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Design of approach informing sound for quiet vehicles that indicates a car traveling

Tsuruta-Hamamura, Mariko[1]
Kobayashi, Toki
Kosuge, Takahiro
Tsujinaga, Tomoya
Hasegawa, Hiroshi[2]
Graduate School of Engineering, Utsunomiya University
7-1-2 Yoto, Utsunomiya, Tochigi Japan 321-8585

ABSTRACT

Quiet vehicles, such as hybrid and electric vehicles, emit less noise than vehicles having an internal-combustion engine, particularly at low speeds. To prevent accidents resulting from this quietness, acoustic vehicle alerting system has been designed to create approach informing sounds. However, a questionnaire survey that we conducted previously revealed that the recognition rate of the approach informing sound was not high (about 40%). To improve the recognition of the approach informing sound, we designed approach informing sounds using onomatopoeic sounds and evaluated them using an evaluation grid method for car-like sounds. We first obtained onomatopoeic sounds that reflected pedestrians' images of approach informing sounds for quiet vehicles. The obtained onomatopoeic sounds frequently included the vowel "u," the consonants "p" and "b," and long tones. According to acoustic characteristics of the obtained onomatopoeic sounds (such as the fundamental frequency and roughness), we created four sound stimuli as samples of approach informing sound. We conducted an experiment using these sound stimuli and an evaluation grid method to examine the factors that affect the perception of car-like sounds as approach informing sounds. We found that sounds that replicated road noise tended to be evaluated highly as indicative of a car traveling on a road and they are thus suitable for approach informing sounds.

Keywords: Quiet vehicles, Approach informing sound, Onomatopoeic sound, Evaluation gird method
I-INCE Classification of Subject Number: 79

1. INTRODUCTION

Quiet vehicles, such as hybrid-electric vehicles and electric vehicles, emit less noise than vehicles having an internal-combustion engine, particularly at low speed. This quietness contributes to a reduction of environmental noise. However, pedestrians are at risk when quiet vehicles approach in a noisy urban environment. The first guidelines for quiet vehicles were published in Japan in 2011 [1]. These guidelines were translated and

[1] mariko@is.utsunomiya-u.ac.jp
[2] hasegawa@is.utsunomiya-u.ac.jp

modified and finally published as international guidelines in 2016 (UN Regulation No. 138 on Quiet Road Transport Vehicles) [2]. These guidelines mandate the installation of an additional sound-emitting system intended to increase pedestrians' awareness of quiet vehicles. Such a sound-emitting system is referred to as an acoustic vehicle alerting system (AVAS) and creates an acoustic approach informing sound in a speed range from 0 to 20 km/h. The guidelines introduce required acoustic characteristics of an approach informing sound relating to the minimum sound level, sound spectrum, and frequency shift. However, the recognition rate of the approach informing sound has not been high (about 40%) [3]. To improve the recognition of an approach informing sound, the present paper proposes a design method based on onomatopoeic sound that reflects the pedestrian's image of a quiet vehicle. In addition, a subjective evaluation experiment adopting an evaluation grid method was conducted in the present study to examine factors affecting the perception of car-like sounds as approach informing sounds.

2. EXPERIMENT FOR EXTRACTING ONOMATOPOEIC SOUND

2.1 Experimental conditions in the case of an actual quiet vehicle

The first experiment was conducted on a traffic comprehensive test road at Nihon University on 16 October 2017 using a Prius (TOYOTA) as an example of a quiet vehicle. The positions of the quiet vehicle and participants are shown in Fig. 1. The quiet vehicle travelled from line AA′ to line BB′ at a constant speed of 15 km/h, which was within the operational speed range of AVAS and ensured the safety of participants. This speed was measured using a speed gun. The participants stood so that they were 2 m from the centre line of the quiet vehicle as the vehicle passed, forming a line with 1-m intervals near line PP′ in Fig. 1. The experimental scene is shown in Fig. 2. The quiet vehicle passed in the front of participants three times. The participants were 10 male students attending Nihon University and having an average age of 21.5 years. The experiment was recorded using a video camera.

