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Subjective evaluation of accelerating car interior noise using brain magnetic field

Kenji Takami[a], Shunsuke Ishimitsu[b], Seiji Nakagawa[c] and Toshihiko Asami[a]

[a]Univ. of Hyogo, 2167 Shosha, 671-2201 Himeji, Japan
[b]Hiroshima City University / National Institute of Advanced Industrial Science and Technology, 3-4-1 Ozuka-Higashi, Asa-Minami-Ku, 731-3194 Hiroshima, Japan
[c]National Institute of Advanced Industrial Science and Technology (AIST), 1-8-31 Midorigaoka, 563-8577 Ikeda, Osaka, Japan
hyogo.takami@aist.go.jp

The production concept of car engine sound has been changing from finding a solution to noise to designing sound. Although many studies have been conducted on creating comfortable car-engine sound, the psychoacoustic effects of time-varying rate for accelerating-engine sounds are still unclear. Thus, we investigated the effects of increasing the frequency rate of car interior noise on auditory impressions using psychological and neurophysiological methods. Harmonic complex tones that simulate acceleration noise were used as stimuli. First, subjective evaluations were examined using the semantic differential (SD) method. Second, neuronal activities of the auditory cortex evoked by these stimuli were measured by magnetoencephalography (MEG). The results indicated that has a significant effect on subjective impressions and on neuronal activities of the auditory cortex.

1 Introduction

Sound has come to be associated with various products. The production concept of car engine sound has been changing from finding solutions to noise to designing sound. That is, most work has no longer focused on reducing engine noise but making it comfortable [1][2][3]. The problem with controlling the engine sound is the method of evaluating the differences in auditory impressions. The components of the engine sound change as the engine speed increases. Increasing the sound gives listeners auditory impressions such as " sporty " and " accelerating. " However, the psychoacoustic effects of increasing frequency for accelerating engine sound have not been sufficiently studied [4].
Moreover, the auditory impressions have been examined using subjective evaluation methods such as the semantic differential (SD) method and the pair comparison method. However, obtaining reliable results with only these methods is difficult. Therefore an evaluation method that is quantitative and objective is required. Also, most studies have used bioinstrumentation for sound quality evaluationsThese methods using bioinstrumentation are established objective tools to evaluate sound quality [5][6]. In this study, the psychoacoustic effects of increasing the rate of frequency for acceleration noise in car interiors were examined using the SD method. Moreover, neuronal activities elicited in the auditory cortex were measured by magnetoencephalography (MEG) to establish an objective evaluation index for the subjective evaluation; we compared the results of the SD method and the auditory magnetic fields evoked.

2 Stimuli

Model sound sources that simulate acceleration noise with an in-line 4-cylinder engine were used as stimuli. With the in-line 4-cylinder engine, the engine fires twice in each rotation, generating a secondary vibration force, and these higher harmonics are the main component of the noise. Therefore, model sound sources were created as harmonic complex tones comprised of even-numbered orders as well as the main components of the in-line 4-cylinder engine noise. These imitated acceleration noise by changing the frequencies of each of its components over time. Five kinds of stimuli were used for this study The increased rates of frequency which were comparable to the second order component of in-line 4-cylinder engine noise, were 15, 25, 35, 50, and 70 Hz/s. The stimulus duration was 4 s, including rise and fall ramps of 10 ms. Furthermore, the frequency of the end was set at 370 Hz.

3 Subjective evaluations using the SD method

3.1 Method

Nineteen subjects (21 - 25 years old; fifteen male, four female) with normal hearing participated in this experiment. Nine of these subjects also participated in a measurement of brain magnetic fields. Stimuli were presented using headphones (SONY, MDRCD280), and the experiment was performed in a noise attenuating room. The SD method was used for the evaluation. This method includes a number of adjective pairs, which are expressive of sound quality and tone. The pairs were prepared, and subjects evaluated them on a likert scale of five or seven ranks. In this experiment, 13 adjective pairs and seven ranks evaluation were used. Fig. 1 shows the adjective pairs used in this experiment. The training part of the experiment involved the presentation of each stimulus twice for each stimulus at random. Subjects evaluated each stimulus twice, ten times in total.

