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SOUND QUALITY EVALUATION USING HEART RATE VARIABILITY ANALYSIS

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Sound induces various emotions or feelings, such as comfort or discomfort. It is difficult to evaluate these impressions as these emotional responses vary among individuals; therefore, subjective evaluation is widely used. Although this method has had some success in evaluating such impressions, it is demanding for participants. A more objective measure is an analysis of heart rate variability (HRV), correlated with fluctuations in autonomic nerve activity. In this study, we investigated the effectiveness of measuring impressions in response to sound using phonocardiography. We measured the HRV of the participants while they listened to music and a car engine sound. The results showed similar trends for each participant according to each type. These results suggest that the analysis of HRV is a useful way of measuring the impression evaluation index of sounds.

Keywords: Heart rate variability analysis, Subjective evaluation, Phonocardiography, Car engine sound, Sound of music

1. Introduction

There are many types of sound in our daily lives. When we hear a sound, we experience feelings, emotions, or impressions such as comfort or discomfort. As sounds can evoke many different impressions and feelings, a range of methods is used to evaluate such sounds, including electroencephalography, magnetoencephalography, and subjective evaluation. In particular, subjective evaluation is widely used and accepted as an evaluation method for this type of examination [1]. However, asking multiple questions is often necessary to establish a correct evaluation, and this can become laborious for the participant.

Thus, we focused on analyzing the heart rate variability (HRV), which is often used to measure fluctuations in the autonomic nervous system. Heart rate activity is strongly related to the autonomic nervous system activity, disorders of which can change the behavior of the heart. Fluctuations in sympathetic nervous system activity are mainly caused by stress or by external factors, which can cause the parasympathetic nerves to become excited, even when the participants are feeling relaxed [2]. Heart rate activity increases when sympathetic nerves are excited, and decreases when parasympathetic nerves are activated. Thus, fluctuations in the autonomic nerve and heart rate activity can be detected upon hearing a sound. We can expect to evaluate emotional responses to sound by examining autonomic nervous system activity data extracted from variations in the heart rate activity. In general, electrocardiography is used to analyze the heart rate activity; however, phonocardiography is another, less used method. Thus, in this study, the effectiveness of phonocardiography to evaluate emotional responses to sounds was investigated.

2. Experimental method

2.1 Experimental outline

2.1.1 Measurement

The participant was a healthy male, and the measurement was performed using a device developed for the study, as shown in Figure 1 [3]. The signals were measured around the fourth intercostal space, close to the sternum edge. The participant was required to sit on a chair, with his eyes closed while the measurements were recorded. Sounds were presented through headphones as shown in Figure 2. In this experiment, the duration of each sound was 3 min, with a 1-min interval between stimuli [4]. After each experiment, over 5 min rest was allowed before subsequent experiments were performed.

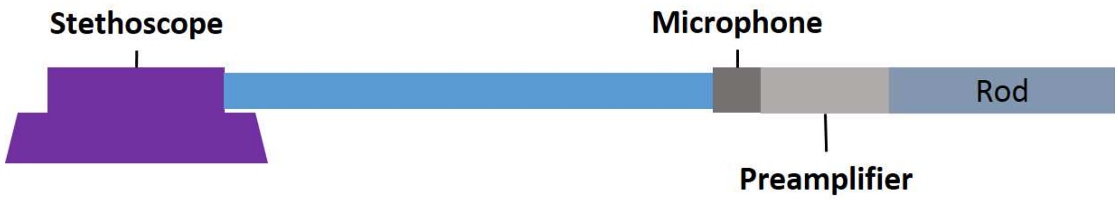

Figure 1: Measuring device.

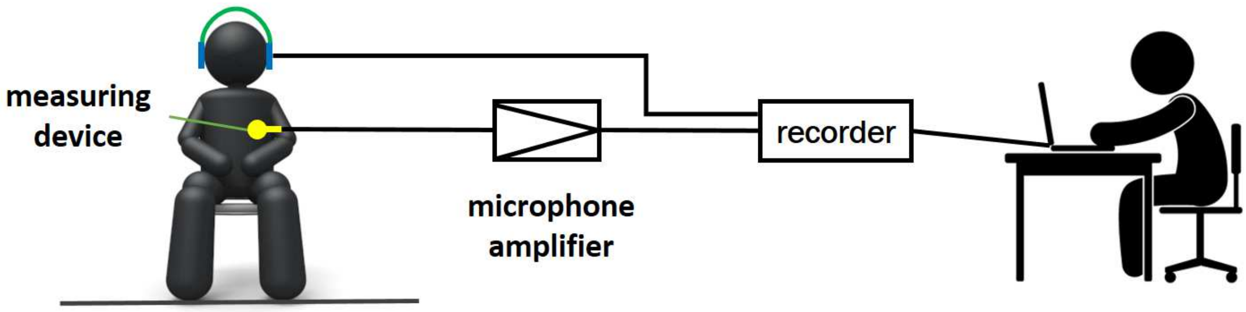

Figure 2: Experiment environment.