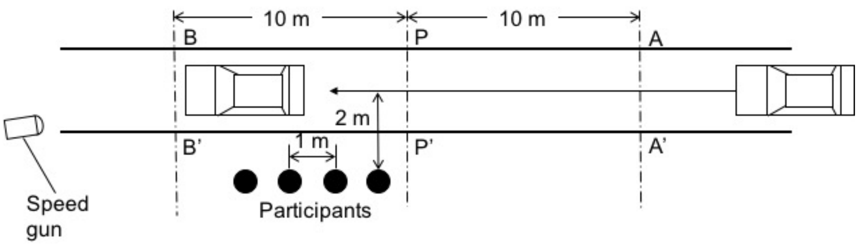

Fig. 1 Scene of the quiet vehicle and participants

Fig. 2 Experimental scene

2.2 Experimental conditions in the case of a video of a traveling car

The second experiment was conducted in a computer laboratory at Utsunomiya University. A video recording of the quiet vehicle traveling in the first experiment was reproduced from the display of a personal computer (DELL, 24 inches) three times. The participants used the displays one by one. The recorded sound was not presented in the experiment. The participants were five male students attending Utsunomiya University and having an average age of 20.8 years.

2.3 Experimental method

After watching the quiet vehicle travel, participants in both experiments were asked to provide as many onomatopoeic sounds that reflect the image of an approach informing sound of a quietly running vehicle as possible. The pattern of onomatopoeic sound was not restricted.

2.4 Experimental results

The onomatopoeic sounds provided by the 15 participants are given in Table 1. Each letter in Table 1 indicates a participant. Participants A to J participated in the first experiment involving an actual quiet vehicle (section 2.1) while participants K to O participated in the second experiment involving a video of the vehicle (section 2.2). It is noted that three participants reported that they had heard an approach informing sound before participating in the experiments in a survey conducted after the experiment. The total number of provided onomatopoeic sounds was 92. The number of provided onomatopoeic sounds did not depend on the experimental conditions; i.e., an actual quiet vehicle or a video of the vehicle. Japanese pronunciation is a combination of consonants and vowels or only vowels. We therefore analysed the results on the basis of consonants, vowels, and long tones.

Table 1. Onomatopoeic sounds provided by each participant

	1	2	3	4	5	6
A	Pi-Pi-	Pohu Pohu	Sa-	Hyu-		
B	Hu-n	Hyu-n	Sa-	Fo-n	Su-	Thi-n
C	Pi-Pi-	Pi-	Kin kin	Vu-vu-	Bi-	Wa-wa-
D	Hyu-n	Foo-n	Saa-	Syu-n	Bu ro ro ro…	Uu-n
E	Syu-	Hu-n	Syu-	Saa-	Hyu-	Su-n
F	Vi-vi-vi-vi-	Bibi…bibi…	Paupau	Kyun kyun	Be-be-	Pon…pon…pon
G	Pi-Pi-	Hyu-n	Za-za-	Byu-n	Ga-	Sa-
H	Ki-n	Hyui-n	Kooooo	Goooo	Gii-n	Doru doru doru doru
I	Vo-	Bu ro ro ro…	Kyuro kyuro kyuro			
J	Buu-n	Fi-	Bu ro ro ro	Do do do	Uuuuu	
K	Bu-n	Don don	Syan syan	Myo-n		
L	Jari Jari	Dosu dosu	Goro goro	Kirakira		
M	Hu-n	Syu-n	Kyui-n	Ui-n	Hyu-	
N	Pi-	Bu-bu-	Pu-	Bu-		
O	Sa-	Syu-	Pi pi	Fan fan	Ki-n	Pyu-n

2.5 Analysis: consonants and vowels included in the first syllable

Frequently provided onomatopoeic sounds are given in Table 2. In the table, similar onomatopoeic sounds, such as “Sa-” and “Saa-”, were counted as the same onomatopoeic sound. Frequently provided onomatopoeic sounds had the consonants /s/, /h/, /hy/, /p/, /b/, /k/, and /f/. Unvoiced consonants would be suitable for representing the image of an approach informing sound. Furthermore, the vowels /a/, /i/, and /u/ and a long tone were frequently used.