3.2 Results

Fig. 2 shows the experimental results. The effects of the time-varying rate of frequency on each adjective pair were statistically analyzed using an analysis of variance (ANOVA). The results were that all adjective pairs except " sporty - not sporty " ($p = 0.11$) demonstrated the effects of the time-varying rate of frequency (Fig. 2). A factor analysis was conducted to determine the main perceptual dimensions. Table 1 shows the fac-

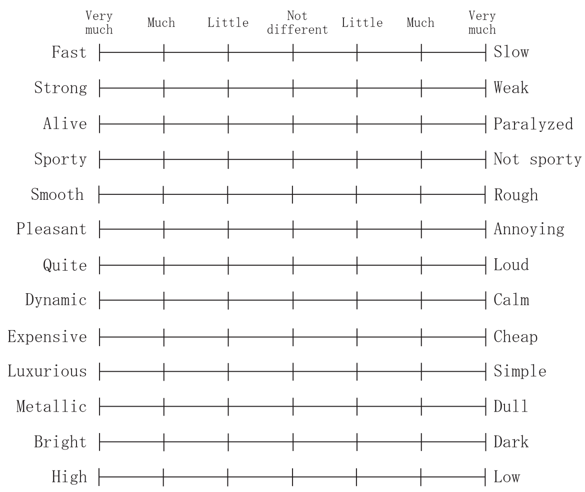

Figure 1: Evaluation paper

Table 1: Factor analysis

Adjectives pairs	Factor1"Powerful・Metallic"	Factor2"Luxurious"	Factor3"Quiet"
Rough-Smooth	0.860	-0.225	0.095
Bright - Dark	0.856	-0.377	0.017
Dynamic - Calm	0.853	-0.154	0.210
High - Low	0.849	-0.338	-0.070
Metallic - Dull	0.791	0.035	0.360
Fast - Slow	0.707	0.175	0.242
Sporty - Not sporty	0.629	0.435	0.288
Alive - Paralyzed	0.557	0.142	0.471
Luxurious - Simple	-0.159	0.900	-0.104
Expensive - Cheap	-0.073	0.773	0.108
Strong - Weak	-0.205	0.719	0.439
Pleasant - Annoying	0.022	0.497	0.002
Quiet - Loud	-0.230	-0.029	-0.547

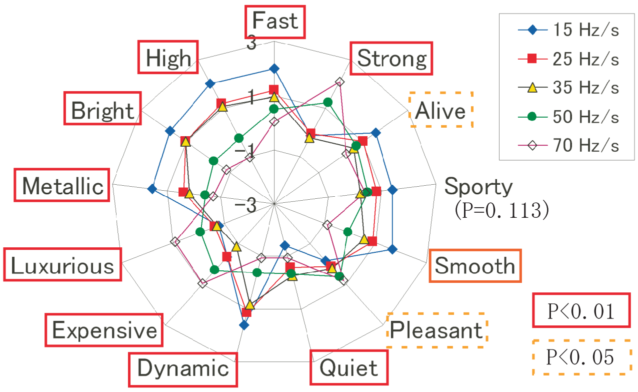

Figure 2: Subjective evaluation

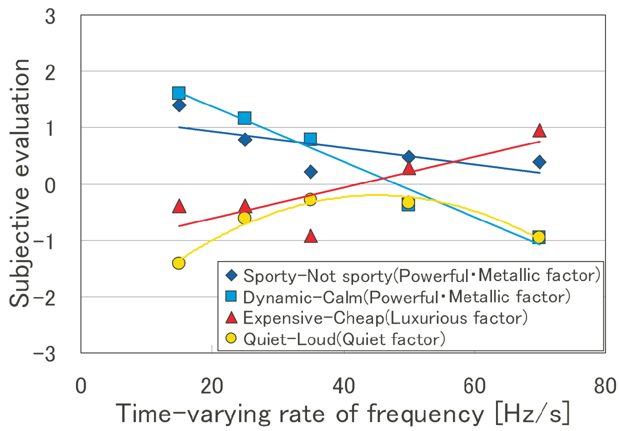

Figure 3: Correlation of subjective evaluation with time-varying rate of frequency.

