisphere were selected for ACF and CCF analysis (Fig. 1). This resulted of 36 channels selected to be analysed. Each response, corresponding to one stimulus, was analysed by ACF and CCF for each subject.

The relationship between the degree of annoyance and the averaged τ_e values at 18 sites, measured at two tangential derivatives, was investigated.

2.3. Procedures for analysing the ACF and CCF of MEG

The ACF provides the same information as the power spectral density of a signal. Fig. 2a shows an example of a measured ACF. A normalized ACF can be expressed by

$$\phi(\tau) = \frac{\Phi(\tau)}{\Phi(0)}, \tag{1}$$

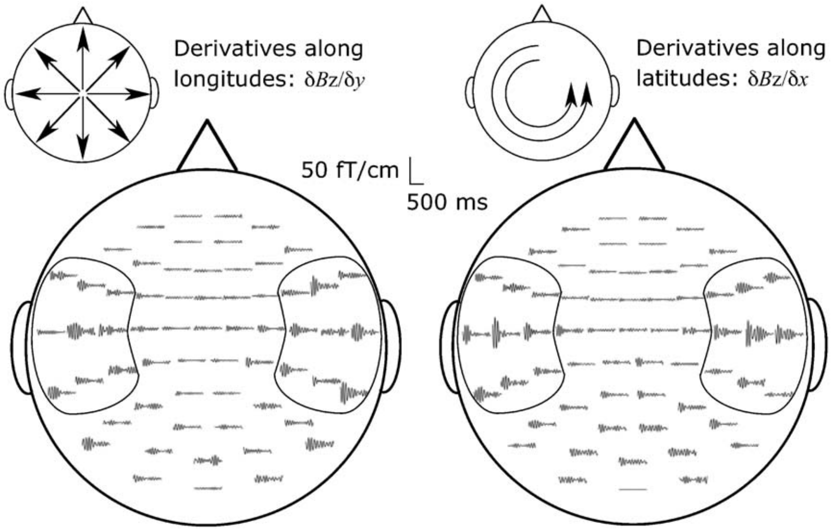

Fig. 1. Examples of recorded MEG responses to bandpass noise with bandwidth of 0 Hz. The passband is 8–13 Hz. Thirty-six channels that were located around the left and temporal area were selected for the ACF and CCF analysis.

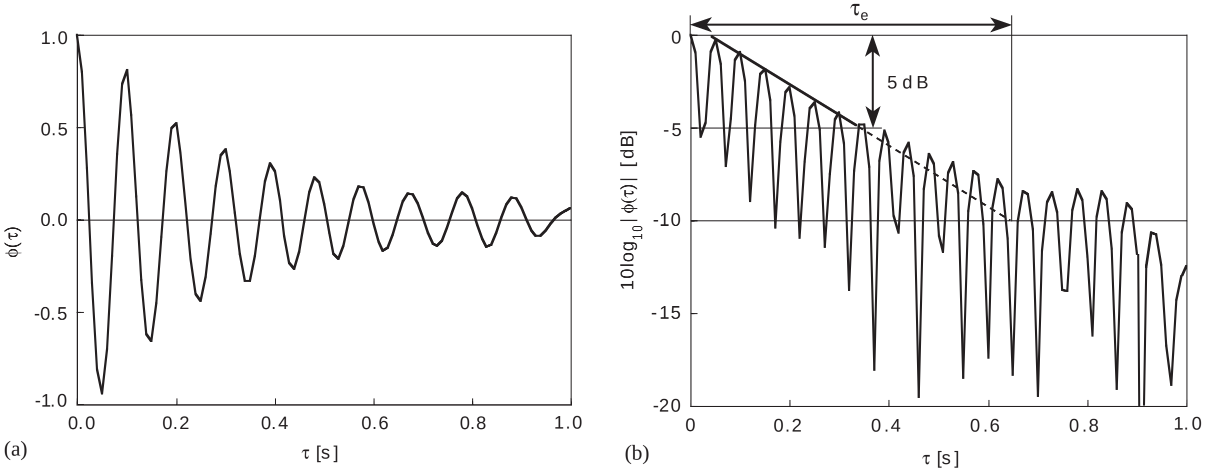

Fig. 2. (a) Examples of normalized ACF of MEGs between 8 and 13 Hz. (b) Examples of determining the effective duration of ACF, τ_e.

where

$$\Phi(\tau) = \frac{1}{2T}\int_0^{2T} \alpha(t)\alpha(t+\tau)\,\mathrm{d}t, \tag{2}$$

where $2T$ is the integral interval, τ is the time delay, and $\alpha(t)$ is the MEG between 8 and 13 Hz. Fig. 2b shows the absolute value of the ACF in a logarithmic form as a function of the time