Table 2. Frequently provided onomatopoeic sounds

Onomatopoeic sound	Number of respondents
Sa-	6
Hu-n	3
Hyu-	3
Pi-Pi-	3
Burororo	3
Ki-n	2
Fo-n	2
Pi-	2

3. DESIGN OF AN APPROACH INFORMING SOUND

We created four samples of an approach informing sound according to the onomatopoeic sounds obtained in Section 2.

3.1 Acoustic characteristics of the extracted onomatopoeic sound

On the basis of frequently provided onomatopoeic sounds (see Table 2, section 2.5) and their constituting consonants and vowels, samples of approach informing sound were created using the four onomatopoeic sounds given in Table 3. Previous studies revealed acoustic characteristics that represent onomatopoeic sound [4,5]. The fundamental frequency of an unvoiced consonant is 125 Hz while that of a voiced consonant is 1461 Hz and those for vowels are given in Table 4 [4,5].

Table 3. Onomatopoeic sounds used to create the samples of approach informing sound

Stimulus No.	Onomatopoeic sound	Consonant	Vowel
1	Sa-	/s/	/a/
2	Pi-Pi-	/p/	/i/
3	Hyu-	/hy/	/u/
4	Bu-	/b/	/u/

Table 4. Average and range of fundamental frequencies of vowels [5]

Vowel	/a/	/i/	/u/
Range [Hz]	35–3300	1800–3800	260–1800
Average [Hz]	880	2800	749

3.2 Design of approach informing sounds

The sound stimulus “Sa-” was created using white noise and a low-pass (below 4 kHz) filter. The amplitude near 1461 Hz was enhanced by 20 dB. The sound stimulus “Pi-Pi-” was created as a sweep sound. Its onset fundamental frequency was 1.8 kHz and its offset fundamental frequency was 3.8 kHz. The sound stimuli had a duration of 0.5 s and was repeated 10 times. The sound stimuli "Hyu-" was also a sweep sound and had onset and offset fundamental frequencies of 2.6 and 2.0 kHz respectively. In addition, the amplitude was modulated at 50 Hz. The sound stimuli had a duration of 10 s and was repeated five times. Finally, the sound stimuli "Bu-" was a sinusoidal wave having a fundamental frequency of 110 Hz and an amplitude modulated at 50 Hz.

3.3 Onomatopoeic sound representing the created approach informing sound

An experiment was conducted to confirm how created samples of an approach informing sound can be expressed by onomatopoeic sound. Participants were 10 students (eight men and two women) attending Utsunomiya University and having an average age of 22.8 years. The experiment was conducted in a soundproof room. Sound stimuli were the four samples of an approach informing sound given in Table 3. Participants were asked to provide as many onomatopoeic sounds that represent the sound stimuli as possible after listening to each sound stimulus three times. The obtained results are given in Table 5. For the sound stimulus "Sa-", five participants gave the onomatopoeic sound "Sa-" as expected. Meanwhile, the most frequently provided onomatopoeic sound was "Ga-". This sound stimulus was created from white noise and included all frequencies under 4 kHz and it might therefore be heard as voiced consonants. For the sound stimulus "Pi-Pi-," all participants gave "Pi-Pi-" as expected. Almost all participants gave "Pyu-" for the sound stimulus "Hyu-" while only one participant gave "Hyu-". This might be due to a factor other than the frequency range of the sound stimulus because /hy/ and /py/ are both unvoiced consonants and have the same frequency range. Finally, the sound stimulus "Bu-" was given as "Bo-" and "Bu-". This was because the fundamental frequency of 110 Hz was lower than that of the vowel /u/ given in Table 4 but was in the frequency range of the vowel /o/ (range: 80–1100 Hz, average: 380 Hz). The results reveal that the created samples of an approach informing sound were expressed by onomatopoeic sound as mostly intended.

Table 5. Expected onomatopoeic sounds and those given by participants.
Numbers of answering participants are given in parentheses.