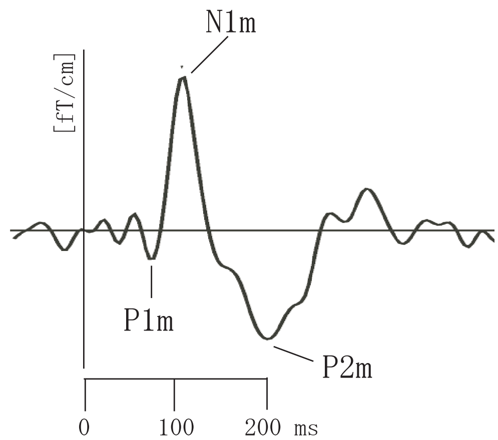

Figure 4: Typical waveform of auditory evoked magnetic fields.

tor loadings. A principal factor method was applied to extract the factors, and varimax rotation was used for the solution. The method revealed three factors, " powerfulĽmetallic factor ", " luxurious factor, " and " quiet factor ". Fig. 4 shows the correlation of the averaged subjective evaluation with the increased rate of frequency. For the powerful metallic factor, such as " dynamic - calm ", we found that the auditory impression worsened as the rate of frequency increased. However, for the luxurious factor, such as " expensive - cheap ", the auditory impression improved as the rate increased. These results indicate that the increased rate of frequency affected auditory impressions.

4 Measurement of brain magnetic fields

4.1 Magnetoencephalography

Neuronal activities of the auditory cortex evoked were measured by magnetoencephalography (MEG) to establish the objective evaluation index of the subjective evaluation. Magnetoencephalography is well suited for studies of the auditory cortex [8]. Fig. 5 shows a typical magnetic response evoked by auditory stimuli. Any sound evokes a typical response, N1m and P2m. N1m is an auditory evoked brain magnetic field with a magnitude of 100 fT observed over the auditory cortex, 100 ms after the onset/offset of auditory stimuli. P2m is a response observed 200 ms after the onset/offset of auditory stimuli[9]. We investigated the peak amplitude and latency for N1m and P2m, respectively.

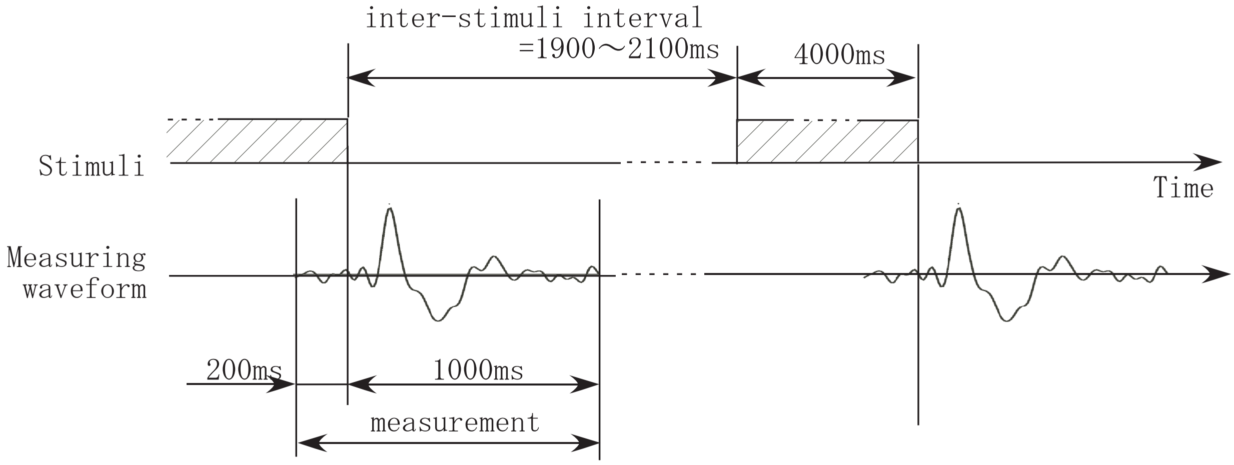

Figure 5: Presentment method of stimuli.

