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IMPROVING THE COMFORT OF A CAR ENGINE SOUND USING AUDITORY MASKING

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Abstract. *In recent years, the global trend of low fuel consumption has made it necessary to improve the environmental performance of automobiles. Therefore, efficient combustion is required for vehicles with gasoline engines. However, rapid combustion increases the engine excitation force, and a "rattle" knocking sound may be generated. A knock is an intermittent fluctuating noise that occurs in synchronization with combustion, and various studies have been conducted on ways to reduce this noise. The present study was conducted to improve the comfort of a car engine sound using auditory masking. First, the properties of the knocking sound maskers were investigated, and their practicality was confirmed by masking with speakers. The results suggested the possibility of improving the comfort of the engine sound using auditory masking.*

Keywords: Gasoline engine, Auditory masking, Knocking sound, Comfort of engine sound

1. **Introduction.** In recent years, vehicles with a low environmental load, such as Hybrid Electric Vehicles (HEVs) and clean diesel vehicles, have received considerable attention to prevent global warming. One method to improve fuel efficiency in vehicles equipped with such engines is to increase combustion efficiency. However, this leads to knocking, an intermittent, fluctuating sound that occurs in synchronization with combustion in vehicles with engines and is particularly noticeable in diesel engines [1]. In previous studies, researchers focused on diesel engines' internal structure and combustion chamber to determine ways to reduce knocking. Toda et al. focused on the cylinder-to-cylinder variability of diesel engines to develop a model for estimating the sense of comfort. They also found that the comfort indexes were different between expert and non-expert drivers [2]. Shirahashi et al. had incorporated dampers inside the engine to suppress the vibrations that caused the knocking sound. As a result, they improved the overall quietness without the knocking sound being apparent [3]. However, because these studies focus on the specific structure of diesel engines, it is challenging to apply their findings to gasoline vehicles and HEVs. Therefore, we propose an auditory masking method that can also be applied to gasoline vehicles, electric vehicles, and HEVs using speakers installed in cars. If it is possible to improve the comfort of the engine sound, it would be possible to realize clean diesel vehicles and HEVs that are both quiet and fuel-efficient. To this end, we first investigated the properties of maskers that could mask the knocking sound. Then, a

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masking experiment was conducted in an anechoic room with speakers positioned as they would be positioned in a real car, and the practicality of maskers was confirmed. The results suggested the possibility of a new sound design as a method to make the knocking sound pleasant. The remainder of this paper includes the following five sections: the definition of auditory masking, the Methods 1-3, and conclusions.

2. **Definition of Auditory Masking.** According to JIS Z 8106:2000 acoustic terminology [4], masking is defined as follows:

a) A phenomenon whereby the auditory threshold of a specific sound increases because of the presence of other sounds.
b) The value of the increase in auditory threshold due to phenomenon a). The unit is decibel. The unit symbol is dB.

The noise that serves as the mask is called the masker. Furthermore, the signal sound to be masked is called the maskee. The essential phenomenon in masking is that the number of masking increases as the frequencies of the masker and the maskee come closer together, decreasing as they move farther apart. As the sound pressure of the masker increases, the frequency range of the masking expands, and the level of masking increases. Conversely, as the sound pressure of the masker decreases, the frequency range of the masking becomes narrower, and the level of masking decreases [5].

3. **Method 1: Investigation of Maskers by Preliminary Experiment.** In this method, the focus is on investigating the properties of maskers based on the principles of auditory masking. As shown in Figure 1, the knocking sound was identified at approximately 1-2 kHz in the interior sound of the vehicle. The maskee was the composite of the road-noise and the knocking sound. The maskers were white noise, pink noise, and brown noise. A narrowband (NB: 800-1200 Hz) and wideband (WB: 10-3000 Hz) bandpass filter were applied to the masker at approximately 1-2 kHz. Furthermore, the Signal-to-Noise Ratio (SNR) was changed to investigate the optimal sound pressure level. Thus, an experiment with 12 types of stimulus sounds (Table 1) was conducted. The sound pressure levels of the stimuli are listed in Table 1.

