Effects of active noise control on subjective annoyance and cortical neural activities for car engine noise

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ABSTRACT

It is thought that active noise control (ANC) is able to control not only loudness but also auditory impression; however, few studies have focused on changes in the auditory impressions of noises through ANC. Some previous studies have reported significant correlations between subjective preference/annoyance of sounds and synchrony of the alpha activity, τe. In this study, auditory impressions of car engine noises varied by ANC were investigated using psychoacoustic and neurophysiological measurements. Car engine noises were modeled as harmonic complex tones. 20 stimuli were obtained by applying ANCs with several reduction-levels. First, Scheffe's paired comparison tests were performed to evaluate subjective annoyance for each stimulus. Next, magnetoencephalographic responses for the reference noise, the intermediate-, and the least-annoyed stimuli for each participant were recorded, and then τe was estimated accordingly. Annoyance decreased as the cut-off frequency and the reduction-level increased. The results indicated that decrease of loudness is important for improvements in auditory impressions. However, no significant effects of ANC were observed in τe. It is difficult to identify the cause, the annoyance levels for each stimulus were not markedly different.

Keywords: ANC, paired comparison test, magnetoencephalography, alpha wave

1. INTRODUCTION

Active noise control (ANC) is a noise-reduction technique that works by the addition of one or several secondary sources to the original sound source. ANC is especially suitable for reducing low-frequency noise where traditional passive noise control techniques based on sound-absorbent materials and acoustic screens are ineffective. Therefore, ANC techniques are widely used for cars, headphones, and so on. It is thought that ANC reduces noise loudness, but also changes auditory impressions. However, few studies have focused on the quantitative effects of ANC on auditory impressions. Gonzalez et al found that auditory impressions were improved by applying ANC to engine noises (1). However, in the case of smoother spectrums, auditory impressions were deteriorated. They suggested the possibility that auditory impressions are affected when the psychoacoustic parameters of expecting loudness are varied. Moreover, ANC is more likely to deteriorate auditory impressions if the original source sound has positive impressions. In accelerating cars, for example, the time-varying characteristics of the engine sound can induce auditory impressions such as "sporty" and "accelerating" in drivers. Conversely, assessment of sound quality is carried out using subjective psychological tests such as the paired comparison method and semantic differential method. However, such psychoacoustic tests usually compel participants to repeat judgments over and over, and often take a long time. Furthermore, it is sometimes hard to obtain an entirely reliable evaluation. It is comparatively easy to improve the sound quality if we can also use an objective measure corresponding to the auditory impression. It is thought that usage of

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neurophysiological data is one of the most reliable methods. We previously examined to reveal the relationships between the brain cortical neural activities and subjective preference or annoyance of sounds (2-4). In these studies, magnetoencephalographic (MEG) components in the 8–13 Hz range, i.e., alpha activities, were recorded and analyzed using an auto-correlation function (ACF). It was found that the effective duration of using the ACF, τe, which is related to repetitive features within the signal itself, was lengthened for the preferred stimuli (2, 3) and shortened for the annoyed stimuli (4). In this study, the effects of ANC on the auditory impression of car-engine noise were investigated using both subjective psychological and neurophysiological measurements. First, the scale values of annoyance for each participant were obtained by paired-comparison tests. Next, MEG measurements and the ACF analyses were conducted. The relationship between the scale value for annoyance of the car engine noise and the factors extracted from the ACF in the brain's magnetic responses were investigated.

2. STIMULI

In this study, we used a 2.3L inline-four engine. The engine condition was set to full constant speed in third gear. Figure 1 shows a spectrogram of an inline-four engine sound, recorded at a sampling frequency of 6000 Hz with a dummy head located on the passenger seat. An inline-four engine explodes twice with each rotation and generates a secondary vibration force. These higher harmonics constitute the main component of the noise. The modeled stimulus was generated based on a recorded sound. We used a sinusoidal model to create the stimulus (5). The model implements analysis and synthesis for sound waves, as shown in Fig. 2. The peaks of the spectrogram in each frame were extracted using a short-term Fourier transform (STFT), and partial sounds were determined by the instantaneous values included in their peaks.