2.1.2 Experiment 1: Evaluation of sound discomfort

Experiment 1 examined the effectiveness of evaluating sound discomfort by analysis of heart rate activity. This experiment comprised one participant. The participant was a healthy male in his twenties. Heart sounds were recorded under conditions of silence, and on hearing wasp-buzzing sounds and classical music. Subjective evaluation was conducted by the participant, who allocated a rating to each sound. Five rating levels were used, with “1” being most uncomfortable and “5” being most comfortable [5].

2.1.3 Experiment 2: Dependence on music type

Experiment 2 comprised four participants. The participants were healthy males in their twenties. To confirm dependency on different types of music, house music and classical music were presented to the four participants, after which their heart rate activity was monitored. Three evaluations were conducted per participant. The average level of sound pressure was 70 dB (A) near the participant, and evaluation was performed at seven levels. The comfort level and favored level for each situation were presented by the participants. The difference between comfort level and favored level included a number of aspects. The favored level took into account various factors, such as excitement factor and desirable beat. The other side possessed only the relaxation element.

2.1.4 Experiment ３: Dependence on car engine sound

Experiment 3 comprised nine participants. The participants were healthy males in their twenties. In an accelerating car, the components of the engine sound change as the engine speed increases. The time-varying nature of the components can induce auditory impressions such as “sporty” and “accelerating” in listeners. In the current study, the psychoacoustic effects of the sound level and its modulation were investigated. Acceleration noise was measured using a straight-four engine, and harmonic complex tones that simulated acceleration noise were used as a stimulant. In a four-cylinder engine, the engine fires twice with each rotation, generating a secondary vibration force, and these higher harmonics constitute the main components of the noise. The engine sound consists of the harmonic components as well as other components. One of the main causes of poor sound quality in a passenger car is the high contribution of multiple half-order components of in-line four-cylinder vibration. Half-order multiple rolling moments caused by torque fluctuation and combined torsional moments act on the cylinder block around the crankshaft axis as internal forces. As such, the torsional vibration shape is excited as half-order multiples of the engine rotation. Model sound sources, created as harmonic complex tones, were comprised of even-numbered order sounds and half-order sounds, as well as the main components of the straight-four engine noise. Each stimulus of the half-order sound level was changed by +20 dB, 0 dB, and −10 dB. Artificial acceleration noises were created by changing the frequencies of each component over time using the sinusoidal model [6]. Sinusoidal modeling is an analysis-by-synthesis technique that sequentially extracts the parameters for each sinusoidal component. The model implements analysis, transformation and synthesis for sound waves, as shown in Figure 3. The peaks of the spectrogram in each analysis frame were extracted using a short-term Fourier transform (STFT), and partial sounds were determined by the information regarding instantaneous magnitude, frequency and phase included in the peaks. In this study a 2.3 L straight-four sedan engine was employed as an object, and the driving condition was set to full acceleration in third gear.

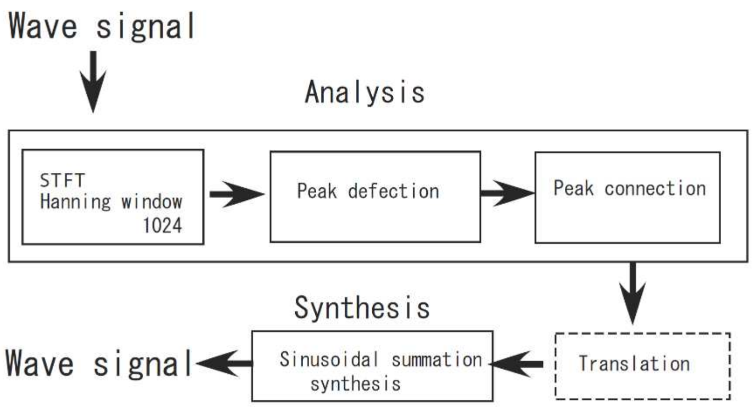

Figure 3: Analysis-by-synthesis with sinusoidal model.

