

Sensory Evaluation of Road Noise with Physiological Reaction using Electroencephalogram

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ABSTRACT

A method for direct measurement of organic reactions (brain waves) was used to evaluate interior road noise. This was used in addition to the conventional, indirect method of descriptive sensory evaluation. The results showed that the annoyance factors in perception of sample sounds that included road noise could be divided into an active pleasant-unpleasant factor and a passive comfort-discomfort factor. The use of brain wave measurement for the passive comfort factor demonstrated the possibility of obtaining objective descriptions that are statistically significant.

1. Introduction

There has been much research presented on the perception of interior road noise based on descriptive sensory evaluation^{(1), (2)}. The tone factors that are referenced in regards to road noise include power, muffling, and comfort-discomfort. While a large body of research and case studies concerning this sort of psychological evaluation of noises based on sensory evaluations exist, conventional sensory evaluations may suffer from limitations in how faithfully they can capture the subjective responses of human test subjects. These limitations stem from the fact that it is impossible to completely avoid any bias that may creep into the results via the subject's thought processes as those subjects record their responses to audio stimuli. This sort of perturbation can be avoided if it is possible to directly measure subjective evaluations. In response to recent demand for results that are very correlated to human responses, there has been tremendous interest in evaluation methods that focus on response to physiological signals^{(3), (4)}. One such example is conducting a psychological evaluation of auditory stimuli by measuring heart rate and electric potential across the skin. These signals convey little information, however, and have been found to be of limited use when attempting to estimate complex mental activity, such as experiencing comfort-discomfort.

This research, intended to clearly define "comfortable" road noise, consists of brain wave testing conducted while exposing the test subjects to noises, which included actual vehicle noises. Objective analyses and evaluations of responses to road noise (such as comfort-discomfort) are then conducted by focusing on the analysis of brain wave responses that electrically reflect the activities of the central

nervous system and brain; both of which govern complex mental activities. Other objectives are to precisely specify the comfort response and to create a formula for estimating the comfort-discomfort of road noise based on the correlation of comfort response with the physical characteristics of certain noises. If these objectives could be achieved, it would be possible to indicate specific targets for the development of comfortable road noise. This article describes this attempt and the results that are derived.

2. Brain Wave Measurement and Evaluation Methods

Feelings of comfort or discomfort that arise from exposure to road noise are the result of brain activity, and it is likely that the effects of such activity manifest themselves in the brain waves. The road noise is a binaural recording made from the passenger seat in a vehicle that is driving on a rough road surface, and is played for the subjects through headphones. However, because the magnets in the headphones introduce noise in the brain wave measurements, the playback signal is passed through a high-pass filter (40 Hz).

Brain waves are measured using an ESA-16 Emotion Spectrum Analysis System manufactured by Brain Functions Laboratory Inc. and the 12 electrodes are placed according to the international 10/20 placement system, using monopolar derivation with the reference electrode on the right ear.

The following three methods for evaluating brain waves are used in this research:

- (1) Emotion spectrum analysis
- (2) Alpha wave band power percentile analysis

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(3) Beta wave band PCA (Principal Component Analysis)

Because these methods of brain wave analysis are not commonly known techniques, they are briefly described below^{(5), (6)}.

2.1. Overview of Emotion Spectrum Analysis

Although some research is conducted on the classification of emotions produced by brain activity, this research will only consider four elementary emotion factors: joy, anger, sadness, and relaxation. Figure 1 shows the scalp electric potential when each of these emotion factors is expressed.