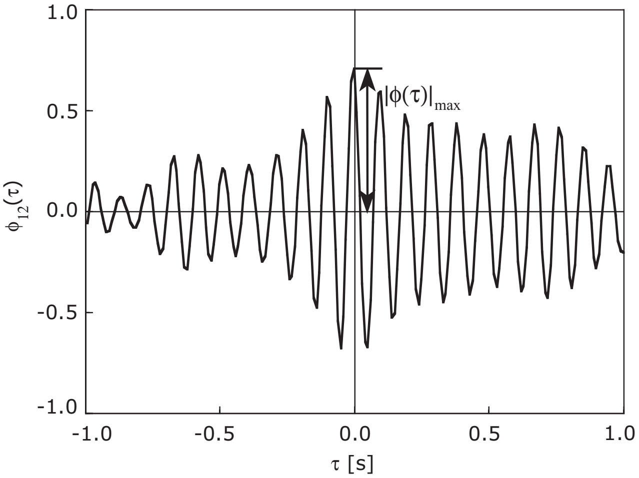

Fig. 3. Examples of normalized CCF of MEGs between 8 and 13 Hz and the definitions of the maximum value of CCF, $|\phi(\tau)|_{\max}$.

delay, τ. To calculate the degree of the ACF envelope-decay, the effective duration, τ_e, is determined. As shown in Fig. 2b, a straight-line regression of the ACF can only be made by using the initial declining portion, $0\,\mathrm{dB} > 10\log|\phi(\tau)| > -5\,\mathrm{dB}$ [21]. In most cases, the envelope decay of the initial part of the ACF may fit a straight line. The values of τ_e were analysed at $2T = 2.0$ s. Given the two signals are $\alpha_1(t)$ and $\alpha_2(t)$, then the CCF is defined by

$$\Phi_{12}(\tau) = \frac{1}{2T}\int_{-T}^{+T} \alpha_1(t)\alpha_2(t+\tau)\,\mathrm{d}t. \tag{3}$$

The normalized CCF is given by

$$\phi_{12}(\tau) = \frac{\Phi_{12}(\tau)}{\sqrt{\Phi_{11}(0)\Phi_{22}(0)}}, \tag{4}$$

where $\Phi_{11}(0)$ and $\Phi_{22}(0)$ are the ACFs of $\alpha_1(t)$ and $\alpha_2(t)$ at $\tau = 0$, respectively. The normalized CCF between the MEG responses recorded at the reference channels, with 18 channels for each hemisphere, and those recorded at the 35 test channels (with the exception of the reference channel) were calculated. Examples of a normalized CCF and the definition of the maximum value of the CCFs, $|\phi(\tau)|_{\max}$, are shown in Fig. 3. The values of $|\phi(\tau)|_{\max}$ were analysed at $2T = 2.0$ s.

3. Results

The results from the site with the highest correlation between the scale values of annoyance and averaged τ_e values showed a significant effect of the stimulus on τ_e values ($p < 0.05$) as shown in Table 1. The values of τ_e for the most annoying stimuli were significantly shorter than those for the least annoying stimuli in six subjects ($F = 5.28$, $p < 0.05$, one way ANOVA), as shown in

Table 1
Analyses of variance of (a) τ_e and (b) $|\phi(\tau)|_{\max}$

	Factor	Degree of freedom	F value	Significance level
(a) τ_e				
	Stimulus	5	4.03	<0.005
	Subject	5	27.58	<0.001
	Stimulus $*$ subject	25	0.84	0.969
	Residual	3564		
(b) $\|\phi(\tau)\|_{\max}$				
	Stimulus	5	25.43	<0.001
	Subject	5	128.61	<0.001
	Stimulus $*$ subject	25	4.59	<0.001
	Residual	64764		

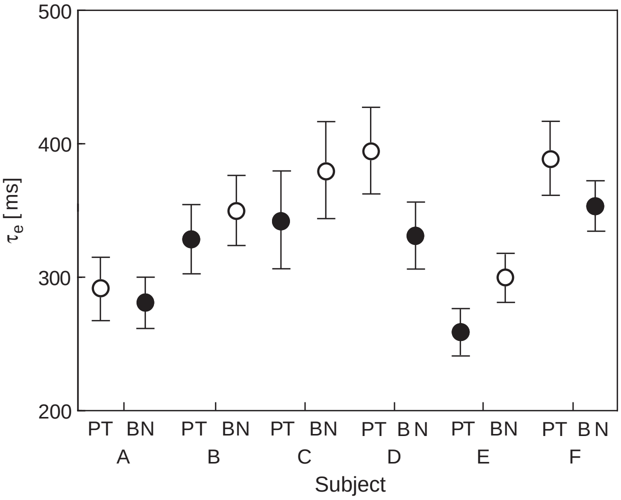

Fig. 4. Measured τ_e of MEGs when the differences of scale value (SV) of annoyance between band noise (BN) and pure tone (PT) [|SV(BN) – SV(PT)|] were largest in five pairs for six subjects. (○) lower annoyance, (●) higher annoyance. Error bars represent 95% confidence.