The average level of sound pressure was 65 dB (A) near the participant, and sound quality evaluation for each level of half-order sound was examined using Scheffe's paired comparison tests. Ten subjects with normal hearing participated in this experiment. Pairs of sounds were presented, and subjects were asked to judge their preferred accelerating car engine sound. Paired-comparison tests were performed for all combinations of pairs of sound stimuli.

2.2 Analysis method.

Noise from heart sound measurements was filtered with a band-pass filter, after which two peaks – the first and second heart sounds – were extracted. The first heart sound was extracted, and the time intervals between the heart sounds were calculated (Figure 4). A trend graph was used to calculate heart rate interval times, after which the third-order spline interpolation and re-sampling with 1 Hz were introduced. Low frequency (LF) and high frequency (HF) components of the trend graph frequency result were defined as 0.005–0.15 Hz and 0.15–0.4 Hz, respectively. Sympathetic nerve activity is reflected in LF and HF component values, whereas parasympathetic nerve activity is reflected only in the HF component. Frequency analysis was conducted using a 256-point fast Fourier transform (FFT) method for 3 min, which corresponded to the duration of the trend graphs. LF and HF components were gained with a defined area. Next, the LF/HF ratio was calculated by dividing the LF and HF areas for each condition, as shown in Figure 5.

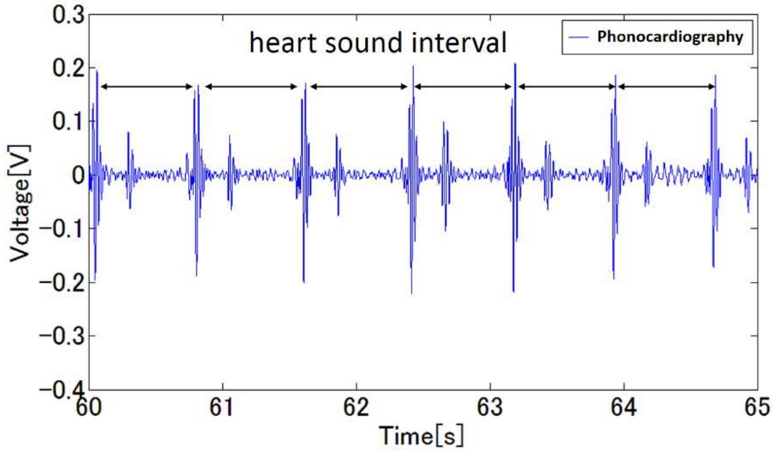

Figure 4: Heart sound interval.

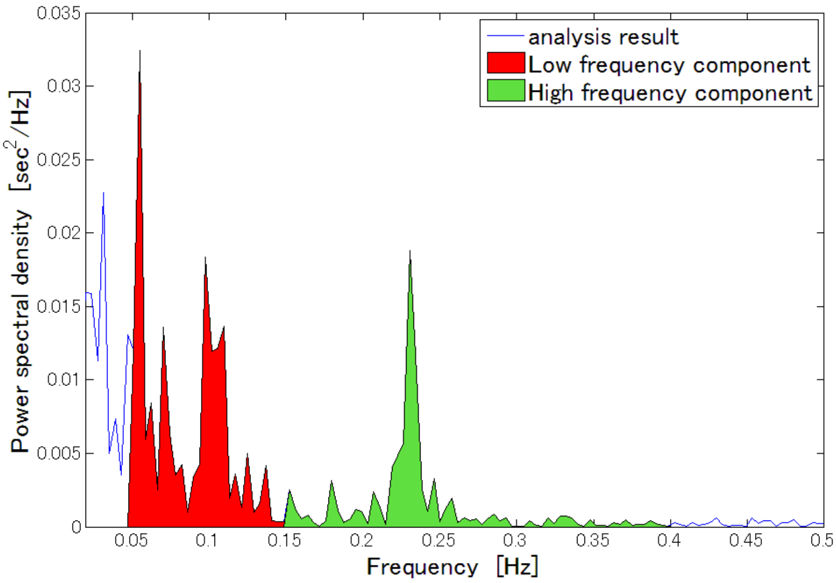

Figure 5: Heart sound interval.

