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Psychoacoustical assessment of thermal impression of automotive HVAC noise

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ABSTRACT
Two subjective assessments were performed focusing on the auditory impression of automotive HVAC noise concerning coolness and warmness. First, paired comparison tests were carried out under various conditions of room temperature. Five stimuli were synthesized by stretching the spectral envelopes of recorded automotive HVAC noise to assess the effect of the spectral centroid. Twelve normal-hearing subjects were asked to rate the auditory impression of the stimuli for each pair on a seven-point scale according to how much the latter is warmer (for the winter tests) or cooler (for the summer tests) than the former. Results show that the spectral centroid significantly affects the auditory impression concerning coolness and warmness; a higher spectral centroid induces a cooler auditory impression regardless of the room temperature. Second, effects of HVAC noises on the subjects' sensation of coolness and warmness were evaluated by using a method of continuous judgment by category. Room temperature were controlled to increase/decrease linearly, and HVAC noise, having warm/cool auditory impressions, were presented. Subjects had to answer their sensation of coolness/warmness at regular time intervals. The results showed that HVAC noise had significant effect on the time change rate of sensation of coolness/warmness.
Keywords: HVAC noise, auditory impression, warmness/coolness

1. INTRODUCTION
Noise is an important factor of the comfort of the interior of the car cabin. In particular, the noise associated with a heating, ventilation and air conditioning system (HVAC) has gained importance since recent advances in the reduction of engine noise. Much effort has been devoted to reducing levels of automotive HVAC noise, however, the reduction of the noise levels beyond a certain level sometimes faces with other problems (1). For example, there might be the relative rise of the secondary noise sources. In addition, silence sometimes causes a loss of operation feeling - we recognize the air-conditioning system doesn't work enough in case it is too quiet, even if it works well actually. Therefore, there is a need for a novel method to 'design' noises. The present study focuses on the thermal impression of sound by designing HVAC noise rather than considering the reduction of noise levels.

Previous literatures have investigated auditory and thermal cross-modal interactions (2–5). They mainly examined the relation between the thermal sensation and noise level, However, the results obtained are heterogeneous and sometimes contradictory. Meanwhile, from the point of view of the sound design of an HVAC system, few studies have focused on the thermal sensation and frequency characteristics of noise. Roussarie et al. (6) found a significant interaction between sound and thermal comfort, in that a specific sound significantly enhanced thermal comfort and that some types of noise are more suited to air-conditioning systems than others. It was thus concluded that HVAC product

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engineers have to account for both auditory and thermal perceptions to provide the most comfortable thermal condition at home or in a vehicle.

The passenger in a vehicle usually obtains information about operating conditions such as the air volume from HVAC noise consciously or unconsciously. It is thus considered that there is the potential to enhance the effects of cooling and heating employing HVAC sounds that better convey cool and warm impressions respectively. In the present study, to clarify the frequency characteristics of the vehicle HVAC sound and auditory impression concerning coolness and warmness, listening tests were performed using a paired comparison technique under various conditions of room temperature.

2. EXPEIMENTS

2.1 Stimuli

Model sounds synthesized from the recorded noise of an actual vehicle HVAC system were used as stimuli. The noise generated by a vehicle HVAC was recorded at approximately the ear position for the driver's seat. The HVAC system were set at the maximum air flow and were operated steadily. The long-term power spectrum and spectrogram of the recorded HVAC noise are shown in Fig. 1.

To extract the spectral envelope, the linear predictive coding (LPC) spectral envelope (7) was calculated from the recorded HVAC noise. Five model sounds were synthesized by stretching the spectral envelope by a factor of 1/2, 2/3, 1, 3/2, and 2 (giving models A, B, C, D, and E, respectively). Here, the number of LPC dimensions for abstraction of the spectral envelope was 150. Generally, the higher the number of LPC dimensions, the higher fidelity the synthetic sound has relative to the original sound. From the results of preliminary studies, we selected 150 LPC dimensions so as to create synthetic sound similar enough to the original sound.

Auditory stimuli with stretching spectral envelopes (i.e., models A, B, C, D and E) were obtained as follows by (1) generating Gaussian noise with sampling frequencies that were a product of the base sampling frequency of 48 kHz and the factor 1/2, 2/3, 1, 3/2, and 2, respectively; (2) passing the generated noise through the LPC filter; and (3) resampling the filtered signals at 48 kHz.