Stimulus No.	Onomatopoeic sound (Expected)	Onomatopoeic sound (Given)		
1	Sa-	Ga- (6)	Sa- (5)	Za- (4)
2	Pi-Pi-	Pi-Pi- (10)		
3	Hyu-	Pyu- (10)	Hyu- (1)	
4	Bu-	Bo- (8)	Bu- (2)	

4. EXPERIMENT ADOPTING AN EVALUATION GRID METHOD

An experiment was conducted adopting an evaluation grid method to evaluate the samples of an approach informing sound created from the pedestrians' image, onomatopoeic sound. The experiment also sought to reveal factors affecting the evaluation of an approach informing sound as "indicating a traveling car".

4.1 Experimental method

An evaluation grid method is used in a semi-structured interview and was originally proposed by Sanui [6]. Participants choose or rank the represented stimuli that they prefer (i.e., a leading question). The experimenter then asked why the chosen stimulus is more preferable to others, repeatedly (i.e., elicitation of the original construct). Next, as the laddering question, participants are asked why they prefer their preferred stimulus (i.e., a higher-level construct) and to explain what would make a stimulus more preferable (i.e., a lower-level construct). A model is finally constructed from the obtained answers.

The present study applied an evaluation grid method following the procedure shown in Fig. 3. The leading question was set to "Which sound indicates a car traveling, A or B?". To elicit the original construct, the experimenter asked the participants "Why do you think sound A (or B) indicates a car traveling?" According to the obtained answer, laddering questions "Why do (answered elements) indicate a car traveling?" and "To have an (answered element), what do you think the sound requires?" were asked. On the basis of these results, a model was constructed with original, higher-level, and lower-level constructs.

