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IMPROVEMENT OF HEART RATE VARIABILITY ANALYSIS FOR SOUND DESIGN

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Abstract. *The sound design of automobiles is one of the many factors that affect their appeal. Some sounds may be described as being pleasant, although they may pose a physical burden. Therefore, we studied the auditory effect of automobile acceleration sound and auditory impression evaluation using heart rate variability (HRV) analysis to design a comfortable sound environment. First, the calculation accuracy of the HRV analysis was improved using a proposed method before investigating the application to sound design. Our approach employed wavelets to detect subtle changes. We observed that the tendency toward excitement in auditory impression coincides with changes in the sympathetic nerve, which were identified using HRV analysis.*
Keywords: HRV analysis, Sound design, Engine sound

1. **Introduction.** Automobiles have become not only a means of transport but also a source of entertainment while driving. The development of automobiles has improved the safety and operability of driving and provided entertainment for drivers. The sound environment in a car has been receiving attention in recent years as an important factor for feeling relief and enjoyment. To develop the sound environment, it is necessary to evaluate how drivers feel. In general, assessment of sound quality has been carried out using subjective psychological tests such as the paired comparison method and the semantic differential (SD) method. However, such psychoacoustic tests usually compel participants to repeat judgment over and over, and often take a long time. Furthermore, quantitative evaluation is necessary for the development of industrial products. Neurophysiological evaluation is considered one of the most reliable methods for such tests. It is comparatively easy to improve the sound quality using an objective measure corresponding to the auditory impression [1]. Physiological indicators as objective evaluation indicators are studied electroencephalogram (EEG), heart rate, body-surface temperature, skin electrical resistance, respiration, etc. [2]. When these physiological measurements are performed at the same time, it is necessary to pay attention to the burden on the examinees. Also, it is not easy to prepare an expensive device like an electroencephalograph. Therefore, we focused on heart rate variability (HRV) analysis as an objective evaluation index. Research that is performing sound quality evaluation by HRV analysis has already been done [3,4]. In these studies EEG and photoplethysmography (PPG) are used to measure heart rate variability. The PPG is easy to measure from anywhere on the skin. However, the PPG detects the heart beat timing by the change in the blood flow, and it is necessary to pay attention that the detection timing does not coincide with the detection timing by the EEG. In the EEG, there are various arrangements when changing the position of the electrode according to the purpose or the measurement site, and it is difficult to handle unless there are medical personnel or knowledgeable persons. In addition, since electrode

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is attached to the skin, if sweat or dirt adheres to the skin, it becomes noise and influences the measurement. In the phonocardiogram, heart sound is measured at one place using a microphone or an electronic stethoscope. In addition, adjustment of the measurement site is easy, and the measurement device is also inexpensive. It is hard to be affected by dirt and sweat on the body surface, and the burden on the subject is small from the small number of measurement points. Therefore, we have analyzed using the heart sound. In our previous study, we examined a sound design method to improve excitement through designing the sound of the car engine [5]. However, the HRV analysis algorithm used in the previous study cannot correctly calculate the heart sound interval under certain conditions. In this study, we aim to develop an objective evaluation index that enables stable evaluation by smoothing with a wavelet and an envelope. Furthermore, auditory tests of the car engine sound and physiological evaluation were carried out using a driving simulator to confirm the effectiveness of this method for sound design.

This paper consists of all five chapters. In Section 2, we describe the principles and problems of HRV analysis and the proposed method. In Section 3, we describe auditory impression evaluation experiments conducted on vehicle acceleration sounds and sound quality evaluation experiments using HRV analysis. In Section 4, we describe the results of each experiment. In Section 5, we conclude with a summary of this paper.

2. Improvement of the Heart Sound Interval Extraction Algorithm.

Even at rest the heart rate interval changes continuously around its mean value. Neural mechanisms account for a part of this variability. Therefore, HRV analysis has been investigated as an index to evaluate the balance between the auto nomic nervous sympathetic and parasympathetic nerves.