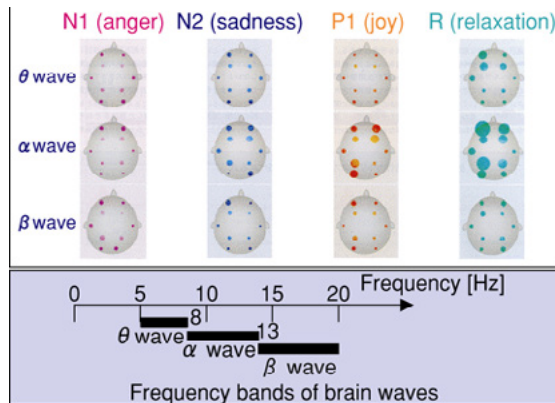


Fig. 1 Contribution of brain wave data for each emotion factor

In emotion spectrum analysis, after eliminating the effects of individual differences in scalp electric potential levels, the cross-correlation coefficients of the electric potential between each electrode position are used as a means of recording in a time series the phase relationship and positional relationship between each electrode potential, and then these coefficients are input to derive the four emotion factors. Figure 2 shows an overview of this process. Because the ten electrodes can be paired up in 45 different combinations (${}_{10}C_2$), and the brain wave measurement bands are the three bands of the theta wave, the alpha wave and the beta wave, the cross-correlation coefficients for the electric potential between electrodes that are input is a vector of which elements are 135 (45 factors multiplied by 3 bands). The four emotion factor vectors are then derived by multiplying these vectors by a 4×135 coefficient matrix called the “emotion matrix”. Emotion spectrum analysis is a method of expressing these changes over time numerically. This emotion matrix is calculated beforehand by other statistical

$$\begin{aligned}
 Z_1 &= C_{1,1}Y_1 + C_{1,2}Y_2 + \dots + C_{1,135}Y_{135} + D_1 \\
 Z_2 &= C_{2,1}Y_1 + C_{2,2}Y_2 + \dots + C_{2,135}Y_{135} + D_2 \\
 Z_3 &= C_{3,1}Y_1 + C_{3,2}Y_2 + \dots + C_{3,135}Y_{135} + D_3 \\
 Z_4 &= C_{4,1}Y_1 + C_{4,2}Y_2 + \dots + C_{4,135}Y_{135} + D_4 \\
 \mathbf{Z} &= \mathbf{C} * \mathbf{Y} + \mathbf{D}
 \end{aligned}$$

$Y_1 \sim Y_{135}$: cross-correlation coefficients between potentials of two electrodes
 Z_1 : anger Z_2 : sadness Z_3 : joy Z_4 : relaxation
 parameters indicating emotional levels (Z: emotion vector)
 $C_{1,1} \sim C_{4,135}$: coefficients (C: emotion matrix)
 $D_1 \sim D_4$: constants (D: constant matrix)

Fig. 2 Calculation method to derive emotion factors from brain wave data

means.

The joy, anger, sadness and relaxation emotion factors that are derived express the respective emotions that their names indicate. Other emotions are also expressed.

- (1) N1 (anger/stress): Although this value is naturally high when the test subject is angry, it is also high when the test subject is under stress or excited.
- (2) N2 (sadness/down): Indicates that the subject is sad or feeling down.
- (3) P1 (joy/accomplishment): Indicates that the subject feels happy or is otherwise feeling positive, after achieving some goal, for example.
- (4) R (relaxation): Indicates that the subject is comfortable and relaxed.

2.2. Overview of Alpha Wave Band Power Percentile Analysis

The power percentile of the alpha wave band among the brain waves indicates the degree of nonalertness. When this value is high, it usually indicates a decrease in brain activity or awakening.

$$\text{Alpha wave band power percentile} = W\alpha / (W\theta + W\alpha + W\beta)$$

$W\alpha$, $W\beta$, $W\theta$: Power of each respective band

2.3. Overview of Beta Wave PCA (Principal Component Analysis)

This method applies principal component analysis to the beta wave band of four points on the forehead, where higher mental activity occurs, and calculates the contribution rate of the first principal component. When this value is high, it can be assumed that the brain cells in the vicinity of the frontal lobe are working in concert with each other; therefore, this contribution rate indicates the concentration or diffusion of mental activity.

3. Preliminary Experiments

The first thing to be confirmed is whether or not changes in brain waves can be elicited through audio stimuli. To determine this, the brain waves of subjects are measured while they listened to sample noises through headphones. Because it is also necessary to study the emotions of each subject, a sensory evaluation using the Semantic Differential method with the same sample noises is also conducted.

3.1. Brain Wave Test

For the sample noises, three recordings (a, b, and c) of road noise are made while driving on a rough road surface. These recordings are used to create five minutes of continuous noise and thirty seconds of intermittent noise. The four test subjects (S1, S2, S3, S4) are all males.

Figure 3 shows the results of the brain wave measurements for subject S2 when listening to the continuous noise. These results show the changes in the values of each emotion factor, the alpha wave band power percentile, and PCA while the noises are played and the subject opened and closed his eyes. The relaxation value is clearly increased before the start of the test, during the breaks, and after the test, showing that the subject felt at ease when testing is not actively in progress.