The power spectra of the synthesized HVAC model sounds are shown in Fig. 2. The spectral centroids of the synthesized stimuli (A, B, C, D, and E) after the sounds passed through an A-weighting filter were 1678, 1896, 2146, 2334, and 2512 Hz, respectively, according to the equation

$$Spectral\ Centroid = \frac{\sum_{k=1}^{N} k\, f(k)}{\sum_{k=1}^{N} f(k)} \tag{1}$$

where f(k) is the amplitude corresponding to bin k in the spectrum.

2.2 Methods and Apparatus

Two listening tests were carried out in a soundproof room, one in the summer (July 15 to 18) and one in the winter (February 2 to 6). Twelve subjects participated in each of the summer and winter tests; five females and seven males aged between 21 and 24 years (mean age of 21.8 years) in the summer experiment and four females and eight males aged between 20 and 23 years (mean age of

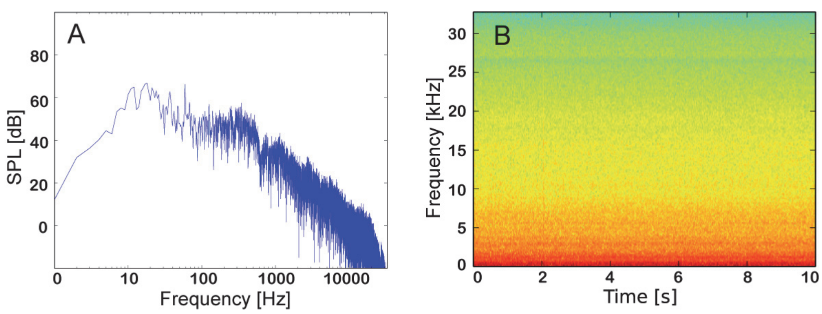

Figure 1 – (A) Long-term power spectrum and (B) spectrogram of the recorded HVAC noise.

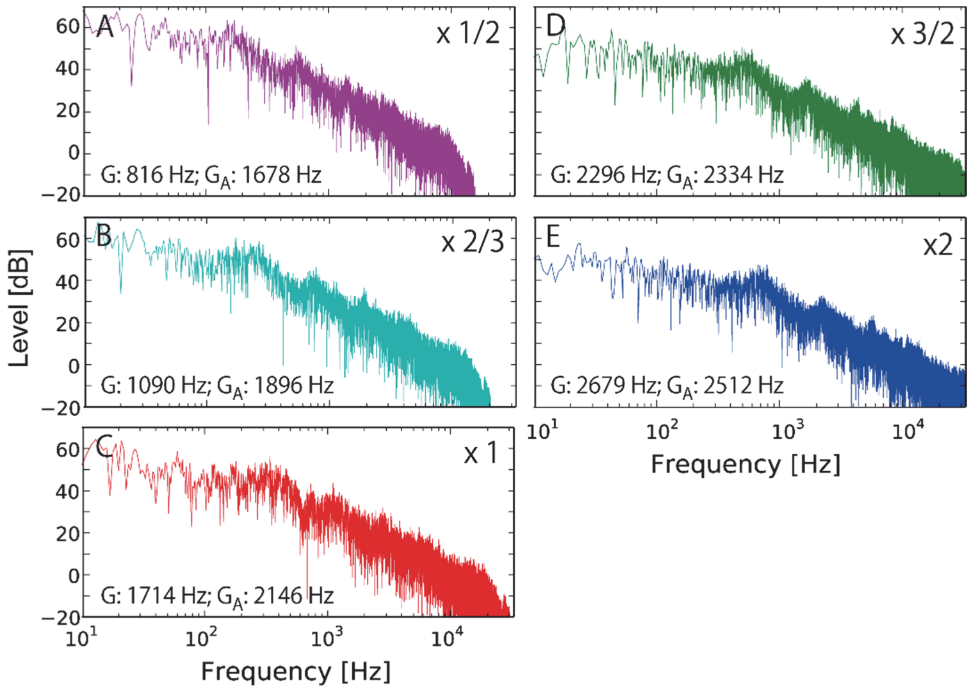

Figure 2 – Power spectrum of the HVAC model sounds synthesized by stretching the spectral envelope of the recorded HVAC noise by a factor of 1/2, 2/3, 1, 3/2, and 2 (referred as models A, B, C, D, and E, respectively). G refers to the spectral centroids of the auditory stimuli and GA refers to those after sounds passed an A-weighting filter.