4.2 Method

4.3 Subjects

Twelve subjects (21 - 30 years old; ten male, two female) with normal hearing participated in this experiment. During recording, subjects sat in a chair with their bodies fixed in a vacuum cast. Subjects were instructed to focus on a point on the wall.

4.4 Presentment of stimuli

Five kinds of stimuli, with different time-varying rates of frequency were presented randomly to the left ear through plastic tubes and earpieces inserted into the ear canals. Fig. 3 shows the presentment of the stimuli. An inter stimulus interval (ISI) was randomly set at between 1900 and 2100 ms. Subjects were instructed to push a switch quickly when they listened to a target stimulus at 1 kHz and 80 ms.

4.5 Measurements and Analyses

Recordings of auditory evoked brain magnetic responses were conducted in a magnetically shielded room using a 122-channel whole-head DC superconducting quantum interference device (DC-SQUID) magnetometer (Neuromag-122$^{\mathrm{TM}}$, Neuromag Ltd.,). We recorded the off responses to the stimuli. Magnetic data were sampled at 400 Hz after being band-pass-filtered between 0.03 and 100 Hz and then averaged more than 50 times for each stimulus. The averaged responses were digitally band-pass-filtered between 1 and 30 Hz. Neuromag-122TM had two pick-up coils in each position, and these coils measured two tangential derivatives, $\partial Bz\ /\partial x$ and $\partial Bz\ /\partial y$, of field component Bz [10]. The root-mean-squares (RMS) of $\partial Bz\ /\partial x$ and $\partial Bz\ /\partial y$ (eq.1) were determined as the amplitude of the response at each recording position.

$$B' = \sqrt{(\frac{\partial Bz}{\partial x})^2 + (\frac{\partial Bz}{\partial y})^2} \qquad (1)$$

In each subject, we used a N1m peak amplitude with a channel that showed the maximum amplitude placed over the right temporal area. These N1m and P2m peak amplitudes were normalized within each subject with respect to the maximum value. The effects of the time-varying rate of frequency on the N1m and P2m normalized peak amplitude and latency were statistically analyzed using an analysis of variance (ANOVA). A Scheffe's test was used in subsequent post-hoc tests.

5 Results and discussion

For all stimuli, N1m and P2m responses were found in the right hemisphere, as shown in Fig. 6. Fig. 7 and Fig. 8 show the N1m peak latency and normalized mean amplitude as a function of the increased rate of frequency. Fig. 9 and Fig. 10 show the P2m peak latency and normalized mean amplitude as a function of the rate of frequency. The analysis of variance of the N1m amplitude demonstrated the effect of the increased rate of frequency ($p<0.01$). However, the P2m amplitude and the mean N1m and P2m peak latencies were not significant. In addition, the Scheffe's test revealed that the N1m amplitudes were significantly larger at 25 Hz/s than at 35 and 50 Hz/s. The analysis of our subjective evaluation (Fig. 5) revealed that the scores of the powerfulĽmetallic impression decreased as the rate of frequency increased. The results of the subjective evaluation with the N1m amplitude were similar to those of the subjective evaluation of the powerfulĽmetallic impression. However, the components, except for the increased rate of frequency, may have affected these results. One of the components was start frequency. The stimuli used in this experiment were fixed end frequency and the duration. That is, each stimulus had a different start frequency. The different start frequencies in each stimulus may have influenced the results in this experiment. Therefore, we need to examine such components except for the increased rate of frequency. Ishimitsu and Kobayashi reported that scores of " powerful, " " metallic, " and " expensive " impressions increased as the rate of frequency increased [1]. This contradicts our results. The sound sources of a real car with an in-line 4-cylinder engine were used as stimuli in their experiment, while harmonic complex tones that simulated acceleration noise were used as stimuli in our experiment.