However, from these results it is difficult to directly discern any differences in the indicated values in response to

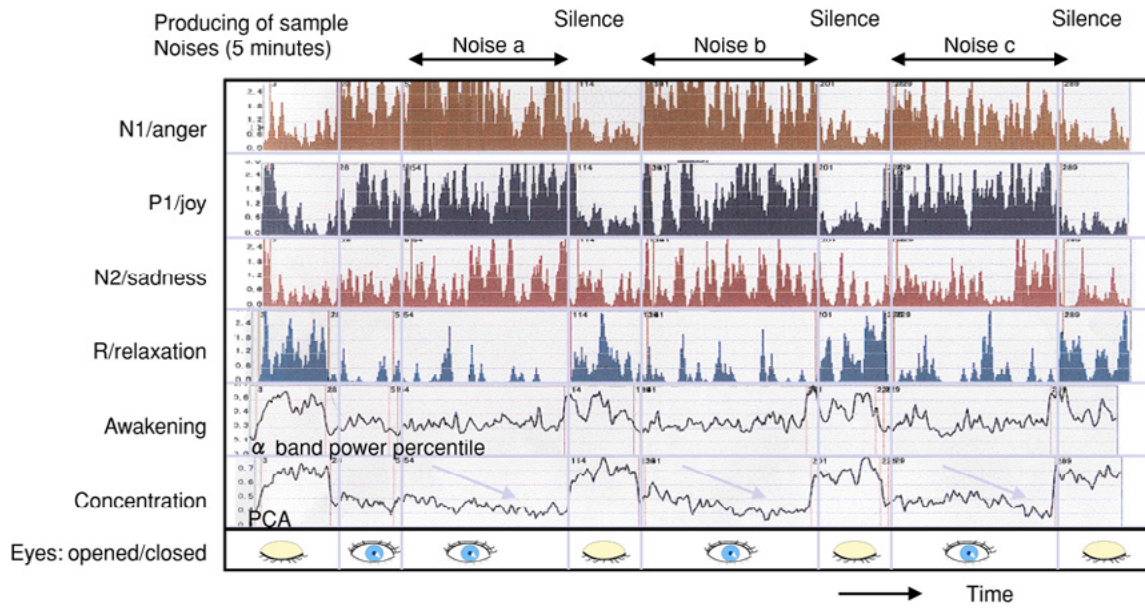


Fig. 3 Variations of emotion spectra for continuing noises

Table 1 Average emotion spectra during one term for each subject

Color of number shows consistency of order between states of eyes opened or closed;

Agree perfectly, Agree partly, Disagree

Sub.S1	Ranking of average emotion spectra						Sub.S3	Ranking of average emotion spectra					
	Eyes opened			Eyes closed				Eyes opened			Eyes closed		
	a	b	c	a	b	c		a	b	c	a	b	c
N1/anger	2	1	3	1	2	3	N1/anger	2	3	1	1	3	2
P1/joy	1	3	2	1	3	2	P1/joy	3	1	2	3	1	2
N2/sad	1	2	3	2	3	1	N2/sad	3	1	2	3	2	1
R/relax	3	2	1	2	1	3	R/relax	1	3	2	1	3	2
Sub.S2	Eyes opened			Eyes closed			Sub.S4	Eyes opened			Eyes closed		
	a	b	c	a	b	c		a	b	c	a	b	c
	a	b	c	a	b	c		a	b	c	a	b	c
N1/anger	3	2	1	3	1	2	N1/anger	3	1	2	1	3	2
P1/joy	1	2	3	1	3	2	P1/joy	2	1	3	2	1	3
N2/sad	2	1	3	3	1	2	N2/sad	2	3	1	2	3	1
R/relax	2	1	3	1	3	2	R/relax	1	2	3	3	1	2

the different samples. Table 1 shows the average values produced while each sample is played, and the comparative ranking of each.

In this table, those cases where the ranking of each sample noise is the same whether the subject's eyes are open or closed are shown in red. Looking at these results, it is easy to see the differences in ranking when the eyes are open versus when the eyes are closed for the same individual subject. Looking at the results for joy, the rankings of the three noises when the eyes are open matched the rankings when the eyes are closed in the case of three of the four subjects (S1, S3, and S4). Even so, the rankings for each subject differed from those of the others, and the differences between subjects are considerable, making it difficult to find a common trend. It is possible that each individual's evaluation axis in regards to noise is different, and there is a need for a study that cross-references these results with the sensory evaluation results. Regarding the alpha wave band power percentiles (indicating the degree of nonawakening), Table 2 shows that noise c caused a decrease in alertness.