2.1. Principle.

In the previous method, we performed HRV analysis as follows.

Extract the valve sound (1st sound/2nd sound) of the heart sound activity using a low-pass filter from the recorded heart sound data. Calculate heart sound intervals by extracting the interval of the 1st sound. Perform AR and FFT analyses on the heart sound interval to find fluctuations of the cardiac cycle. Low frequency (LF) component and high frequency (HF) component are defined as components between 0.05 to 0.15 Hz and 0.15 to 0.4 Hz, respectively. Sympathetic nerve activity is reflected in both the LF and HF components, while parasympathetic nerve activity is reflected only in the HF component. Generally, the HF component indicates the activity index of the parasympathetic nerves while, the ratio of LF/HF indicates the activity index of sympathetic nerves [3].

2.2. Conditions for possible errors.

In the previous method [1], the components exceeded the threshold value for finding the 1st sound, which was extracted with a minimum separation interval of 0.5 [s] to calculate the heart sound interval. In this case, the heart sound interval could not be calculated correctly when the 1st sound was less than the 2nd since it was assumed that the reverse is the case. Moreover, the heart sound interval could not be calculated correctly in the presence of noise in the recorded sound. Therefore, we propose the calculation method using wavelet.

2.3. Proposed method.

In the proposed method for extraction, only the time change point in the heart sound was extracted using wavelet. The proposed method is as illustrated below. First, the heart sound signal is analyzed by the wavelet and converted into an envelope of a power-waveform. At this time, Morlet waveform was used as the mother wavelet. We choose 1/4 or more of the sampling frequency from the amplitude of each frequency obtained by the wavelet, and obtain the sum of them. The power waveform was obtained by squaring the sum. The envelope was performed by linearly interpolating all extreme values of the power waveform. Figures 1 and 2 show the envelope transformation before and after. Then, the 1st and 2nd sound peaks are extracted from the envelope.