Fig. 4. Fig. 5 shows the relationship between the ratio of averaged values of τ_e of bandpass noise to those of a pure tone, and the difference between the scale values of bandpass noise and those of a pure tone. The ratio of τ_e increases as the difference of scale values of annoyance decreased (except for one subject). This indicates that the value of τ_e became shorter during the presentation of an annoying stimulus. The correlation coefficient between the ratio of τ_e values and the difference in scale values of annoyance was $-0.83\,(p<0.01)$.

The results from the reference channel with the highest correlation between the scale values of annoyance and averaged $|\phi(\tau)|_{\max}$ values of all test channels showed a significant effect of the stimulus on $|\phi(\tau)|_{\max}$ values ($p<0.001$) as shown in Table 1. The values of $|\phi(\tau)|_{\max}$ for the most

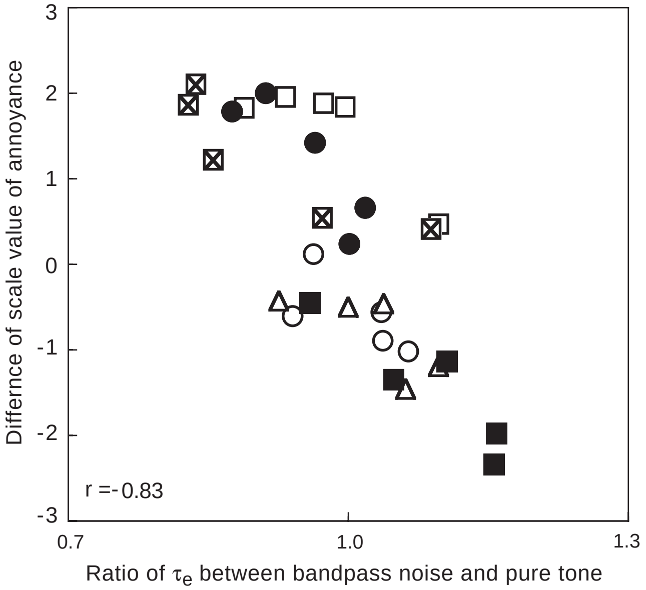

Fig. 5. Relationship between the difference of scale values (SV) [SV (bandpass noise) - SV (pure tone)] and the ratio of τ_e values of bandpass noise to τ_e values of a pure tone. Each symbol represents one subject.

annoying stimuli were significantly smaller than those for the least annoying stimuli for six subjects ($F = 16.85, p < 0.001$, one way ANOVA), as shown in Fig. 6. The results indicate that the ratio of $|\phi(\tau)|_{\max}$ increases as the difference of scale values of annoyance decrease (except for one subject), as shown in Fig. 7. This indicates that the value of $|\phi(\tau)|_{\max}$ becomes smaller during the presentation of an annoying stimulus. The correlation coefficient between the ratio of $|\phi(\tau)|_{\max}$ values and the difference in scale values of annoyance was $-0.72\,(p < 0.01)$.

4. Discussion and conclusions

Alpha activity is commonly defined as fluctuations between 8 and 13 Hz that can be detected on the occipital scalp [29]. Similar oscillatory activity, seen over the auditory cortex, is called τ rhythm [30–32]. It is this τ rhythm that is analysed by the ACF and CCF in this study.

The value of τ_e becomes shorter and the values of $|\phi(\tau)|_{\max}$ becomes smaller during presentation of an annoying stimulus. The τ_e is the degree of similar repetitive features included in MEG between 8 and 13 Hz and the $|\phi(\tau)|_{\max}$ signifies the degree of similar repetitive features that appear in MEG between 8 and13 Hz recorded at two different channels. Thus, the brain is unstable over a wider range, in both space and time during annoying conditions. Previous studies on EEG and MEG between 8 and 13 Hz show that the τ_e becomes significantly longer and $|\phi(\tau)|_{\max}$ significantly larger in preferred sound fields [21–25]. This indicates that the brain repeats a similar rhythm over a wider range, in both space and time in preferred conditions. These are considered to be consistent with our results in the study.