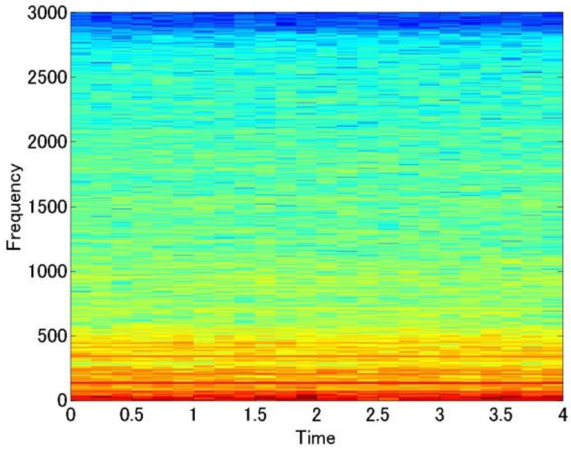


Figure 1 - Spectrogram of engine noise recorded by a dummy head located on the passenger seat.

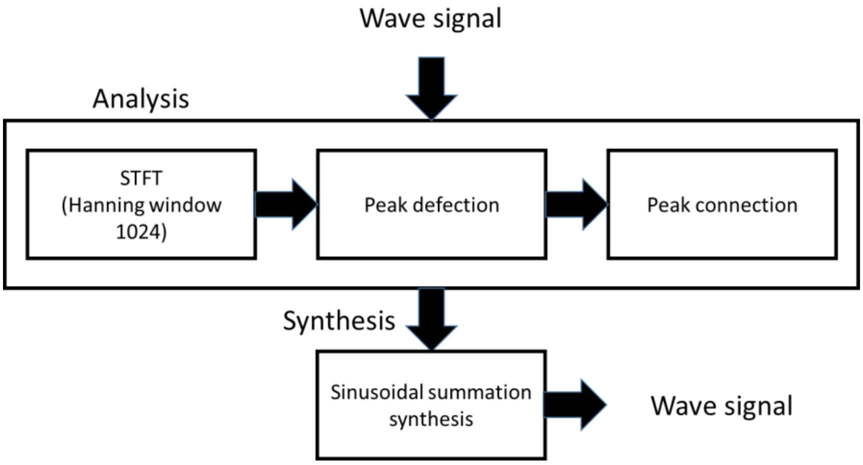


Figure 2 - Analysis-by-synthesis with Sinusoidal Model

Reference noises were created from the real car engine noise using the sinusoidal model. Modeled car engine noise means the harmonics up to the 42nd based on a real inline-four engine noise. Random phase noise means the collapsed phase of the modeled car engine noise. To make the A-weighted sound pressure level (LA) equal to the level of the recorded real car sound, the amplitude of the reference noises were adjusted. Moreover, one of the following actions was performed on these stimuli. For ideal-reduction noise, four stimuli had their amplitudes reduced by 5, 10, 15 or 20 dB. For modeled ANC noise, low frequency parts of the reference noises were reduced. The cut-off frequencies and levels of reduction were set at 200, 400 or 800 Hz, and 5, 10, 15 or 20 dB, respectively. To evaluate equal L_A noise, i.e., the equal L_A of the ideal-reduction noise, the levels of reduction in each frequency part were adjusted between 0 and 20 dB.

3. SUBJECTIVE ANNOYANCE MEASUREMENT

3.1 Participants

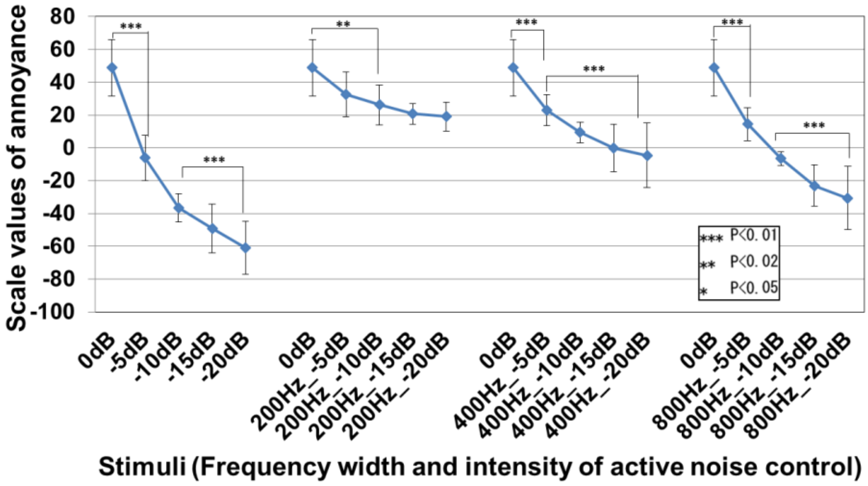
Ten volunteers (18–25 years old; seven male, three female) with normal hearing participated in this experiment. They were seated in a soundproof room with a comfortable thermal environment.