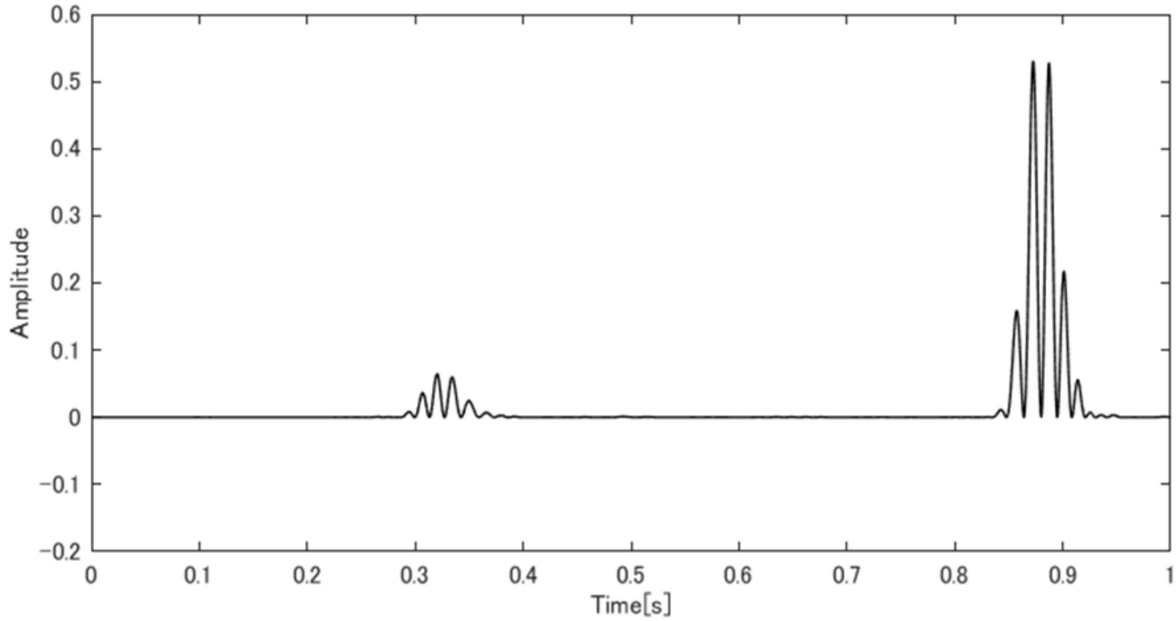

Figure 1. Waveform of before envelope

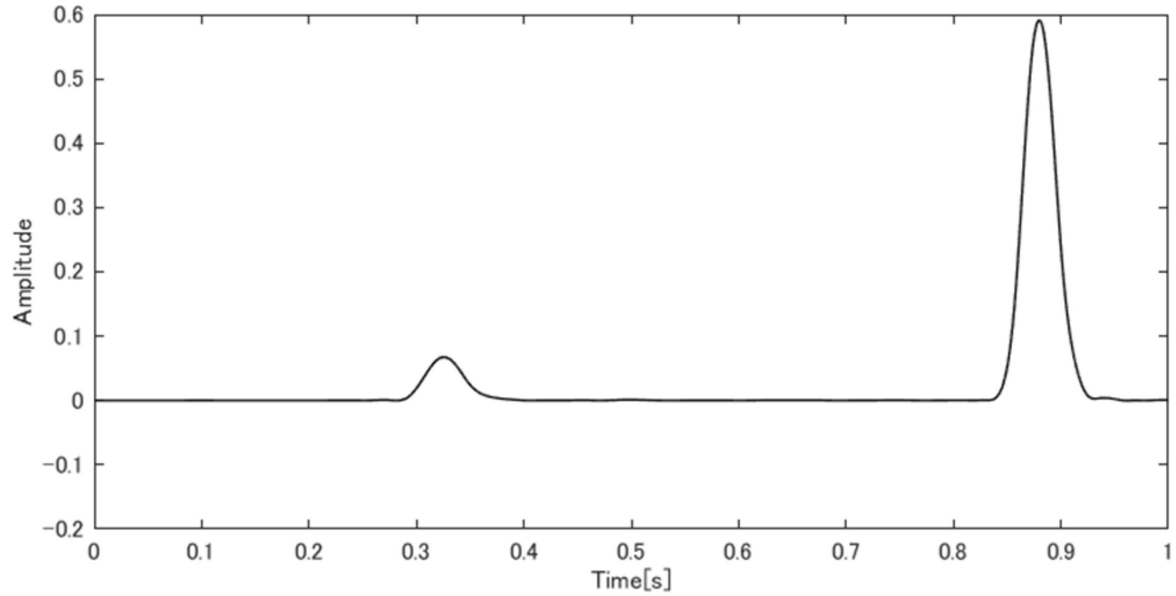

Figure 2. Waveform of after envelope

The heart sound intervals are calculated from the 1st sound, after which a trendgram is created by calculating the interval of the heart sound. The proposed method reduces noise and the heart sound interval can correctly be extracted even under conditions in which it would conventionally have been impossible. A comparison of the trendgrams from the conventional method and the proposed method is shown in Figure 3. As seen from the trendgram, it can be confirmed that the pulse-like fluctuations of the cardiac cycle is reduced by the proposed method.

3. **Experiment of Sound Quality Evaluation.** We conducted an auditory test for five kinds of engine sound and measured the physiological index using a driving simulator.