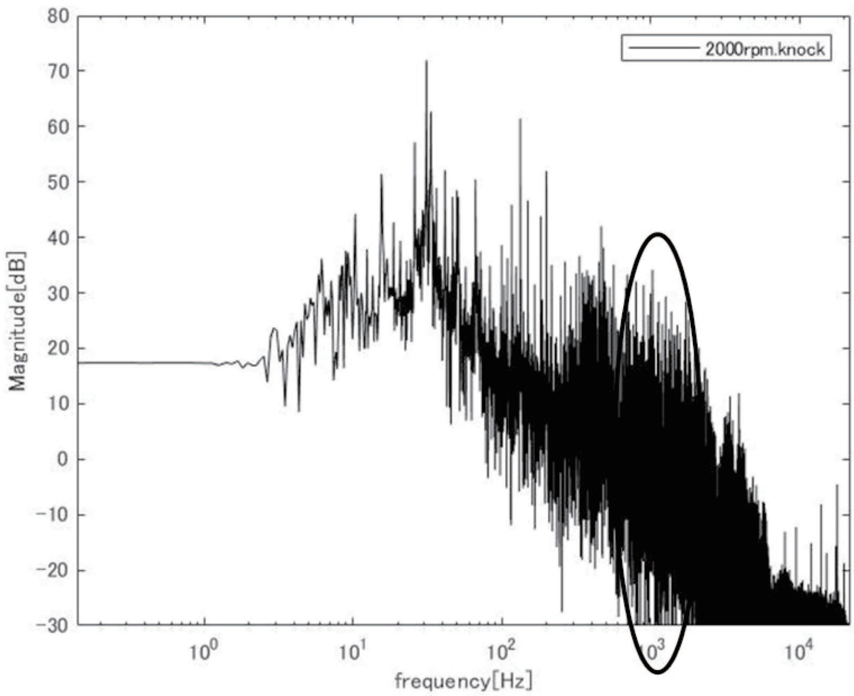

FIGURE 1. Frequency response of the knocking sound

Table 1. Stimulus sounds used in Method 1

Sounds	White noise [dB]	Pink noise [dB]	Brown noise [dB]
Reference	66		
Hidden anchor	67		
N +10 dB (A)	68	66	62
W +10 dB (B)	68	64	65
N +6 dB (C)	65	62	65
W +6 dB (D)	65	63	65
N ±0 dB (E)	67	66	65
W ±0 dB (F)	66	63	63
N −6 dB (G)	65	63	64
W −6 dB (H)	63	66	63
N −10 dB (I)	63	64	65
W −10 dB (J)	68	65	64

3.1. **MUSHRA method.** When evaluating impressions of sound sources with tiny differences, it is sometimes difficult to observe the differences using evaluation methods such as the semantic differential method. Therefore, the "MUltiple Stimuli with Hidden Reference and Anchor (MUSHRA)" method [6] was developed; MUSHRA is a subjective acoustic quality evaluation method that can be used when the difference between sound sources is slight. Applying the MUSHRA method is beneficial, as it can present several stimuli simultaneously, thereby enabling participants to make direct comparisons. As stipulated by ITU-R (The International Telecommunication Union Radiocommunication Sector) BS.1534-3, one or more excerpts assessed as reference signals must be given a grade of 100 as the unprocessed reference signal is included as one of the excerpts to be graded. The reference sound (score 100) was set to remove approximately 1-2 kHz from the maskee, and the hidden anchor (score 0) was set to the sound emphasizing approximately 1-2 kHz of maskee. When the knocking sound was not perceived as the reference sound, they were scored approximately 100. Conversely, When the loudest knocking sound was perceived in the stimulus sound, the participants were scored close 0.

3.2. **Participants.** Five participants (between the ages of 21 and 24 years; five males) with normal hearing abilities participated in the experiment. Moreover, the driving experience was not considered a factor, as this experiment was conducted to investigate the properties of maskers. In this study, we explained to the participants that a third party would not identify their names, participation was voluntary, and there would be no disadvantage in refusal, and that the purpose and content of this study would be explained to them and their verbal consent would be obtained.

3.3. **Experimental environment.** The experiment was conducted in an anechoic room. Participants were seated, and comfortable temperature conditions were maintained. Figure 2 presents a schematic of the experimental environment in the anechoic room. The experimental setup was explained to the participants fully. Stimulus sounds were sent from the PC and played through a speaker (BH162A, MPOW).