3.2 Apparatus and tasks

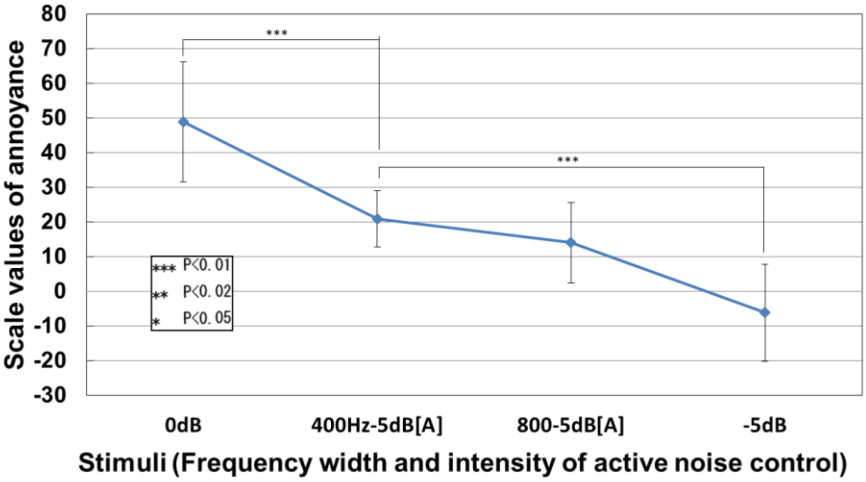
Scheffe's paired-comparison tests were performed for all combinations of the pairs of stimulus for each reference noise, i.e., 190 pairs (N(N−1)/2, N=20) of stimuli with a different order of each pair per session, and random presentation of the pairs. Each pair of stimuli was presented four times to determine the annoyance scale value. Pairs of sounds were presented, and participants were asked to judge their annoyance at the constant speed car engine noise to estimate the annoyance scale value on a scale of 1 to 7. These auditory stimuli were presented through plastic tubes and earpieces (ER-2, Etymotic Research) inserted into the ear canals. The scale values of the annoyance were calculated according to Scheffe's theory.

3.3 Results

Figure 3(a) and (b) shows the relationship between the frequency width and intensity of active noise control and the scale values of the annoyance for the modeled ANC noise and the equal L_A noise in the modeled car engine noise, respectively. When the level of the ideal-reduction noise increased, the annoyance was decreased from the reference noise, as shown in Figure 3(a). Furthermore, the width and level of the modeled ANC noise increased, while the scale values of the annoyance decreased. In comparing the equal L_A noise, the annoyance of the modeled ANC noise was smaller than the reduction level of the ideal-reduction noise, as shown in Figure 3(b). However, the frequency width of the modeled ANC noise increased, and the annoyance was closer in the case of the ideal-reduction noise. Figure 4(a) and (b) shows the relationship between the frequency and the intensity of active noise control and the scale values of the annoyance for the modeled ANC noise, the equal L_A noise and the random phase noise. In the random phase noise, the result showed the same tendency as the modeled ANC noise.