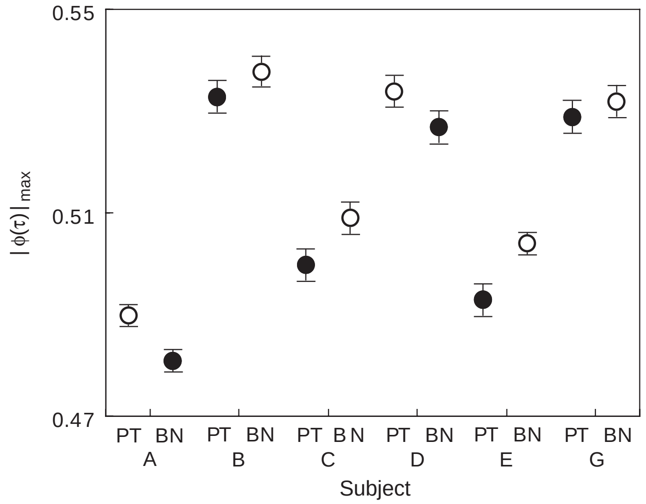

Fig. 6. Measured $|\phi(\tau)|_{\max}$ of MEGs when the difference of scale value (SV) of annoyance between band noise (BN) and pure tone (PT) [SV(BN) – SV(PT)|] were largest in five pairs for six subjects. (○) lower annoyance, (●) higher annoyance. Error bars represent 95% confidence.

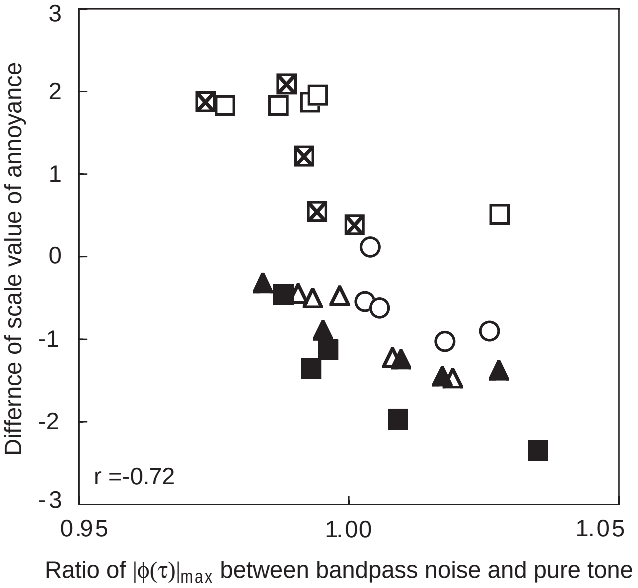

Fig. 7. Relationship between the difference of scale values (SV) [SV (bandpass noise) - SV (pure tone)] and the ratio of $|\phi(\tau)|_{\max}$ values of bandpass noise to $|\phi(\tau)|_{\max}$ values of a pure tone.

Difference between individuals is commonly experienced in subjective studies on annoyance (e.g. [33]). From previous research on loudness, it was predicted that perceived annoyance of a sharply filtered noise increases as τ_e increases, even when the bandwidth of the signal is within the

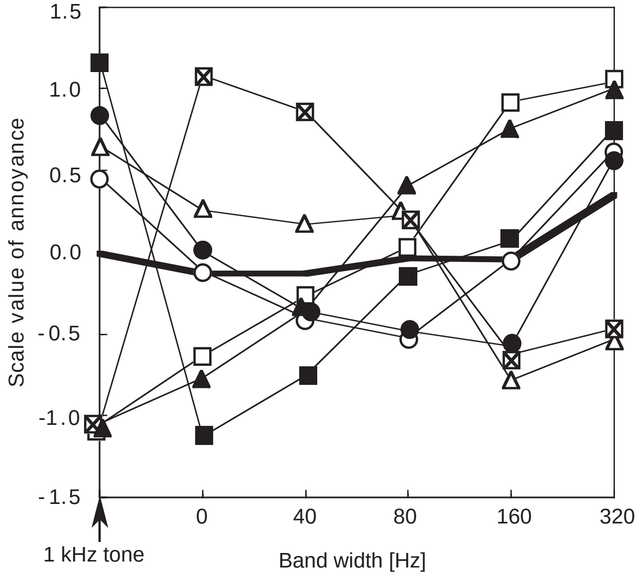

Fig. 8. Scale values of annoyance as a function of the bandwidth of bandpass noise.

critical band, and then increases with increasing bandwidth at the same sound pressure levels [17,18]. The scale value of annoyance as a function of bandwidth is shown in Fig. 8. There was a degree of consensus between most subjects (except for one subject), with the most annoying stimulus being a pure tone or bandpass noise with 320 Hz bandwidth. Relatively large individual differences were found among bandpass noises within the critical band.

The results of the study lead to the following conclusions:

1. The effective duration of the ACF, τ_e, of the MEGs between 8 and 13 Hz becomes shorter during the presentation of an annoying noise stimulus.
2. The maximum value of the CCF, $|\phi(\tau)|_{\max}$, of the MEGs between 8 and 13 Hz becomes smaller during the presentation of an annoying noise stimulus.

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