3.4. **Experimental results.** Figures 3-5 present a box plot of the evaluation results for each noise. White noise and pink noise show significant individual differences in the scores. Brown noise shows slight variance, and even stimulus sounds F, H, J with an SNR less than 0 can mask the knocking sound. However, in this experiment, the focus was on investigating the properties of the masker. Thus, the masker was played only on the

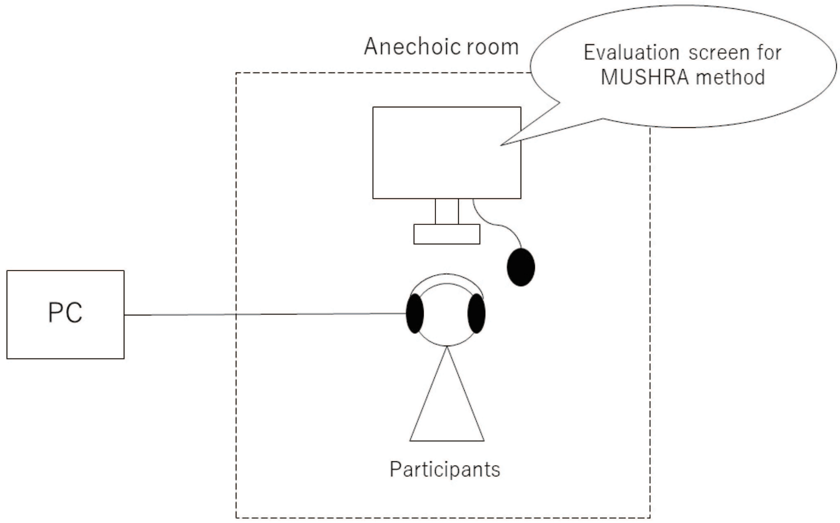

FIGURE 2. Schematic of the experimental environment in Method 1

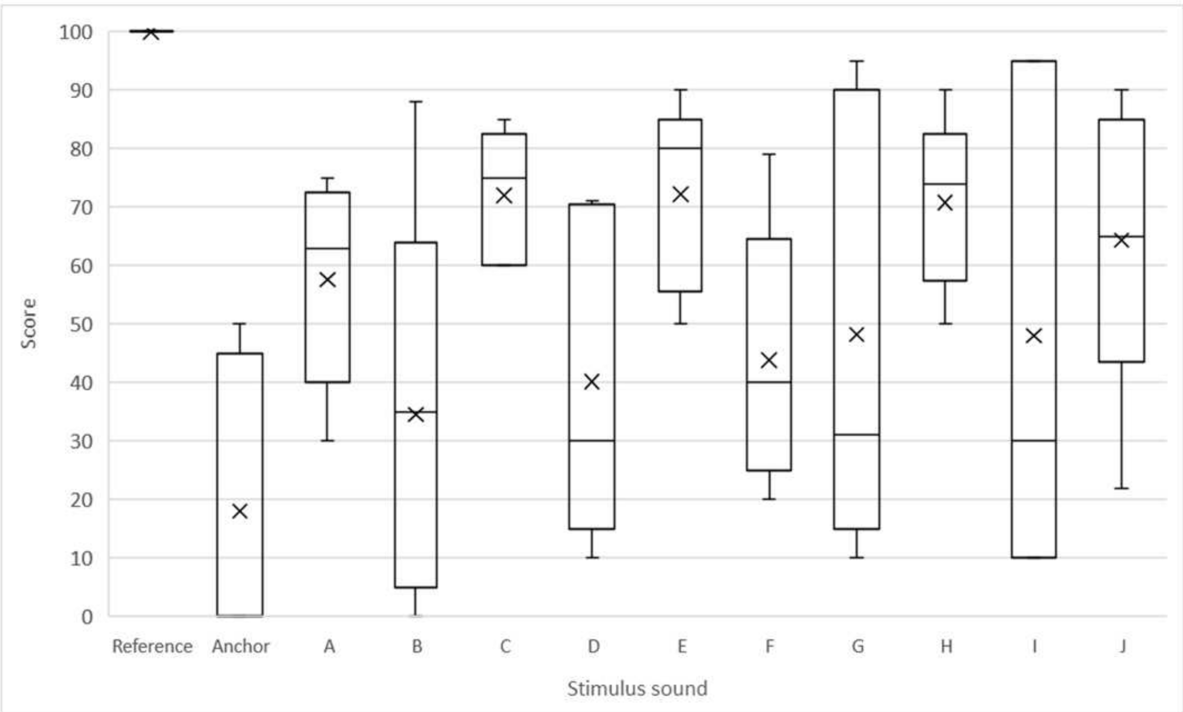

FIGURE 3. White noise

left side. If there is a difference in intensity between the two ears, it is perceived not as masking but as directional localization, such as identifying the location and direction of a sound source [7]. Therefore, the results of this experiment are considered to be invalid for a masking experiment.

3.5. **Properties of maskers.** Although the effectiveness of this experiment could not be demonstrated, the brown noise results also confirm that the slopes of the frequency response of the masker and the maskee affect auditory masking [7]. It is possible to increase the amount of masking by using a masker with the same slope as road-noise. Therefore, the proposed noise was created by passing white noise through a −13 dB/oct bandpass filter (800-2100 Hz).