21.9 years) in the winter test. Six subjects participated in both the summer and winter tests. Table I gives the room-temperature conditions used in the experiments. In each experiment, there were three sessions with different conditions of the room temperature, and subjects judged the auditory impression concerning coolness and warmness in the summer and winter tests for the synthesized HVAC model sounds employing the Scheffe's paired comparison. For the control of the room-temperature condition, the air conditioning equipment of the soundproof room was used. In both summer and winter tests, the sequence of the change in the room temperature was from warm to cold for half of the subjects, and from cold to warm for the other half. The ambient dry-bulb temperature (Ta, °C), relative humidity (RH, %) and predicted mean vote (PMV) of the soundproof room and anterior chamber were measured using a portable amenity meter (AM-101, Kyoto Electronics Manufacturing Co. Ltd., Japan).

Subjects were instructed to wait approximately 10 minutes before the start of the experiment in an anterior chamber where the room temperature was kept constant at about 25 and 22 °C in the summer and winter tests, respectively. Furthermore, at the end of each session, subjects were instructed to wait approximately 20 minutes in the anterior chamber. Subjects wore their own clothing for the experiments, but they were instructed to adjust their clothing so that they were thermally comfortable in the anterior chamber. Roughly estimated overall clothing insulation values for the test subjects were 0.5 and 1.1 clo for the summer and winter tests, respectively. During the experiments, the room temperature was monitored and the temperature change was confirmed to be within 1 °C.

Subjects were first asked to imagine a scenario: "HVAC noise is heard from the front unit when you are driving a vehicle." Additionally, subjects were instructed to assume a cooling operation in the summer experiment and heating operation in the winter experiment. Auditory stimuli were synthesized with Matlab (The Mathworks, Inc., MA, USA) and presented diotically through a digital-to-analog converter (Audiofire12, Echo Digital Audio Corporation, CA, USA) and headphones (HD650, Sennheiser Electronic GmbH & Co. KG, Germany). The intensity of the stimulation was adjusted to 70 dBA for all auditory stimuli. The duration of each stimulus was 1.0 s. A comparison pair consists the auditory impression of the stimuli for each pair on a seven-point scale (−3, −2, −1, 0, 1, 2, 3) according to how much the latter is warmer (for the winter tests) or cooler (for the summer tests) than the former. Scores of ±3, ±2, ±1 and 0 respectively indicate extreme, moderate, and slight differences

Table 1 – Room-temperature conditions

Experiment	Condition	Ta [°C]	RH [%]	PMV
Summer	hot2	31	62	2.1
	hot1	28	61	1.1
	even	25	59	0
Winter	even	22	62	-0.3
	cool1	19	61	-1
	cool2	16	59	-1.7

At end of the experiment, the subjects were asked to answer the following simple queries about the judgments.

(1) Were you able to judge the auditory stimuli as vehicle HVAC noise?
(2) Was there any difficulty in judging?
(3) Did you apply any conscious criteria in judging? If so, what were the criteria?
(4) Were you aware that the room temperature affected the thermal impression of the auditory stimuli?

3. RESULTS

The results obtained in the tests were analyzed employing Scheffe's paired comparison method (Nakaya variation) [8]. Figure 3 shows the subjective scale values of each auditory stimulus on yardstick scales as the results of the summer and winter tests. Since the scale value obtained in the winter experiment

was inverted in terms of the sign, the lower scale values indicate a warmer impression and the higher scale values indicate a cooler impression in both summer and winter tests. For all conditions, results show that the auditory stimuli were arranged in the order of the spectral centroid: the stimuli with a higher spectral centroid gave a cooler auditory impression. The differences in the results for stimuli A to E, taken as the largest difference in subjective scale values for all conditions, were larger for a high room temperature in both summer and winter tests.