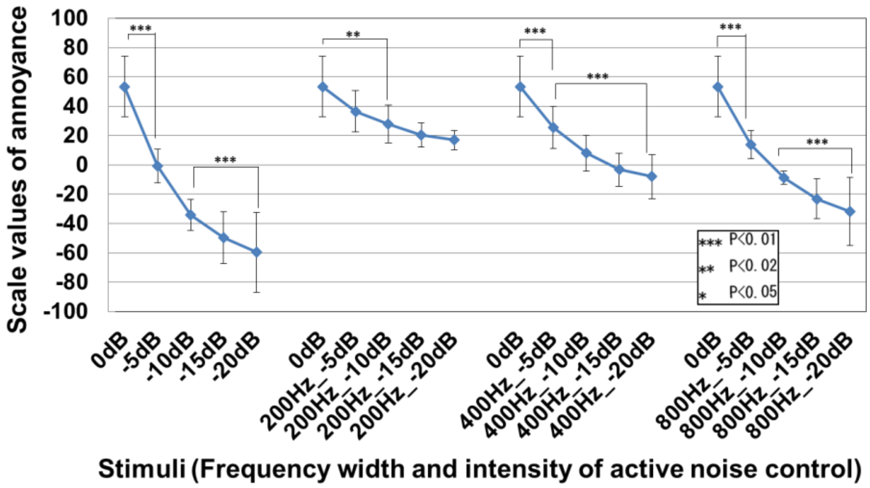


(a) Reference noise

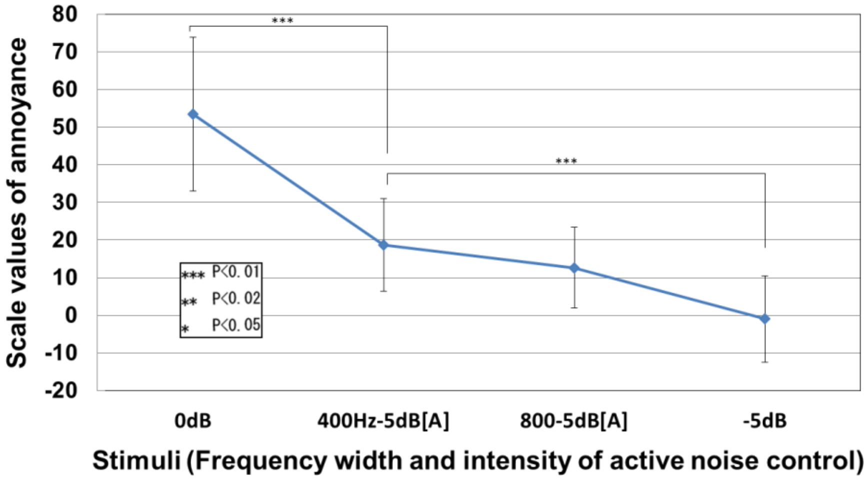


(b) Equal L_A noise

FIGURE 3. Scale values of annoyance and frequency width and intensity of active noise control in the modeled car engine noise.



(a) Reference noise



(b) Equal L_A noise

FIGURE 4. Scale values of annoyance and frequency width and intensity of active noise control in the random phase noise.

4. MEG MEASUREMENT

4.1 Participants

The same volunteers used in the Scheffe's paired comparison tests participated in the recording of MEG responses. They were seated in a magnetically-shielded room with a comfortable thermal environment. The auditory stimuli were presented using the same earpieces as in the paired comparison test (ER-2, Etymotic Research).

4.2 Tasks

According to the annoyance levels of Scheffe's paired comparison test, the reference noise, the intermediate- and the least-annoyed stimuli in the modeled ANC noise were decided for each participant and each reference noise. Participants were requested to carry out Thurston's paired-comparison tests for all combinations of stimuli for each reference noise, i.e., three pairs ($N(N-1)/2$, $N=3$) of stimuli with a different order of each pair per session, and random presentation of the pairs. They were asked to judge the annoyance of the constant speed car engine noise, and to close their eyes.

4.3 MEG recording and analysis

MEGs were recorded with a 122-channel whole-head MEG system (Neuromag-122^{TM}, Neuromag Ltd.) in a magnetically shielded room in AIST Kansai Center. MEG recordings were conducted at the same time as the Thurston's paired-comparison tests. The effective durations of autocorrelation functions (ACF) of the alpha wave, τe, previously reported as an objective index of preference/annoyance, were obtained (2-4). In this study, the alpha wave was extracted by bandpass filtering between 8 and 13 Hz. Autocorrelation functions (ACF) of the alpha wave were calculated for each stimulus. Figure 5 shows an example of a recorded MEG between 8 and 13 Hz. We defined three channel sets, the left and right temporal and occipital areas, as shown in Fig. 5. ACF of the alpha wave and its effective duration, τe, were calculated using the same method as previous study [5].

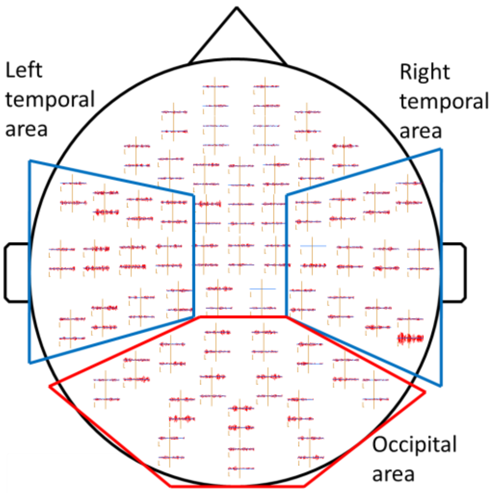
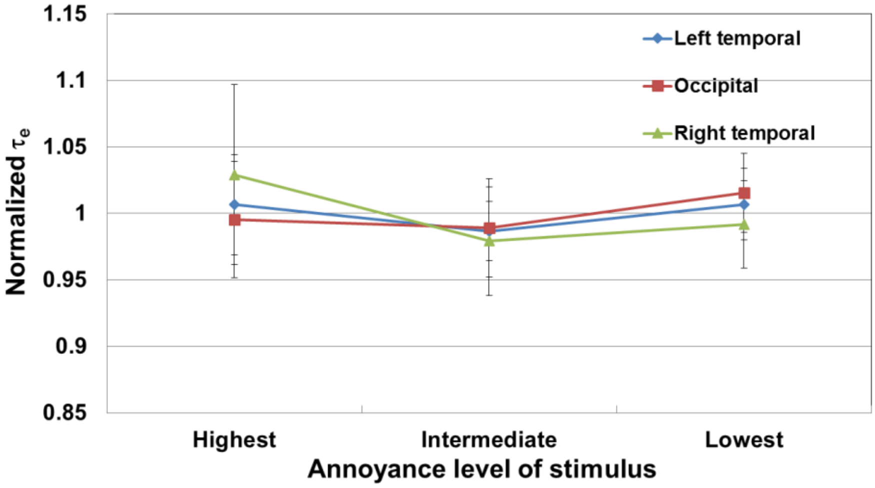