3. Experimental results

3.1 Experiment 1: Evaluation of sound discomfort

From the results of the comparison of silence with two different types of sound, it was confirmed that the HF component of classical music was 22% lower than that of the silence condition. Moreover, the HF component of the wasp-buzzing sounds was 28% lower than that of silence. When the LF/HF ratio was used to represent the activity index of the sympathetic nervous system, the rate was found to be twice that of silence for both classical music and wasp-buzzing sounds. Thus, there were no differences in discomfort caused by presenting classical music or wasp-buzzing sounds to the participants. However, it was confirmed that the LF/HF ratio for wasp buzzing was slightly higher than that for classical music. The results of impression evaluations revealed that classical music scored a slightly more comfortable score of "4" compared with wasp buzzing, which had a score of "3."

3.2 Experiment 2: Dependence on music type

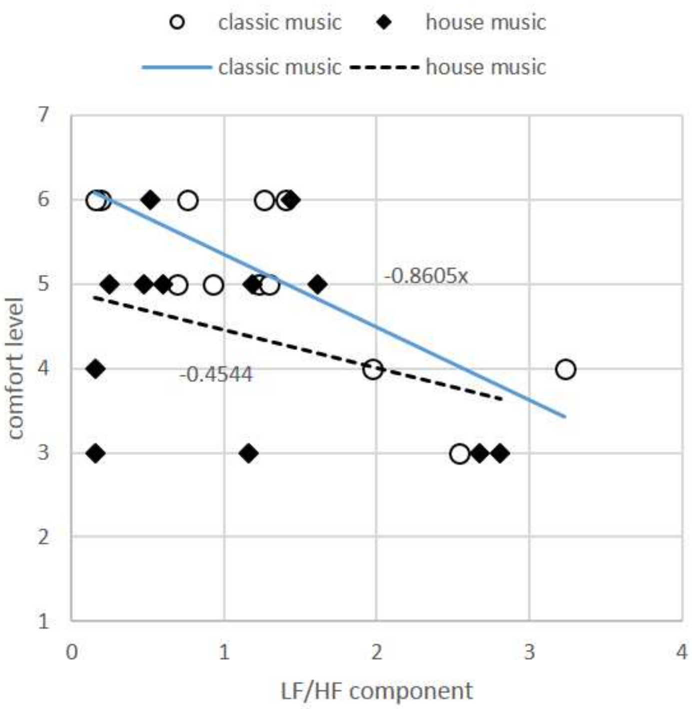

Figure 6: Experiment 2 result (Comfort level).

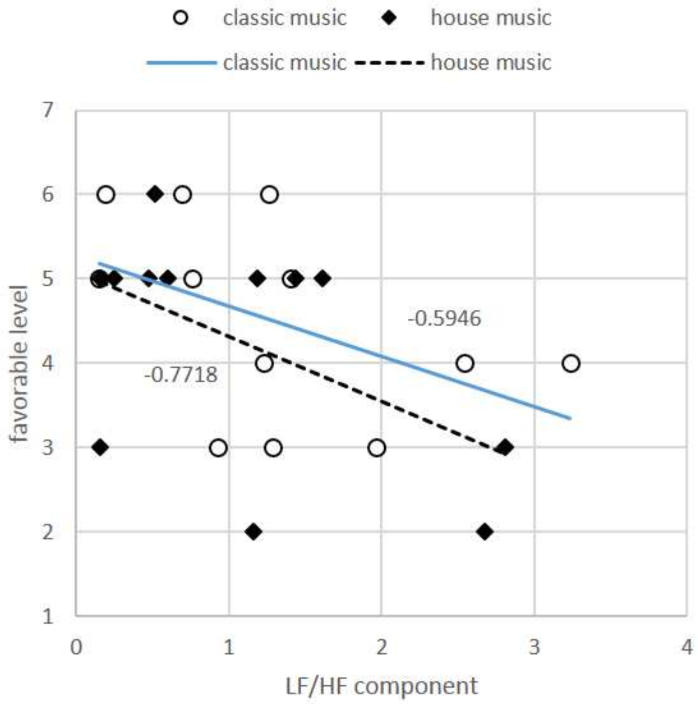

Figure 7: Experiment 2 result (Favorable level).

For each participant, we compared the results obtained from listing to classical and house music under the same conditions as those of Experiment 1. The relationship between subjective evaluation and an LF/HF frequency analysis are shown in Figures 6 and 7. These results were calculated by regression analysis using the least squares method. We compared the results of the subjective evaluation and the time-frequency analysis. From these observations, we confirmed a similar tendency for all conditions. When participants listened to music that they rated as having a high comfort level, we observed a tendency towards a decreasing LF/HF value (Figure 6). For classical music, a correlation coefficient of −0.78513 was found between comfort level and LF/HF ratio; for house music, the correlation coefficient was −0.35832. Similarly, when participants listened to music they rated as highly favorable, we observed a tendency towards a decreasing LF/HF value (Figure 7). For classical music, a correlation coefficient of −0.46282 was found between preference level and LF/HF ratio; for house music, the correlation coefficient was −0.52242.