3.1. **Experiment 1: Hearing impression evaluation.** In Experiment 1, we evaluated the auditory impression for the stimulus sound. The participants evaluated the impression

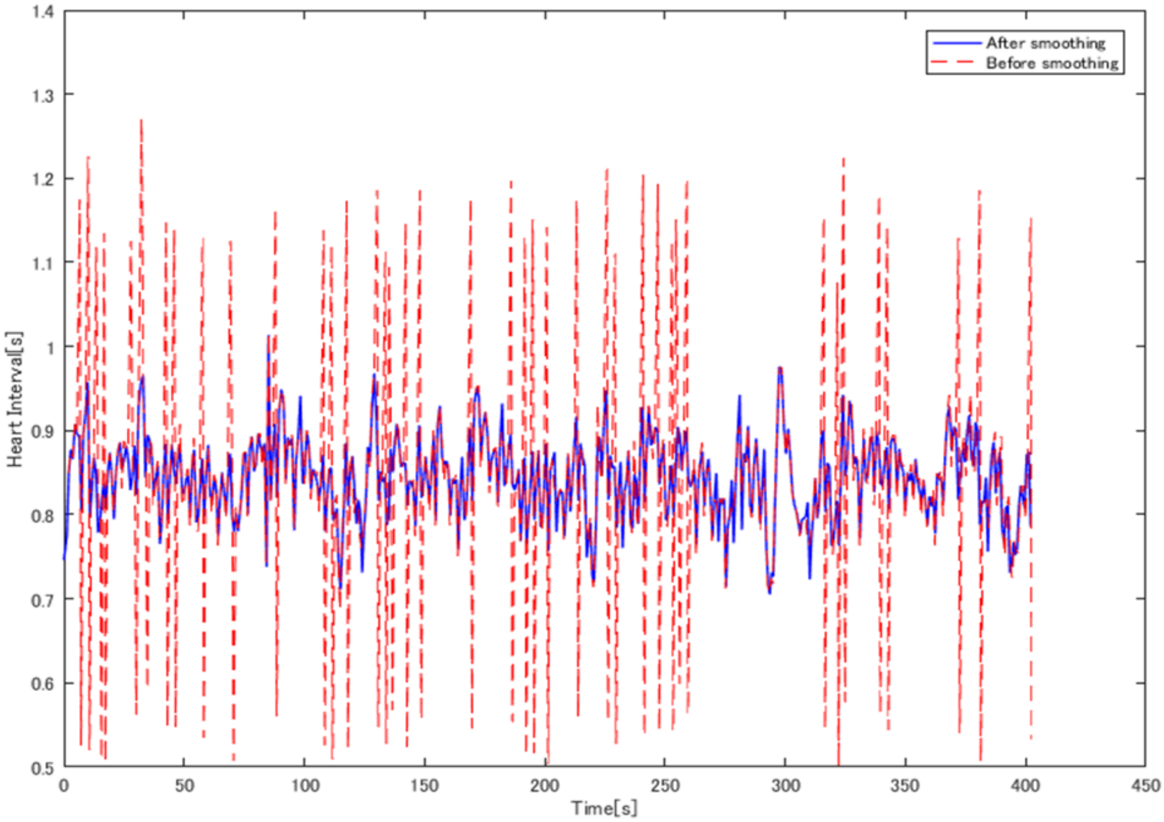

FIGURE 3. Comparison of trendgrams before and after

TABLE 1. Stimulus sounds

Order component of the engine sound	Sound pressure
Original	±0 dB
1st-order components	+20 dB
1st- and 2nd-order components	+20 dB
1st-order component	−20 dB
1st- and 2nd-order components	−20 dB

from listening to five kinds of engine sounds using the SD method (seven methods). We used 14 kinds of adjective pairs selected from the previous research [4].

3.1.1. *Participants.* The participants were 22 healthy males (aged 21-24). We explained the purpose of our research to each participant and obtained their cooperation. They were classified as “driver who drives a car everyday”, “rider who usually takes a motorcycle” or “rarel-driver that does not usually drive a car.”

3.1.2. *Apparatus.* They were seated in the vehicle cabin of the driving simulator. The stimulus sounds were the accelerated engine sounds recorded and processed from a real car. They consisted of processed engine sounds that were increased or decreased by only the 1st-order component, 1st- and 2nd-order components increased or decreased by 20 dB, and the originally recorded engine sound (Table 1). The stimulus sounds were presented through open type headphones (HD 650, SENNHEISER, Co.), and amplified using a headphone amplifier (HC6S, RANE).

