

# On Emotional State Measurement of Inaudible High-Frequency Sounds Based on EEG Analyses

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**Abstract** In recent years high-frequency sound including sounds with frequency bands higher than are audible to the human ear have attracted attention and the merits of analog recording techniques that preserve these frequencies used predominantly in the past are herein reviewed. Furthermore, there has been increased interest in high-resolution sound as evidenced by the introduction of many new products that create these high-frequency sounds. In this study, we confirm what kind of emotional state subjects experience while listening to high frequency sounds with emotional state analysis based on electroencephalographic fractal characteristics. The results indicate that these high frequency sounds may bring out more positive emotional states and may neutralize negative ones when specific recording and playback conditions are met.

**Keywords** EEG, Fractal, Emotional State analysis, Inaudible High-frequency Sounds

## 1. Introduction

Previous studies report that the typical audible sound frequency range for humans is 20Hz - 20KHz. However, in recent years, by measuring brainwaves, cerebrospinal fluid, and cerebral blood flow, signals that are higher than this range, and thus inaudible to the human ear, affect brain activity with or without consciousness [1-5]. Also, by including higher frequencies above 20KHz, the sound can be perceived 0.5-2dB louder [6-8].

The RINSHU sound system from Hibino Sound Therapy Lab, one of the playback devices used in this study, uses curved wood amplification in a manner that is similar to

acoustic instruments made of wood. Preliminary data show that the abundance of high-frequency sounds produced in this way may be transmitted over large distances without a drop-off in intensity versus conventional high-resolution playback systems. In this study we explore how this difference in signal transmission affects the emotional state of subjects listening select music recordings.

Conventionally, in measuring emotional state and associated feelings, the SD (Semantic Differential) method has been used. However, emotional state and feelings are mainly subjective, and vary among individuals, and are hard to assess in objective and quantitative ways. Therefore, for objectively assessing emotional state, measurement of brain activity has been used [9-11]. Sato (2002) established the Emotion Fractal-dimension Analysis Method (EFAM) based on chaos fractal characteristics of brainwaves [12-13]. This method has been used in market research to analyze how individuals respond to and generally feel about commercial products [14-19] and for BCIs (Brain Computer Interfaces) that control devices with biological signals such as human brainwaves.

In this thesis, we measure emotional state in subjects when listening to music that includes higher frequency sounds that are inaudible to the human ear by utilizing this fractal analysis method to objectively measure emotional state.

## 2. Analysis Method

### 2.1 Fractal analysis method

Focusing on the fractal nature of the EEG signal, we can calculate fractal dimension values. In this study, using the fractal dimension estimation method with a dispersion of the scaling characteristics, we calculate the fractal dimension value.

Value (q) is the dimension moment of the series data  $f(t)$  and the time  $\tau$  apart data  $f(t + \tau)$  is expressed by the following equation.

$$\sigma_q = \langle |f(t+\tau) - f(t)|^q \rangle \sim |\tau|^{qH}. \quad (1)$$

Here,  $\langle \cdot \rangle$  means the statistical average. By assuming the stationarity and ergodicity to the time-series data, it is replaced by a time average to obtain the scaling characteristics of Figure 2.1 from the equation (2).

$$\sigma_q = \lim_{T \rightarrow \infty} \frac{1}{T} \sum_{t=0}^{T-1} |f(t+\tau) - f(t)|^q. \quad (2)$$

It is possible to determine the Hurst index from the following formula from the scaling properties (3)

$$H_q = \frac{1}{q} \frac{\Delta \log \sigma_q(\tau)}{\Delta \log |\tau|}. \quad (3)$$

Fractal dimension can be calculated by the use of this Hurst exponent, assuming an embedded dimension of (d), one dimensional signal is  $d = 1$ , and the fractal dimension can be calculated by the equation (4) [12-14].

$$D_q = d + 1 - H_q = 2 - H_q. \quad (4)$$

## 2.2 Time-dependent fractal dimension estimation method

The EEG signal delivered in this study is considered to have a steadiness between 1 second and 2 seconds [21]. So when performing the analysis in 2.1 fractal dimensions, the above-mentioned analysis must be carried out in this range. Therefore, by introducing a transition width (Wm) and analysis window width (Ws) to the time-series analysis of the EEG signal line, we can perform the time series analysis of the EEG signal.