3.3 Experiment 3: Dependence on car engine sound

Figures 8 and 9 show the relationship between the half-order sound level and annoyance rating value, which was obtained by subjective evaluation. The results revealed that when the level of the half-order sound increased, the level of annoyance was increased for some listeners (A, B, C, E, F, G, H, I, and J), but decreased for others. The result of variance analysis was significant for participants A, B, C, E, F, H, I, and J.

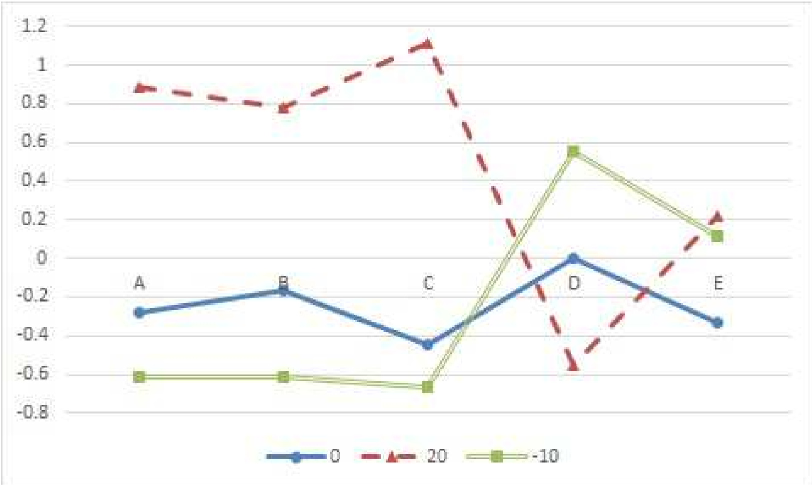

Figure 8: Relationship between the half-order sound level and annoyance rating value for A, B, C, D, E.

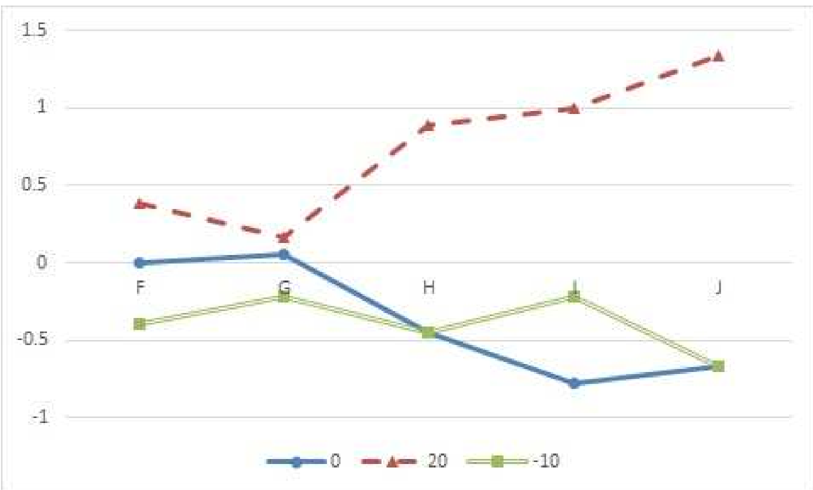

Figure 9: Relationship between the half-order sound level and annoyance rating value for F, G, H, I, and J.

Figures 10 and 11 show the results for the changes in HRV based on LF/HF before presenting the stimuli, using HRV analysis. For A, B, E, F, H, I, and J, the annoyance value is maximum for +20 dB of the half-order sound increased. The tendency of annoyance level was consistent with the tendency for HRV results.