3.1.3. *Procedure.* Participants performed all five trials. For each trial, participants listened to one type of stimulus sound when they stepped on the accelerator. The experimenter read out adjective pairs to them and they evaluated each pair orally while driving on a virtual straight road. The stimulus sounds were presented even during the evaluation. They scored each element using 7 grades $(+3, +2, +1, 0, -1, -2, -3)$.

3.2. **Experiment 2: Evaluation using HRV analysis.** In Experiment 2, we recorded the heart sound while the participants listened to the stimulus sound. The experimental environment was the same as in Experiment 1.

3.2.1. *Participants.* The participants were 10 healthy males (aged 21-24). We explained the purpose of the research, to each participant and obtained, their cooperation and agreement for the heart sound recording.

3.2.2. *Apparatus.* Participants were seated in the vehicle cabin of the driving simulator, as done in Experiment 1. The heart sounds were recorded around the fourth intercostal space left sternal border with the measuring microphone.

3.2.3. *Procedure.* We asked the participants to be in a state of rest for 5 min and then to operate the driving simulator for about 6 min. They drove on a straight road and performed five trials by changing the stimulus sound. The stimulus sounds were the same as those used in Experiment 1. We recorded the heart sounds of the participants at rest and while driving.

3.3. **Data analysis.**

3.3.1. *Factor analysis.* Hearing impression evaluation was conducted using factor analysis. We used a maximum likelihood method for the analysis, and selected the varimax rotation. The adjective pairs can be divided into two or four-dimensional groups with factor analysis. In this study, we decided to use three dimensions from the scree plot result.

3.3.2. *HRV analysis.* The recorded heart sounds were analyzed using the method proposed in Chapter 2. We used the LF/HF change rate from rest time to operation time as an evaluation index for the sympathetic nerve. An increase in the change rate implies a feeling of excitement, while a decrease implies a feeling of relaxation. We analyzed the data obtained from each stimulus sounds and considered the relationship between the stimulus sounds and the factor analysis results.

4. Results.

4.1. **Factor analysis.** Table 2 shows the results of the factor analysis while Figure 4 and Figure 5 show the scatter plot of each factor score. The following three parameters were obtained from the factor analysis: exciting factor, brightness factor, and response factor. The exciting factor included excitement, luxury, and sporty feeling. The brightness factor included brightness and the pitch of sound. The response factor refers to sound responsiveness. As the order components of pressure level of the sound increased, the factor score of the exciting factor tended to increase, too. Conversely, as the order components of the pressure level of the sound decreased, the brightness factor score tended to increase. The response factor did not correspond to any changes in the order of the pressure level of the sound. From the ongoing results, it was suggested that participants tended to feel excited when they heard amplified low-frequency sound from the engine. From Figure 5, it is confirmed that score of response factor is dispersed regardless of the kind of the stimulus. In other words, it was suggested that the change of the order component had less influence on the responsiveness.

Table 2. Results of the factor analysis

Factor name	Adjective pair
Exciting	Excited-not excited
	Satisfying-unhappy
	Expensive-inexpensive
	Sporty feeling-non-sporty feeling
	Growing-not growing
Brightness	Bright-dark
	High-low
	Urban-wild
	Positive-negative
	Soft-hard
Response	Good response-bad response
	Good rise-poor standing up