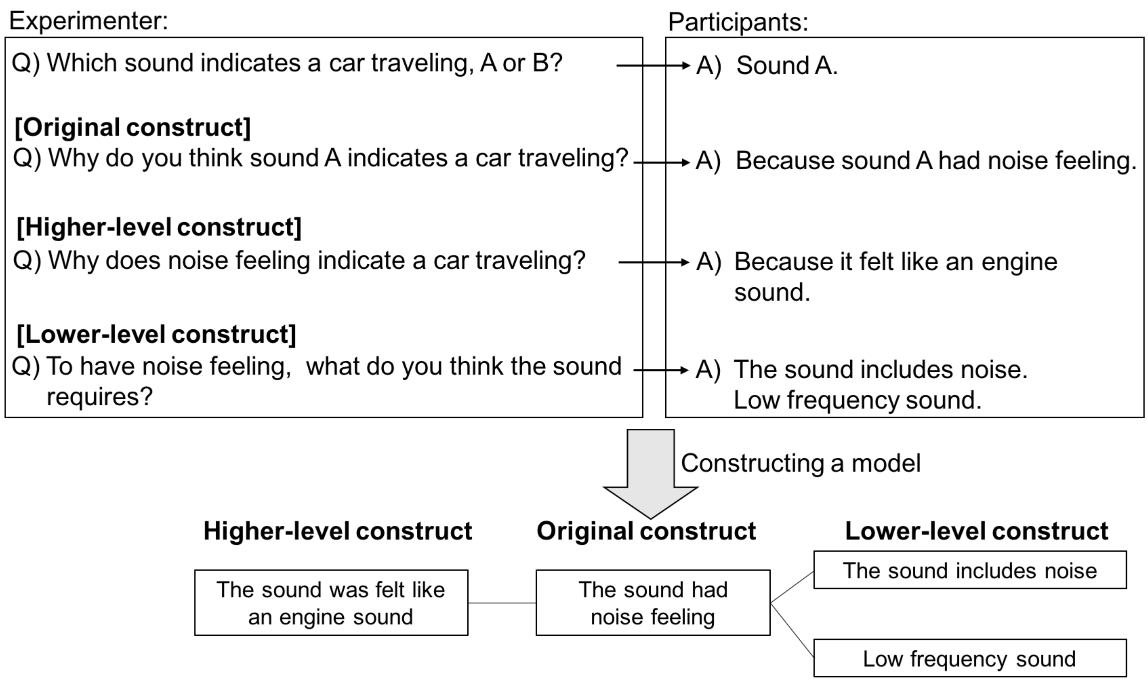

Fig. 3 Procedures of the evaluation grid method and constructing a model

4.2 Experimental conditions

Participants were the same 10 Utsunomiya University students who participated in the experiment described in section 3.3. The experiment was conducted in a soundproof room. The sound stimuli were reproduced by a loudspeaker (Victor, PS-S202) connected to an amplifier (ONKYO, CR-D2), audio interface (Audient, iD22), and personal computer (Microsoft, Surface). The loudspeaker was at a height of 1.2 m and positioned 2 m in front of the participants. The sound pressure levels (L_{Aeq}) of sound stimuli were adjusted to about 65 dB using a sound level meter (RION, NL-62) at the position of the participants. The experimenters recorded the answers of participants using a personal computer (Apple, MacBook Pro).

4.3 Sound stimuli

Sound stimuli used in the experiment are given in Table 6. Sound stimuli 1 to 4 were the samples created from the onomatopoeic sounds in section 3 while stimuli 5 to 10 were sweep sounds and Shepard tones that were highly or lowly evaluated as friendly (including evaluation of car-likeness) and notifying in a previous study [7]. Other sound stimuli were recordings of approach informing sounds used for commercially available quiet vehicles of car manufactures A, B, and C.

Table 6. Sound stimuli used in the experiment

Stimulus No.	Content
1	Onomatopoeic sound "Sa-", unvoiced consonant /s/ and vowel /a/
2	Onomatopoeic sound "Pi-Pi-," unvoiced consonant /p/ and vowel /i/
3	Onomatopoeic sound "Hyu-," unvoiced consonant /hy/ and vowel /u/
4	Onomatopoeic sound "Bu-," voiced consonant /b/ and vowel /u/
5	Sweep sound (evaluated highly): onset frequency was 1 kHz and one-octave variation time was 0.25 s
6	Sweep sound (evaluated highly): onset frequency was 2 kHz and one-octave variation time was 0.25 s
7	Shepard tone (evaluated highly): eight harmonic tones, mid-frequency band filter, one-octave variation time of 0.5 s
8	Sweep sound (evaluated lowly): onset frequency of 500 Hz, one-octave variation time of 1 s
9	Shepard tone (evaluated lowly): 16 harmonic tones, low-frequency band filter, one-octave variation time of 0.25 s
10	Shepard tone (evaluated lowly): 16 harmonic tones, narrow-band filter, one-octave variation time of 0.25 s
11	Approach informing sound of car manufacture A
12	Approach informing sound of car manufacture B
13	Approach informing sound of car manufacture C

4.4 Experimental results and analysis

The obtained results can first be analysed adopting Thurstone's paired comparison, because the participants chose one sound stimulus that indicates a car traveling from a pair of sound stimuli. The analysis results are shown in Fig. 4. Sound stimuli 11, 12, and 13 were clearly evaluated as indicating a car traveling. These sound stimuli were approach informing sounds used for commercially available quiet vehicles. Additionally, sound stimuli 1, which was created from the onomatopoeic sound "Sa-", was evaluated highly. The acoustic characteristics common among these sound stimuli might have cues that indicate a car traveling. Other sound stimuli created from onomatopoeic sounds were evaluated as slightly effective (sound stimuli 2 and 4) or ineffective (sound stimulus 3) in indicating a car traveling. The evaluation of sound stimuli created with a sweep sound or Shepard tone (sound stimuli 5–10) was not high and the order of the evaluation results generally followed those obtained in a previous study [7].

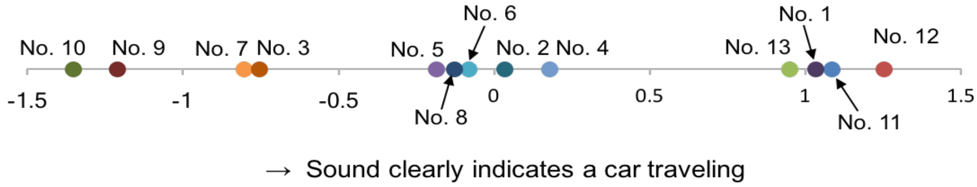

Fig. 4 Evaluations in terms of a "sound indicating a car traveling"

Employing the evaluation grid method, the results of interviews are presented as a model of evaluation of each sound stimuli. In each model, higher-level constructs on the left are connected by original constructs to lower-level constructs on the right [6]. Figures 5 and 6 show the models obtained for sound stimuli 1 (onomatopoeic sound "Sa-") and 12 (approach informing sound of car manufacturer B). The numbers of answering participants are given in parentheses. Similar answers were gathered as the same answer.