The results of an analysis of variance (ANOVA) reveal that the effect of the stimulus (the main effect) was significant in both summer and winter tests (summer: $F(4,12) = 77.6$, $p < 0.01$; winter: $F(4,12) = 277.2$, $p < 0.01$). Interaction effects of the stimuli and the room temperature conditions were not significant in either the summer or winter test. The combination effect of stimulation was significant in the winter test ($F(6,12) = 3.25$, $p < 0.05$), while it was not significant in the summer test.

Table II gives the subjective scores of the auditory stimuli obtained for the individual subjects in the summer and winter tests. In the results of the summer test, the effect of the stimulus was significant for 10 subjects of the 12 subjects, and its trend corresponded with the overall results: the auditory stimuli with a higher spectral centroid were considered cooler, and those with a lower spectral centroid were considered warmer. For one of the remaining two subjects, the effect of the stimulus was not significant. For the other subject, the effect of stimulus was significant but the trend was the opposite of that for the overall results (in SS9): the auditory stimuli with a higher spectral centroid were considered warmer. Meanwhile, in the winter test, the effect of the stimulus was significant for 11 subjects of the 12 subjects, and its trend corresponded with the overall results. Again, the results for one subject show that the effect of the stimulus was significant but the trend was opposite that of the overall results (in SW6). This subject was not a participant in the summer test.

In the questionnaire that was conducted after the experiment, all subjects answered that they could accept all the auditory stimuli as vehicle HVAC noise. In addition, most of the subjects whose results corresponded with the overall results reported that they consciously judged the stimuli using a criterion: they perceived the auditory stimuli having "high-frequency" sound as cool and those having "low-frequency" sound as warm. Meanwhile, the subjects whose results opposed the overall results also consciously used a judging criterion: the opposite of the general trend mentioned above. In

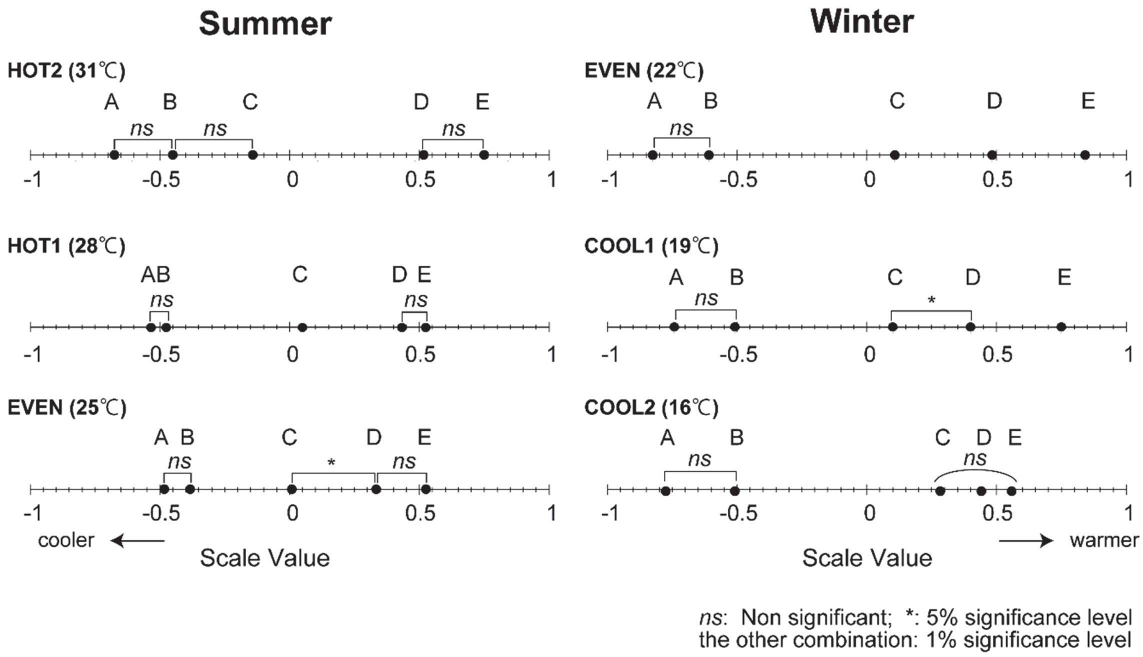

Figure 3 – Subjective scores of each auditory stimulus on yardstick scales as the result of the Scheffe's paired comparison of the summer and winter tests.