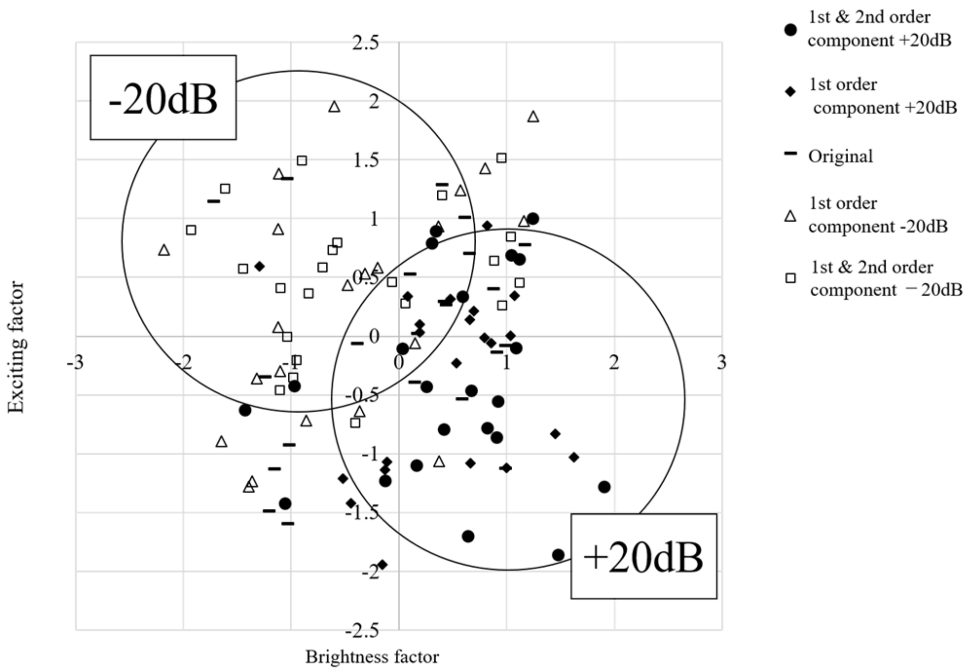

Figure 4. Exciting factor – Brightness factor scatter plot

4.2. **Results from the HRV analysis.** The LF/HF change rate at rest and while driving through the simulator is shown for each stimulus sound in Figure 6. As seen from the figure, the LF/HF ratios recorded during operation was lower than those while at rest, since the average values of each result were lower than 0%. Moreover, we confirmed that the rate of change of the LF/HF approached 0% as the sound pressure level of the order components increased.

5. **Conclusion.** In this paper, we introduced a wavelet for heart sound analysis to calculate the heart sound interval more accurately. Results from the HRV analysis suggest that the change in the sound pressure level of the order components affects the autonomic nervous system. Moreover, it was inferred from the results of the factor analysis that the LF/HF under feelings of excitement tend to be almost the same as that under a state of rest. Results from Experiments 1 and 2 are in agreement with the respective evaluation results from subjective and objective evaluation using SD method and HRV analysis. Agreement between subjective and objective evaluation is important for sound