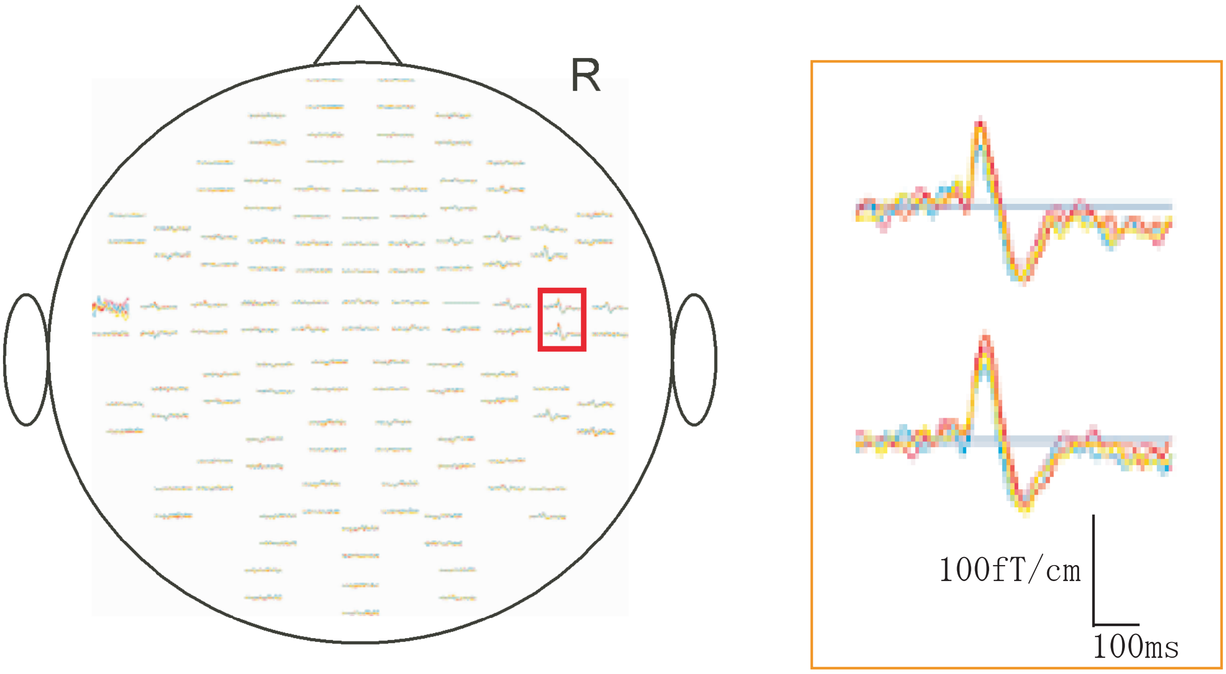

Figure 6: Typical waveform of auditory evoked magnetic fileds from 122 channels in a subject.

That is, subjects in the subjective evaluation may have sensed stimuli as a signal and not as engine noise. These problems require further investigation.

6 Conclusion

In this study, we investigated the psychoacoustic effects of increasing the frequency rate of acceleration noise in cars using the SD method. Moreover, we measured the brain magnetic fields of subjects for an objective evaluation of auditory impressions. The results were that the increased rate of frequency affected auditory impressions such as " powerful "" metallic ", and " expensive. " The results of the subjective evaluation with the brain magnetic fields revealed that the differences of auditory impressions reflected the N1m amplitude of brain magnetic fields evoked by noise. A more detailed investigation involving an estimation of the parameters associated with auditory impressions, an examination using the sound sources of real car noise, and other tests are needed.