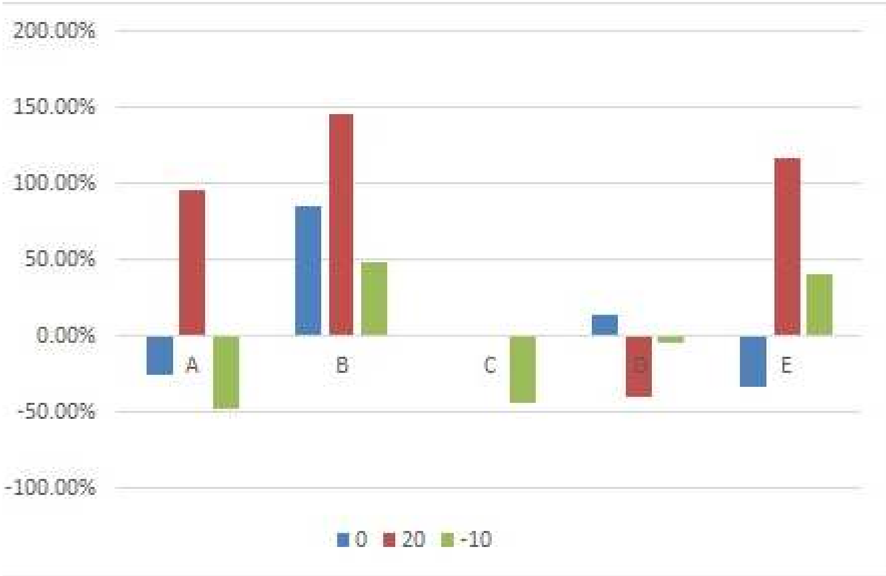

Figure 10: Relationship between the half-order sound level and the HRV for A, B, C, D, E.

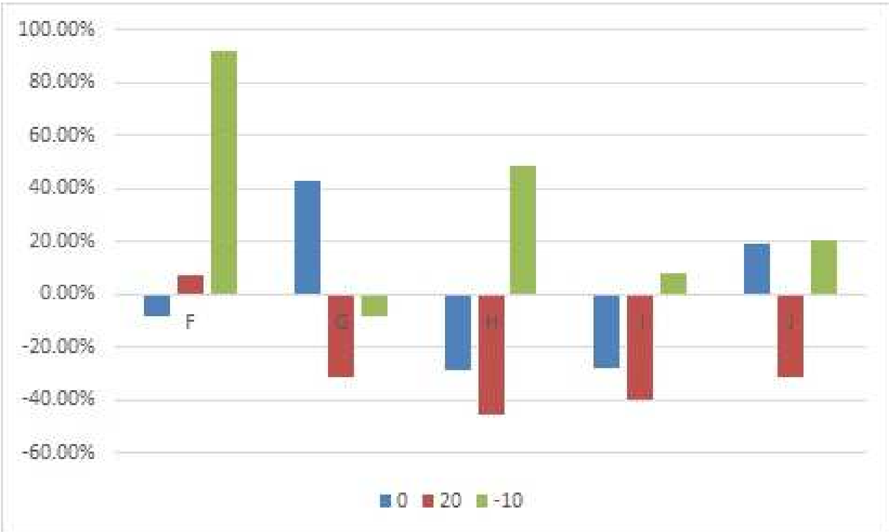

Figure 11: Relationship between the half-order sound level and the HRV for F, G, H, I, J.

4. Discussion

In Experiment 1, when an evaluation was conducted using the HF component and LF/HF ratio, the HF component of the wasp-buzzing sound was low, and the LF/HF ratio was high compared with those of classical music. Although it was possible to analyze the difference between the silence and different sounds, the difference between classical music and wasp buzzing could not be analyzed. Both sounds may have induced similar reactions because of similar stress experienced by the participants.

In Experiment 2, we confirmed a negative correlation between the time-frequency analysis result and the subjective evaluation. As in Experiment 1, the LF/HF ratio decreased with music of a high comfort level and high favorable level, and a reaction was evoked with each music type. This trend suggested that HRV analysis could capture a variety of autonomic nervous system responses. However, in terms of participant reactions, we observed a contrast between the HRV analysis results and the subjective analysis results. For those cases where the subjective evaluation did not correlate with the HRV analysis, the absence of correlation may have been due to the participants being unable to concentrate, or because the listening time was short.

In Experiment 3, many participants were annoyed with the +20 dB half-order sound level and were not annoyed with the −10 dB level for the car engine sound. For the result of HRV analyses, the rate of change based on LF/HF was in correspondence with subjective annoyance.

5. Conclusion

In this study, we evaluated emotional responses to sounds using HRV analysis of heart sounds. HRV was observed for each sound, and the relationship between the participant reactions and impression evaluations was also confirmed. Thus, phonocardiography has a potential use in evaluating auditory impressions by an analysis of HRV.

Future studies are required to improve the accuracy of phonocardiography and to evaluate emotional responses to sounds using larger numbers of participants and stimuli.

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