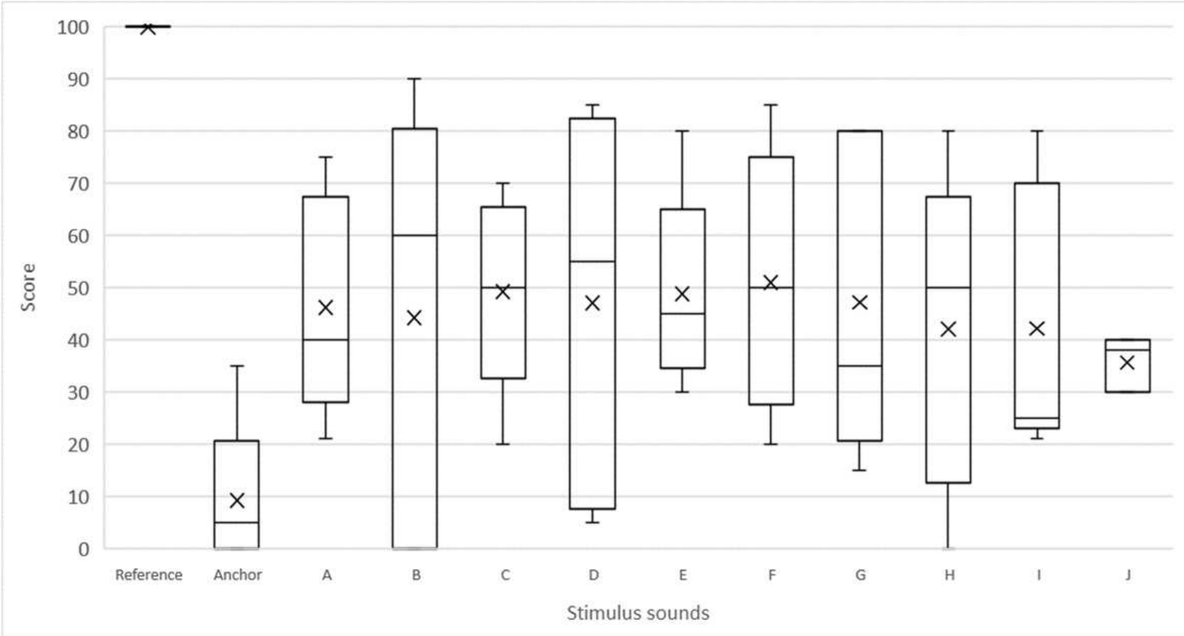

FIGURE 4. Pink noise

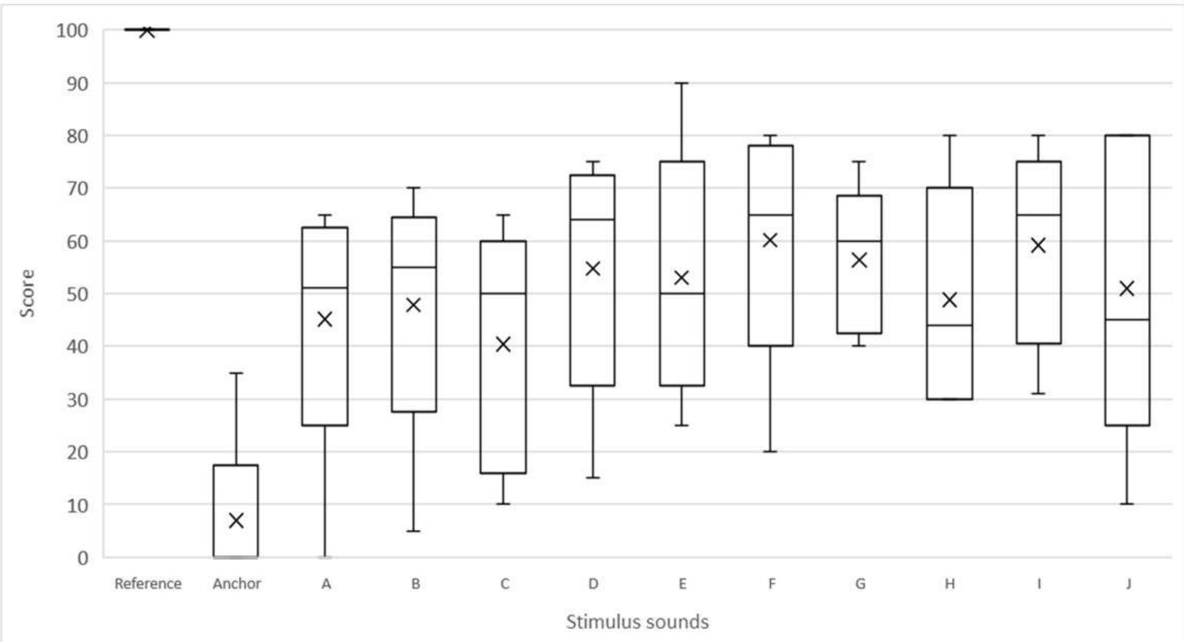

FIGURE 5. Brown noise

4. **Method 2: Spatial Masking Experiment.** In space, the effect of masking changes depending on the placement of loudspeakers and other factors. Thus, the effect of masking is quite different from hearing with headphones and speakers. In this method, to demonstrate the effectiveness of masking, the experiment was conducted in an anechoic room with speakers. The maskers used white noise, pink noise, brown noise, and the proposed noise with a wide bandpass filter, as in Method 1. As for the SNR of the maskers, only positive values were used because the noise was more significant in the preparation phase of the experiment. An experiment with six types of stimulus sounds (Table 2) was conducted. The stimulus sound pressure levels are listed in Table 2. The participants and evaluation method were the same as in Method 1.

Table 2. Stimulus sounds used in Method 2

Sounds	White noise [dB]	Pink noise [dB]	Brown noise [dB]	Proposed noise [dB]
Reference	68			
Hidden anchor	66			
0 dB (A)	65	65	66	66
6 dB (B)	67	66	67	67
12 dB (C)	69	68	69	68
20 dB (D)	67	70	75	73

4.1. **Experimental environment.** The experiment was conducted in an anechoic room. Participants were seated, and comfortable temperature conditions were maintained. Figure 6 presents a schematic of the experimental environment in the anechoic room. The experimental setup was fully explained to the participants. Stimulus sounds were sent directly from the tablet, and the maskee was played through a speaker (400-SP0698K, SANWA SUPPLY). The maskers were played from the left and right speakers (LYSB00064X4QM-CMPTRACCS, BOSE). Moreover, the participants switched the sound with the tablet (STQ-00012, Microsoft) by hand.