addition, some subjects made their judgment according to scenes recalled by the auditory stimuli (e.g., a low-frequency stimulus recalled a fireplace, and a high-frequency stimulus recalled a cold wind). Furthermore, although the stimulus intensity was set to 70 dBA for all stimuli, there were some subjects who answered that a difference in stimulus intensity was a judging criterion. Most subjects answered that they were unaware that the room temperature affected the thermal impression of the stimuli, while some subjects answered that the auditory impressions were enhanced when the room temperature was lower/higher.

4. DISCUSSIONS

The results of the present study reveal that the spectral centroid significantly affects the auditory impression of coolness and warmness; i.e., a higher spectral centroid induces a cooler auditory impression regardless of the room temperature. This robust response of the auditory impression of coolness and warmness to vehicle HVAC noise having different spectral centroids is similar to the thermal impressions induced by "warm" and "cool" colors (see (8) for a comprehensive review). However, it is clear that the effect is the opposite for some people: a higher/lower spectral centroid induces a warmer/cooler auditory impression. This suggests that the cultural background and experience are factors.

5. CONCLUSIONS

The results of the study reveal a tendency that the difference in impressions is wider at higher room temperature, regardless of the cooling or heating operation. This result suggests that the design of the spectral centroid of HVAC noise would be more effective for the cooling operation in summer, although there is a need for further investigation.

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Table 2 – Subjective scores of the auditory stimuli obtained for individual subjects

	Subject	Stimuli					Significance level			Yardstick (Y)	
		A	B	C	D	E	S_α	$S_{\alpha\ (B)}$	S_γ	Y(0.05)	Y(0.01)
Summer	S_S1	-1.00	-0.70	-0.23	0.73	1.20	**			0.60	0.77
	S_S2	-0.40	-0.17	-0.07	0.20	0.43	**			0.63	0.81
	S_S3	-0.80	-0.73	0.10	0.63	0.80	**			0.49	0.62
	S_S4	-0.57	-0.67	0.77	0.27	0.20	**			1.01	1.30
	S_S5	-0.73	-0.70	0.07	0.37	1.00	**			0.59	0.76
	S_S6	-1.30	-1.03	-0.17	0.97	1.53	**			0.72	0.92
	S_S7	-1.47	-0.80	0.10	0.90	1.27	**			0.69	0.89
	S_S8	0.07	0.27	-0.03	0.03	-0.33		**		0.90	1.16
	S_S9	1.17	0.40	-0.03	-0.53	-1.00	**			0.62	0.79
	S_S10	-0.57	-0.37	-0.20	0.67	0.47	**			0.82	1.05
	S_S11	-1.10	-0.70	-0.03	0.53	1.30	**			0.79	1.01
	S_S12	-0.07	-0.03	-0.60	0.37	0.33	*			0.91	1.17
Winter	S_w1	-0.87	-0.80	0.43	0.53	0.70	**			0.80	1.02
	S_w2	-1.43	-0.70	0.27	0.80	1.07	**		*	0.60	0.77
	S_w3	-0.87	-0.73	0.23	0.70	0.67	**			0.61	0.78
	S_w4	-1.53	-1.07	0.53	0.90	1.17	**	*		0.44	0.56
	S_w5	-0.33	-0.47	-0.10	0.23	0.67	**			0.80	1.03
	S_w6	1.47	0.97	-0.67	-0.87	-0.90	**			0.71	0.91
	S_w7	-0.83	-0.70	0.43	0.57	0.53	**	**		0.16	0.21
	S_w8	-1.20	-0.63	0.43	0.43	0.97	**			0.68	0.87
	S_w9	-0.90	-0.53	0.13	0.50	0.80	**			0.52	0.67
	S_w10	-1.13	-0.40	-0.27	0.53	1.27	**			0.76	0.97
	S_w11	-1.03	-0.70	0.47	0.37	0.90	**			0.70	0.90
	S_w12	-0.70	-0.73	0.07	0.60	0.77	**			0.33	0.43

*: 5% significance level; **: 1% significance level

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