Using the electrode arrangement based on the international 10-20 system (Fig. 2.2) [22], the EEG signal (Fig. 2.3 (a)) is measured with an analysis window width (Ws). We calculate a fractal dimension using a 2.1 fractal dimension estimation method within the width, and then shift by the transition width (Wm), then calculate a fractal dimension in analyzing the window width. By repeating the same operation, we calculate the time-dependent fractal dimension value (Fig. 2.3 (b)). Figure 2.3 is a result of Fp1 in Figure 2.2, with 0 – 30 seconds occurring while viewing images associated with various emotional states and the subsequent 30 seconds being a measurement of when subjects recall the image in their head. [12-14].

## 2.3. Emotion Fractal-dimension Analysis

By classifying fractal dimension which is a feature amount of the calculated EEG signal, we can perform a emotional state analysis based on Emotion Fractal-dimension Analysis Method (EFAM).

If the fractal dimension from the fractal dimension analysis based on the distribution of the scaling properties is set as the input vector  $x(t)$ , and if the emotional state is set as the output and  $z(t)$ , the relational equation of EFAM can be expressed by diagram (5) and (6).

$$\begin{bmatrix} C_{1,1} & C_{1,2} & \cdots & C_{1,M} \\ C_{2,1} & C_{2,2} & \cdots & C_{2,M} \\ \vdots & \vdots & \ddots & \vdots \\ C_{N,1} & C_{N,2} & \cdots & C_{N,M} \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \\ \vdots \\ x_M(t) \end{bmatrix} + \begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_N \end{bmatrix} = \begin{bmatrix} z_1(t) \\ z_2(t) \\ \vdots \\ z_M(t) \end{bmatrix}. \quad (5)$$

$$Cx(t) + d = z(t). \quad (6)$$

Here, (M) is the number of channels of the electrodes, (N) is the number of emotional state as we test different types, C is the emotional state matrix, and (d) is a constant vector. Determining the emotional state matrix C and the constant vector (d) is performed by the teacher signal and input vector derived from fractal dimension analysis from the EEG signal. For example, in identifying three types of emotional state, if we assume that the input vector in the emotion "rest" is the teacher signal,  $Z(t) = (1,0,0) T$ . Similarly, the emotion "comfort" is  $Z(t) = (0,1,0) T$ , and "discomfort" is  $Z(t) = (0,0,1) T$ , equation (7) and (8) become equation (9), and the emotional state matrix C and constant vector (d) can be calculated.

$$c^* = [C \ d] . \quad (7)$$

$$x^* = \begin{bmatrix} x(t) \\ 1 \cdots 1 \end{bmatrix} . \quad (8)$$

$$C^* = Z_i(x^*)^T \{ x^*(x^*)^T \}^{-1} . \quad (9)$$

And applying the emotional state matrix to equation (6), by inputting the evaluation data, a emotional state output  $z(t)$  is obtained [12 14].

## 2.4. Evaluation method

Quantification of emotional state by EFAM is the emotional state in one individual subject, and cannot be compared to other subjects. In order to make the relative

comparison, the rate of change in emotional state output due to differences in our sound source (speakers) was calculated from equation (10). Here,  $Z_{HR}$  is the emotional state output at the time of listening to the sound source with inaudible high frequencies with the RINSHU sound system, and  $Z_{ctrl}$  is a emotional state output at the time of listening with an ordinary speaker system. In addition, the final output is obtained by averaging the emotional state output at the time of listening.

$$\text{Rate of change in emotional state output} = \frac{\langle Z_{HR} \rangle - \langle Z_{ctrl} \rangle}{|\langle Z_{ctrl} \rangle|} \times 100 [\%] \quad . \quad (10)$$

Also we performed a Smirnov-Grubbs test with a significance level of 5% to the calculated emotional state change rate.