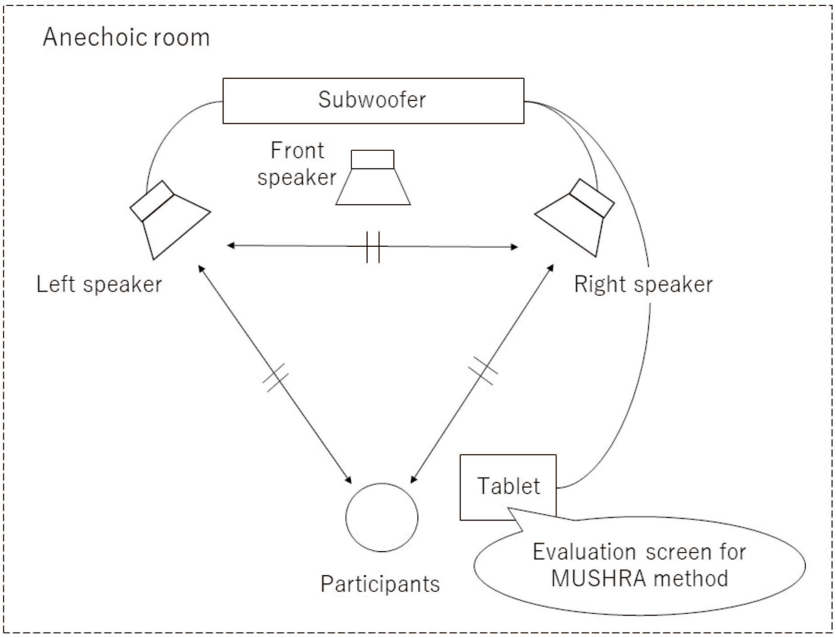

Figure 6. Schematic of the experimental environment for Method 2

4.2. **Experimental results.** Figure 7 presents a bar graph of the average value for each noise type. The score for white noise was proportional to the SNR of the masker, but the score for pink noise was the highest when the SNR was 0 dB. There was little difference between the scores for brown noise and the proposed noise due to SNR. Generally, the number of masking increases as the sound pressure of the masker increases [8]. Therefore, a high score should be obtained when the SNR is 20 dB. However, Figure 7 shows that the score is almost 60, irrespective of the SNR. This result indicates the possibility of masking even when the SNR of the maskers is low. Moreover, this result is also effective in not destroying the car's sales potential, such as both quietness and sound quality.

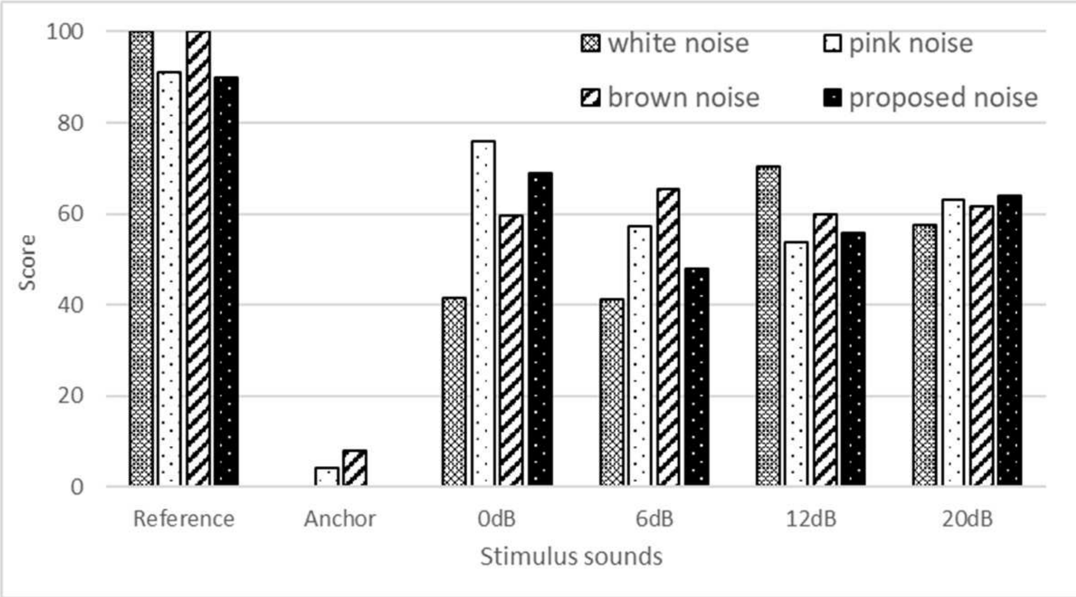

Figure 7. Experimental results of method

5. **Method 3: Annoyance Evaluation Experiment.** In Method 2, the results suggest that a knocking sound can be masked even when the SNR is 0 dB. Furthermore, the SNR of the maskers used only 0 dB. Therefore, in this method, the focus was on determining which maskers had minor annoyances [9]. Annoyance is a general term for the discomfort caused by noise, which includes the discomfort of the sound itself and the discomfort associated with it. The stimulus sound used white noise, pink noise, brown noise, and the proposed noise with a wide bandpass filter as in Method 2. Twelve combinations of stimulus sounds were presented randomly. The participants and experimental environment were the same as in Method 2.