Regarding PCA, the differences between the sample noises are small, making this method unsuitable for the evaluation of audio stimuli.

Table 2 Result of a band power percentile

Color of number shows consistency of order between states of eyes opened or closed;

Agree perfectly, Agree partly, Disagree						
	Ranking of average value					
	Eyes opened			Eyes closed		
	a	b	c	a	b	c
Sub.S1	2	3	1	2	1	3
Sub.S2	1	3	2	3	2	1
Sub.S3	3	2	1	1	2	3
Sub.S4	3	2	1	1	2	3

3.2. Sensory Evaluation

A sensory evaluation is conducted with the same four test subjects, using a procedure similar to that used in the brain wave test. Each subject is asked to evaluate three sample noises. As shown in Table 3, a principal component analysis is performed using the Semantic Differential method with seven grades and 15 different adjectives for noise evaluation. Three principal components are extracted, based on the results; however, because principal components 1 and 2 had a cumulative contribution rate of 80%, principal components 1

Table 3 Condition of sensory evaluation

Sample noise	Subject	Adjective				
1 Continuing noise a	1 S1	1 fresh	6 stagnant	11 powerful		
2 Continuing noise b	2 S2	2 high-pitched	7 rough	12 rich		
3 Continuing noise c	3 S3	3 unpleasant	8 offensive	13 dry		
4 Alternate noise a&b	4 S4	4 annoying	9 bright	14 smooth		
5 Alternate noise a&c		5 alive	10 loud	15 booming		
6 Alternate noise b&c						
Grade for estimation						
1	2	3	4	5	6	7
agree			neutral			disagree

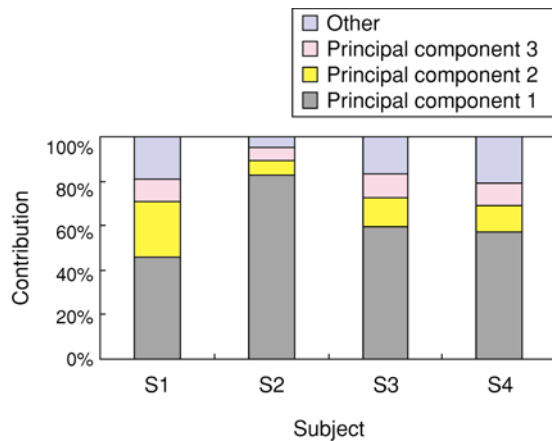


Fig. 4 Component contribution of each subject

and 2 are sufficient for describing the tone structure of the road noise for these four subjects. (Refer to Fig. 4.)

Principal component 1 consists of:

- Positive noise parameters in the positive direction
- Negative noise parameters in the negative direction

Those parameters with large factor loading are “fresh” and “smooth”, supposed “aesthetic clarity” indicating comfort-discomfort. (Refer to Fig. 5.)

Principal component 2 indicates a muffled feeling.

Figure 6 shows how each of the four subjects scored each sample noises according to the two principal components. The only area in which the four subjects scored the sample noises in the same order is in the relative positioning of intermittent noises a and b (a1 and b1), a and c (a2 and c2) and b and c (b3 and c3), expressed by principal

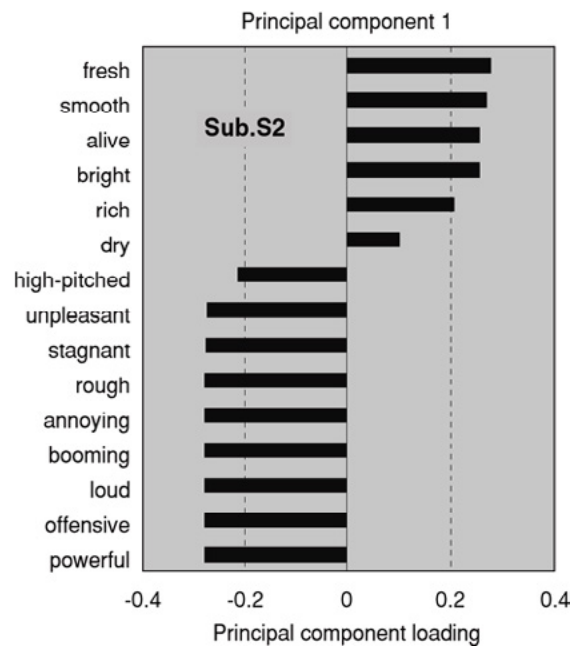


Fig. 5 Principal component loading for principal component 1 (subject S2)