In Fig. 5, the most frequently given higher-level constructs are "The sound was like that of a car traveling" and then "The sound was like that of an engine sound". Original constructs include "It sounded like cutting through wind," "I felt friction from the sound," "It sounded like the operation of a machine", and "It had a driving feeling". Lower-level constructs are "The sound included noise" and "A muffled sound", and the onomatopoeic sounds "Koo-," "Ga-," "Sa-", and "Za-" are given as the characteristics of sound that indicate a car traveling. Similar to the results presented in Fig. 5, "The sound was similar to an engine sound" is the most frequently given higher-level construct in Fig. 6. In addition, the word "noise" is frequently included in both original and lower-level constructs.

Sounds from tires, the road, and engines mainly constitute noise emitted from an accelerating vehicle [8]. Moreover, car interior noises mainly comprise four sounds, namely the engine sound, a muffled sound, sound from the road, and wind noise [9]. Words related to these sounds are observed in both Figs. 5 and 6, possibly because the participants evaluated the sounds that indicate a car traveling using the sound emitted and heard from vehicles in daily life as criteria.

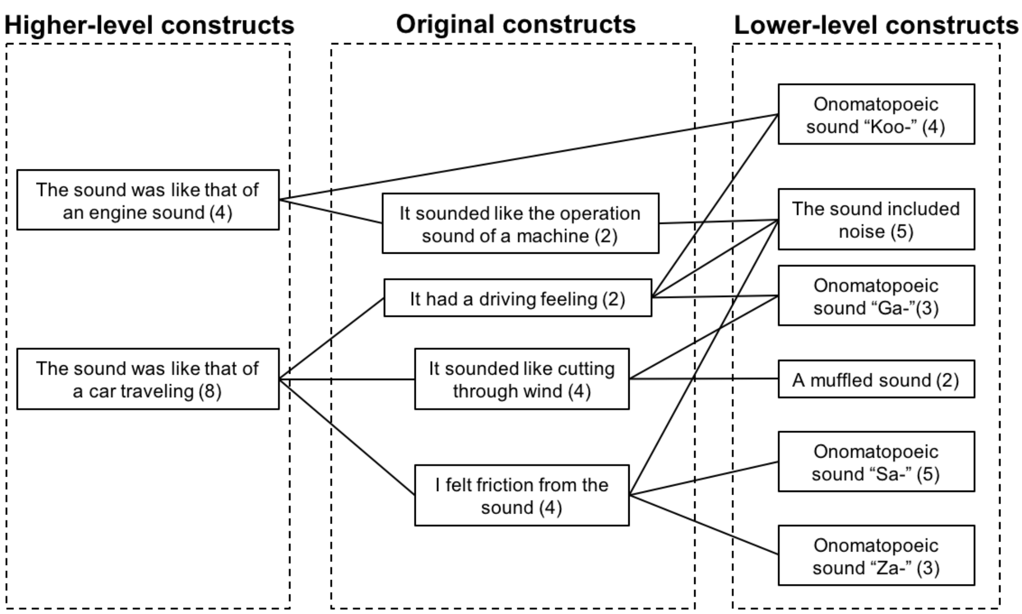

Fig. 5 Evaluation constructs for an approach informing sound created from the onomatopoeic sound "Sa-" (sound stimuli 1).