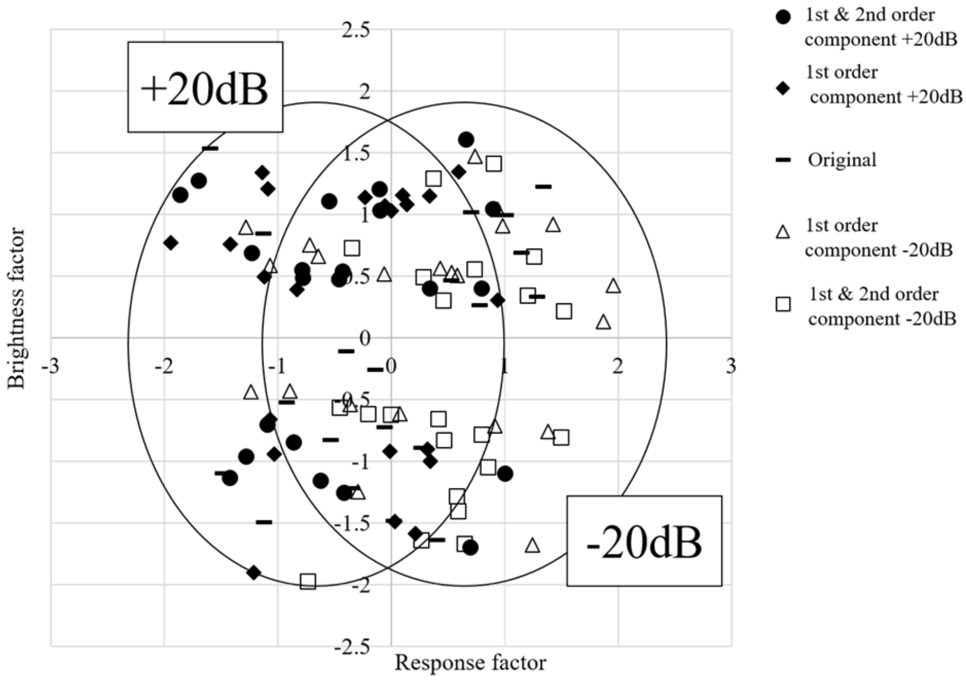

Figure 5. Brightness factor – Response factor scatter plot

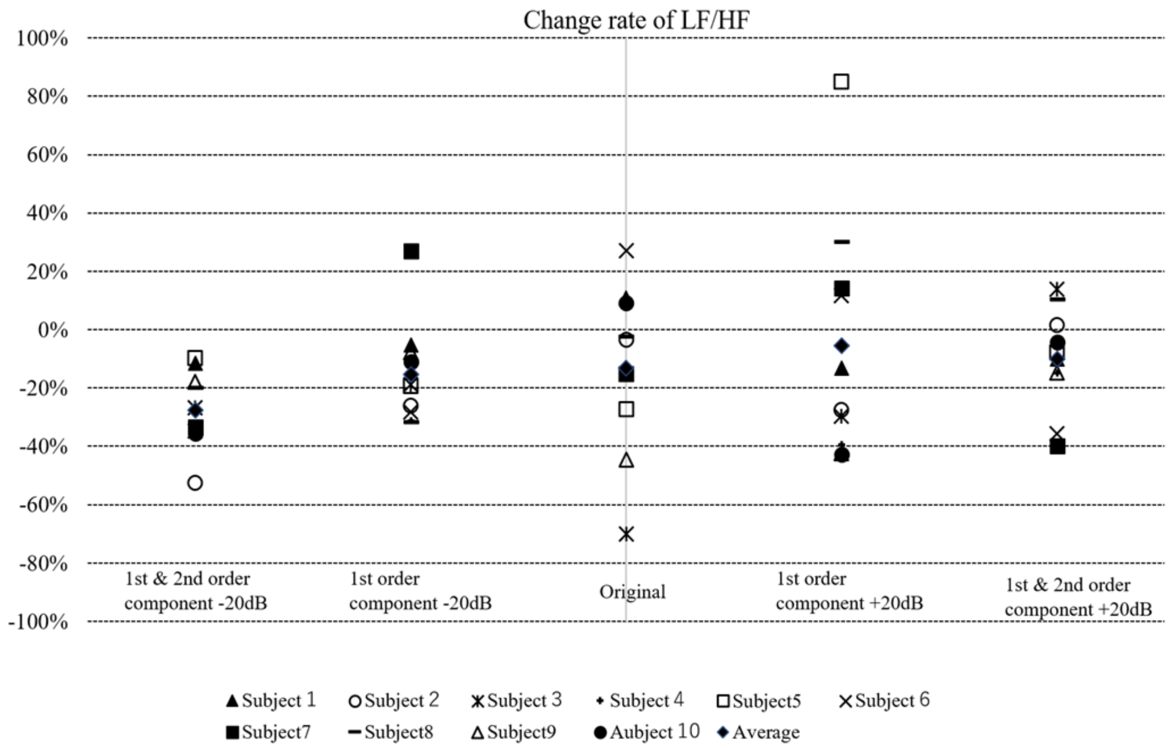

Figure 6. Results from the HRV analysis

design. Hence, it is believed that this method can be applied to automobile sound design. As future research we will try evaluation experiment with more diverse engine sound.

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