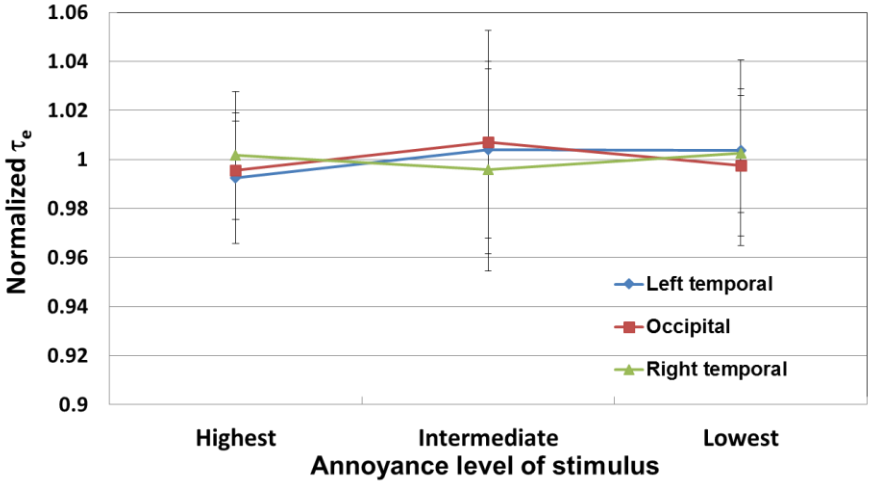
FIGURE 5. An example of recorded MEG alpha activities between 8 and 13 Hz.
Three channel sets, the left and right temporal, and the occipital areas, were analyzed.

4.4 Results

Figure 6(a) and (b) show the relationships between the scale values of subjective annoyance and the τe, obtained from the three channel sets in the modeled car engine noise and the random phase noise, respectively. The subjective annoyance of stimuli had no significant effect on τe for these noises.



(a) Modeled car engine noise



(b) Random phase noise

FIGURE 6. Relationships between the scale values of subjective annoyance and values of τe.

5. DISCUSSION

In the subjective annoyance measurement, the annoyance of reference noises was the highest in most participants. When the cut-off frequency and reduction-level of the modeled ANC noise increased, the annoyance decreased. Generally, the sharpness of the stimulus was increased by ANC. The results indicated that the decrease in loudness was more effective than for the equal LA noise; when the cut-off frequency of ANC was increased, the annoyance was decreased. We came to the conclusion that the effectiveness of reduction in the sharpness was perceived owing to the high frequency parts. In the MEG measurement, unlike the previous study, the subjective annoyance of stimuli had no significant effect on the duration of the alpha wave. As the car engine noise is considered an active sound, it is possible that the impression was not reflected the relaxed state to the alpha wave. The effectiveness of ANC was confirmed for constant speed engine noise, as in random phase noise. Further investigations of other vehicle operations, such as acceleration, are topics for future research.

6. CONCLUSION

Subjective annoyance decreased as cut-off frequency and reduction-levels of ANC increased. Moreover, in the equal L_A noise, when the cut-off frequency of the modeled ANC noise increased, the annoyance was closer to the ideal-reduction noise. Conversely, no significant effects of ANC were observed in τe of the alpha activity in the MEG measurement. In the random phase noise, the result showed the same tendency as the modeled ANC noise in both the results of subjective annoyance measurement and MEG measurement. These results indicated that a decrease in loudness is important for improvements in the auditory impression of constant speed car engine noises.

7. REFERENCES

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