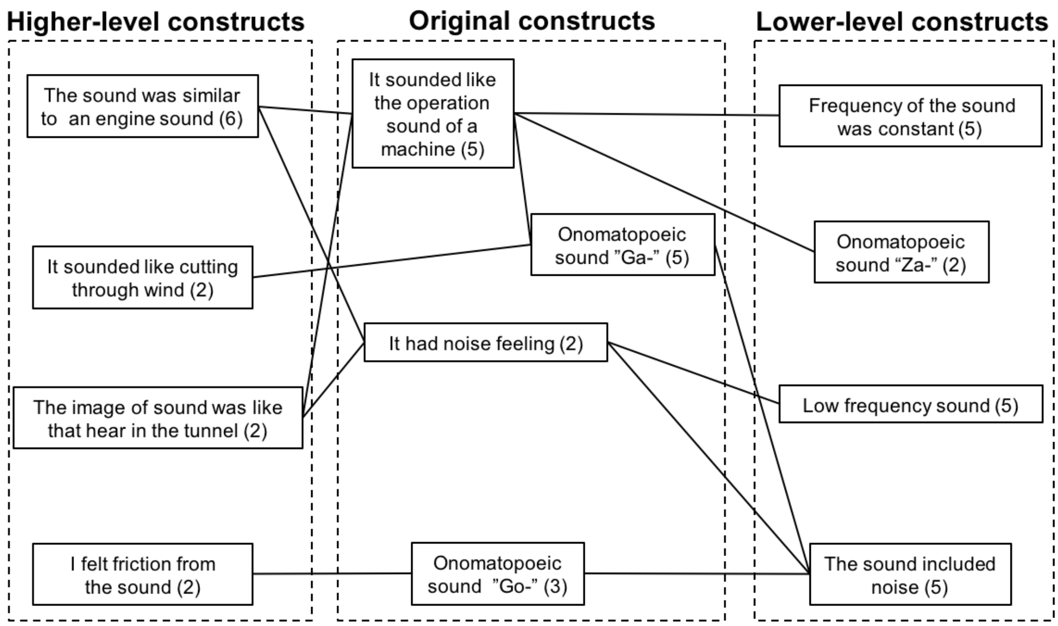

Fig. 6 Evaluation constructs for an approach informing sound of car manufacturer B (sound stimuli 12). The numbers of participants are given in parentheses.

In addition, only two of the 10 participants answered that "I associated the sound with quiet vehicles". This tendency was also observed for sound stimuli 11–13, which are approach informing sounds used for commercially available quiet vehicles. Because the sound stimuli were recorded using actual quiet vehicles, they might include road noise or sound emitted from tires. The sound stimuli were therefore evaluated as clearly indicating a car traveling. Additionally, sound stimulus 1, created from the onomatopoeic sound "Sa-", included white noise and might sound like noise emitted by vehicles. This sound stimulus was thus evaluated as strongly indicating a car traveling. As shown in Figs. 5 and 6, answers related to engine sound or wind noise were frequently given for each construct. These results and tendencies indicate that the participants might evaluate sound stimuli on the basis of not quiet vehicles but rather vehicles with internal-combustion engines.

6. CONCLUSIONS

Onomatopoeic sounds that reflect the pedestrians' image of sound were extracted to create samples of an approach informing sound. The onomatopoeic sounds frequently given by participants included unvoiced consonants, such as /s/, /hy/, and /p/, and the vowels /a/, /i/, and /u/. Samples of approach informing sound were created according to the acoustic characteristics of these consonants and vowels. These created sound stimuli were generally represented by expected onomatopoeic sound. An experiment adopting an evaluation grid method revealed that the approach informing sounds used for commercially available quiet vehicles were evaluated as indicating a car traveling. The same tendency was observed for sound stimuli created from the onomatopoeic sound "Sa-". The constructs obtained from the results of the experiment for these sounds frequently included words relating to sounds emitted and heard from vehicles in daily life, such as engine sound, road noise, wind noise, and sound from tires. Sound stimuli that included sounds like these sounds therefore tended to be evaluated as clearly indicating a car traveling. Additionally, the sound stimuli were evaluated on the basis of not quiet vehicles but rather vehicles having internal-combustion engines. An evaluation of whether a sound indicates a vehicle traveling might be conducted using criteria based on the sounds emitted and heard from vehicles having internal-combustion engines.

7. ACKNOWLEDGEMENTS

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