5.1. **Method of paired comparison.** The paired comparison method facilitates the evaluation of several stimuli by dividing them into pairs [10]. There are two methods: one is to rank the samples (Thurstone), and the other is to calculate the degree of difference in addition to the rank (Scheffé). Scheffé's paired comparison method incorporates categorical judgments, which require judgments of how much one likes the presented pairs of stimuli. In this method, Scheffer's paired comparison method was used to ask the participants to rate which sound they found unpleasant. Participants evaluated stimulus sounds on a seven-point scale.

5.2. **Experimental results.** Figure 8 shows the average preference of each stimulus sound. A high average preference indicates intense discomfort. Therefore, the most uncomfortable masker was the pink noise. Conversely, the most comfortable masker was the proposed noise. This result suggests the possibility of using a masker that has the same slope as the frequency characteristics of road-noise, such as the proposed noise, to make the knocking sound less audible without causing discomfort.

6. **Conclusions.** In this study, we investigated ways to improve the comfort of the sound of a car engine using auditory masking. To this end, we first investigated the properties of maskers based on the principles of auditory masking with a preliminary experiment. Then, an auditory experiment was conducted using four noise types to clarify the optimal sound pressure level for masking. Furthermore, we clarified the characteristics of a masker that could reduce the audibility of knocking sounds without discomfort by the annoyance evaluation experiment. The proposed noise with the same slope as the driving noise could

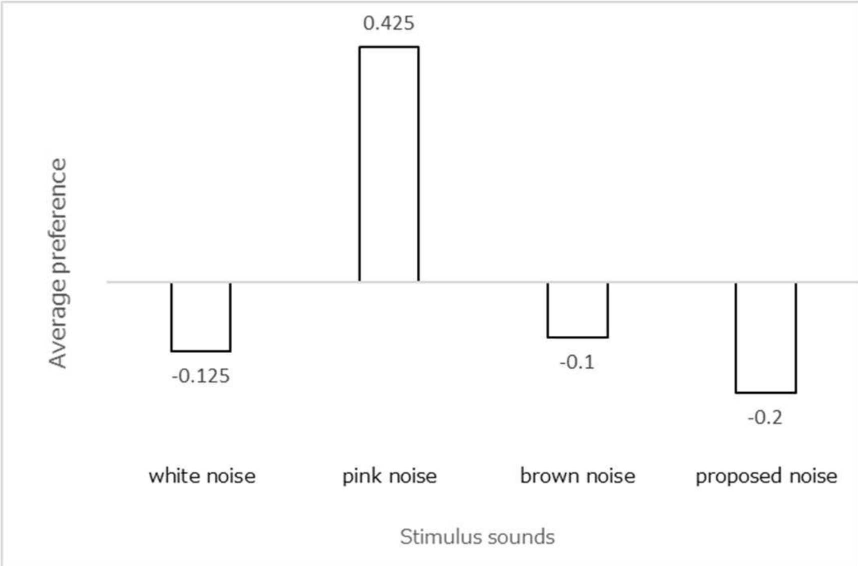

FIGURE 8. Experimental results of Method 3

be masked without causing discomfort. However, in this study, the filter bandwidth did not consider the critical bandwidth. Critical bandwidth means that when band noise is selected as a masker, the amount of masking will not change even if the band noise is extended beyond a certain width [11]. Because the masker used in this study is much wider than the critical bandwidth, the masker may become less obtrusive by setting the appropriate bandwidth. Additionally, the scores did not change even though the SNR changed, which may be due to the effect of co-modulation masking release [12]. In future works, we will increase the number of participants and investigate the effects of critical bandwidth and co-modulation masking.

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