Acknowledgement

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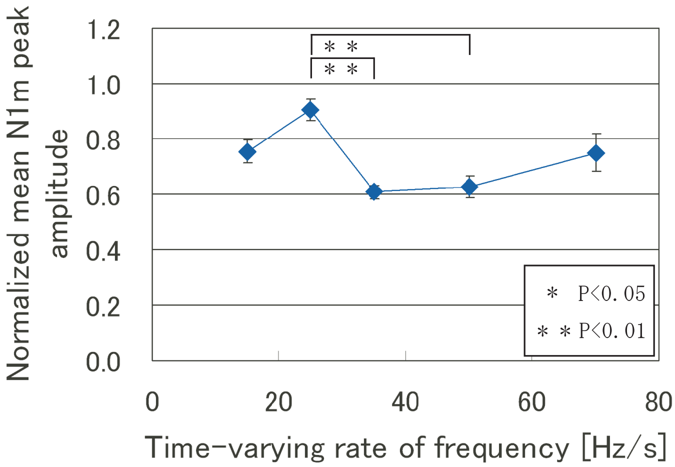

Figure 7: Normalized mean N1m magnitude as a function of the time-varying rate of frequency. The bars indicate the standard error of mean (SEM) used in this experiment.

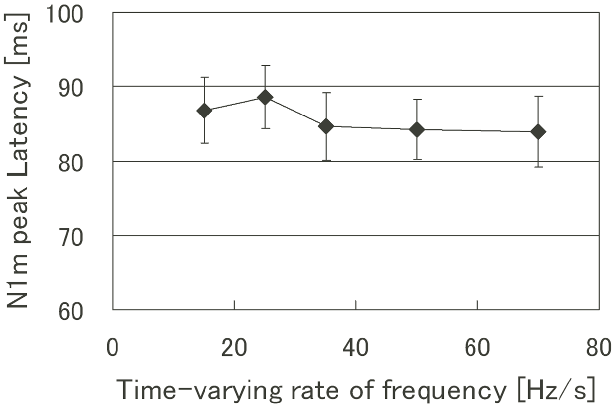

Figure 8: Mean N1m peak latency as a function of the time-varying rate of frequency. The bars indicate the standard error of mean (SEM).

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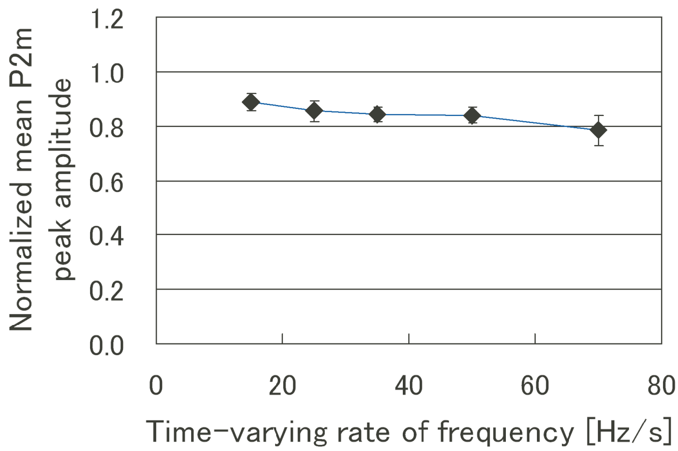

Figure 9: Normalized mean P2m magnitude as a function of the time-varying rate of frequency. The bars indicate the standard error of mean (SEM).

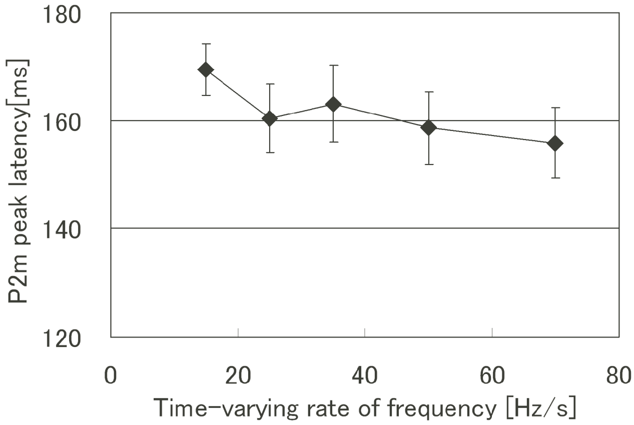

Figure 10: Mean P2m peak latency as a function of the time-varying rate of frequency. The bars indicate the standard error of mean (SEM)