### **3. Experimental method**

#### **3.1. Subjects**

Upon measuring brainwave activity when listening to music, we randomly selected 21 subjects from age 20s-70s. Furthermore, in order to obtain a emotional state range from potential effects on the human body not related to the physical process of hearing, 5 additional hearing-impaired subjects were selected.

#### **3.2. The measurement conditions**

For the EEG measurement, polymate (AP1532NS) by DigiTex Institute, Inc. was used, and the sampling frequency was measured at 2kHz. Also as a filtering process on the hardware side, a LPF (low-pass filter) was set to 600Hz and HPF (high-pass filter) to 0.5Hz, and a notch filter as a filtering process on the software side was set to 50Hz. As for the measurement site, based on the aforementioned international 10-20 system, 16ch were used. The electrodes in the right ear lobe were set as the reference voltage to measure the potential difference between two points.

As for the sound source, the RINSHU sound system by Hibino Sound Therapy Lab was used to produce sound that includes the inaudible high frequencies under investigation, which are produced by its curved wood amplification, with a spec frequency response of 45Hz to 100KHz. As a comparison, ONKYO's D-308M was used as the conventional sound source, with a spec frequency response of 55Hz to 100KHz. The song used in

this study was titled "Peace," composed and produced by Hibino Sound Therapy Lab, and performed by live saxophone and piano and recorded in 24bit 96KHz. As a comparison, the same song with the same tempo, arrangement, and dynamics performed by a computer software synthesizer (computer-generated) was prepared in 24bit 96KHz as well.

### **3.3. Flow**

The protocol of the experiment consisted of 1) reference measurement #1, 2) assignment measurement, and 3) reference measurement #2.

First, the subjects were asked to select from a series of pictures those which evoked the following emotional states: "neutral," "comfort," "uncomfortable," "joy," and "anger." We prepared 6 pictures to select from for each emotional state for a total of 30 pictures, and the subject was asked to pick the one that most easily recalled the respective emotional state. All pictures were obtained from the IAPS (International Affective Picture System) from the image group employing the James A. Russell's circumplex model of affect.

Reference measurements were performed by showing subjects their selected pictures of the "neutral," "comfort," "uncomfortable," "joy," and "anger" emotional states for 30 seconds on a computer monitor positioned in front of the subject, followed by a period of 30 seconds where the subject was instructed to close their eyes and recall these associated emotions.

Reference measurement #2 was performed in exactly the same way.

For the assignment measurement, we used 4 different configurations using the 2 types of sound sources (RINSHU versus the D-308M) and 2 types of recordings (live performance versus computer-generated). We didn't notify the subject as to which configuration was being used in order to eliminate preconceptions and bias. Subjects listened to the music for two minutes with their eyes closed, and we measured the EEG data at that time.

In addition to completing this process one time for each subject, each subject also completed a 7-stage evaluation.

#### **4. Experimental Results**

After performing outlier tests, the emotional state variation rate is shown in Figure 4.1. The vertical axis represents the number of subjects and the horizontal axis represents the value of the emotional state variation rate. Healthy young subjects are shown in dark blue, elderly subjects in light blue, and hearing-impaired in white. Additionally, the average and median values are presented in the upper-right corner. () is for hearing-enabled subjects and [] is for hearing-impaired subjects. Figure 4-1-1 shows the result of the live performance recording, and Figure 4-1-2 shows the result of computer-generated recording. In the “comfort” emotional state, both hearing-enabled and hearing-impaired subjects have the same average value.

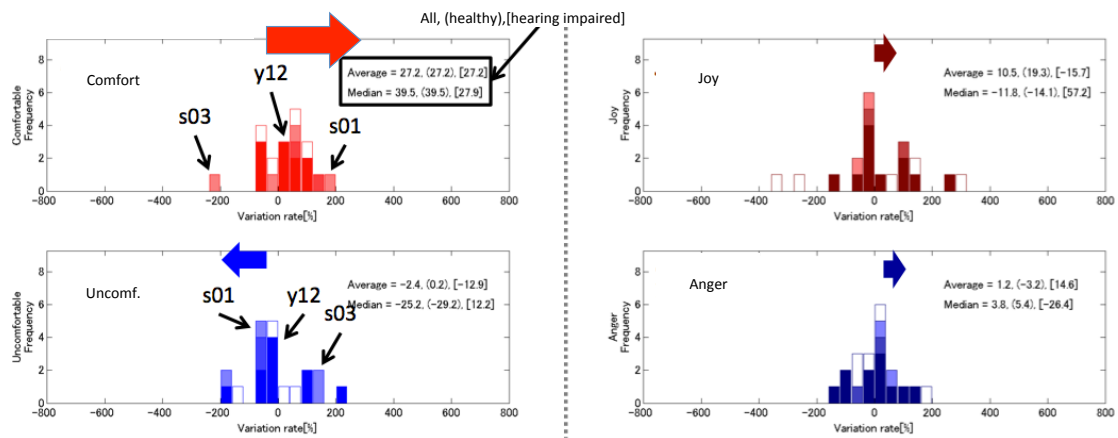
Figure 4.2 summarizes the emotional state variation rate, comparing each emotional state to the “neutral” one as a control. Colored bars represent the average while white bars represent the median.

According to these data, listening to the live performed recording resulted in a 35% increase in feelings of “comfort” while “uncomfortable” feelings were decreased by 54.6% ( $P < 0.05$ ). On the contrary, when listening to computer-generated recording, feelings of “anger” were increased by 16.6%, feelings of “comfort” were decreased by 51.5%, “uncomfortable” feelings were decreased by 5.7%, and feelings of “joy” were decreased by 4.6% ( $P < 0.05$ ).

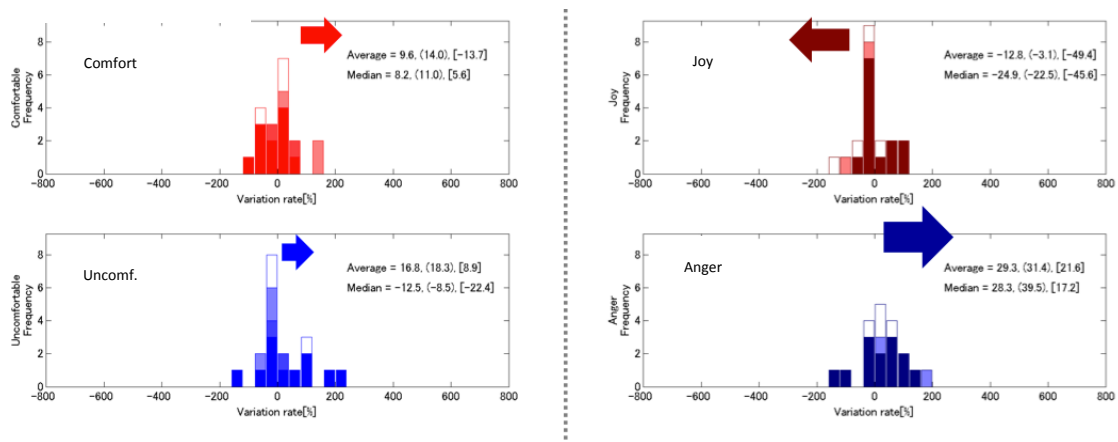
Thus, when compared to a conventional compression-based sound source, it’s possible that sound sources that preserve high-frequency bands enhance comfort and reduce uncomfortable feelings provided that the recording meets the specifications used in this study, namely live performed music recorded using high resolution techniques that retain the high frequency bands that are inaudible to the human ear.

Figure 4.3 shows a typical subject’s EEG brain topography in the “comfort” emotional state (top = anterior). Previous studies have shown that the right frontal lobe is where

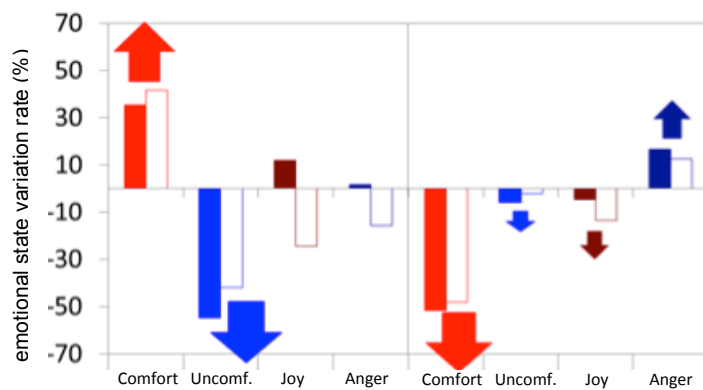
humans perceive “comfort,” and the left frontal lobe is where humans perceive “fear”[23]. In listening to the RINSHU sound system, the topography data show that the right frontal lobe is more active and the left frontal lobe is less active compared to the conventional sound source used in this study.



4-1-1. emotional state variation rate (live performance recording)

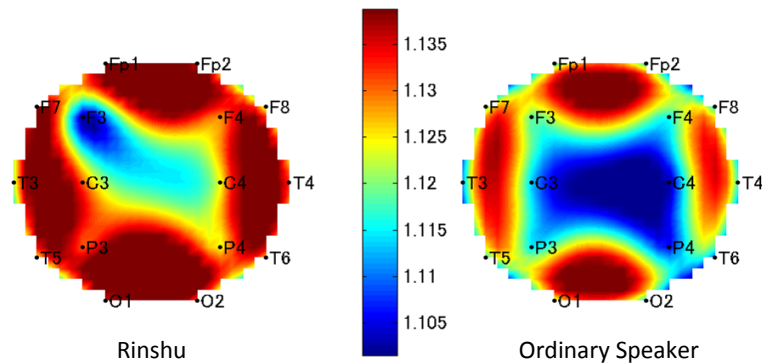


4-1-2. Emotional state variation rate (computer-generated recording)





4-2. Summary of emotional state variation rate (left: live performed / right: computer-generated))

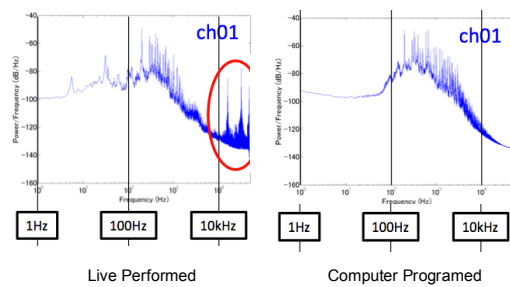


4-3. Brain EEG brain topography in “comfort” emotional state

## 5. Discussion

High frequency sounds that are inaudible to the human ear are commonly generated by acoustic instruments being performed live as a result of resonance and overtone harmonics. However, these frequencies are greatly diminished in recorded music due to modern recording techniques and conventional compression-based playback systems (5-1). The data from this study show that a decrease in negative feelings was only achieved with live performed music played using the RINSHU sound system, which may be attributed to the RINSHU’s curved wood design to deliver sound in a similar fashion to that of a live acoustic instrument.

Previous studies have shown that music can reduce anxiety and increase non-active comfort regardless of the melody or tempo [24] [25]. Thus, if the emotional states are compared relatively, (10) "comfort" should increase and "discomfort" should decrease, regardless of the song that’s being played. However, Figure 4.2 shows that this may not be the case. Even when a piece of music was played with the same melody, arrangement, and tempo, the effects on emotional state varied due to the way the music was recorded (live versus computer-generated) and how the sound was produced (conventional speaker system versus the RINSHU sound system).



### 5-1. Frequency response to the study song “Peace” (produced in 24bit 96KHz, Lch only)

Some limitations of this study include the small sample size and the fact that listeners were likely able to discern the difference between the live recording and computer-generated recording based on their sound despite using an identical arrangement and melody. To hone in on the subconscious effects that these high-frequency bands may have on emotional state, which we briefly explored by including hear-impaired subjects in this study, it may be worth attempting a study design where all subjects are given sound-deafening earmuffs to determine if the soundwaves themselves, without context of the sound, have an effect on emotional state.

### Summary

In this study, we explored how high frequency sounds may affect a human’s emotional state. Our data show that this effect is only significant when the recording techniques and playback device are properly selected. Our future challenge will be to apply this effect to music therapy, especially for those with dementia, autism, insomnia, chronic pain, and depression.

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Live performed

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