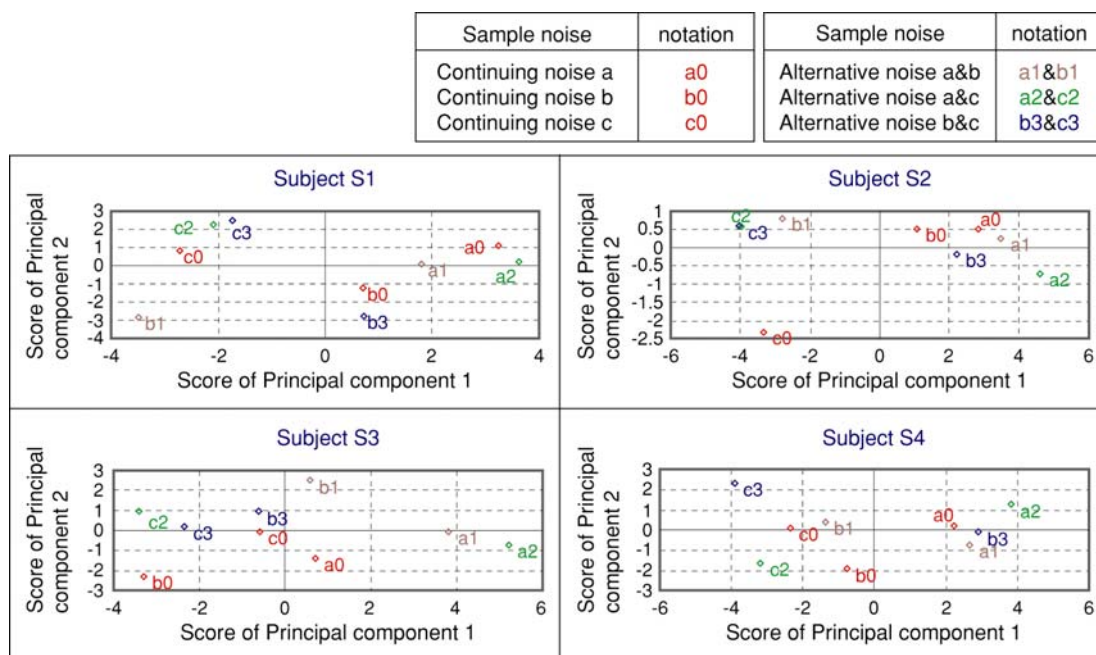


Fig. 6 Principal component score for each sample noise; horizontal: principal component 1, vertical: principal component 2

component 1 (aesthetic clarity). Accordingly, the results of principal component 1 testing using intermittent noise are deemed suitable for comparison with organic response tests.

3.3. Comparison of the Brain Wave Measurement Data with the Sensory Evaluation Results

Because the purpose of this research is to define comfortable road noise, the focus is placed on principal component 1, and a comparison is made between the brain wave measurement data and sensory evaluation results for subject S2, for whom principal component 1 accounted for 80% of his response. Figure 7 shows the results.

For subject S2, for whom principal component 1 determined 80% of his response, the sensory evaluation results and emotion spectrum measurement results for intermittent noise have correlation with the emotion vector that shows comfortableness ($[P1 + R] - [N1 + N2]$) which is composed by subtracting the emotion vectors that indicate

discomfort (anger/N1 and sadness/N2) from the emotion vectors that indicate comfort (joy/P1 and relaxation R).

The importance of the results obtained from these preliminary experiments is that there are significant differences in brain wave measurements when subjects are exposed to road noise, and that the emotional state of subjects can be identified by measuring their brain waves in response to audio stimuli.

In addition, because there is a need for a detailed analysis of comfort and discomfort, four more adjectives are added for a separate sensory evaluation in order to emphasize and draw out comfort-related emotions: vigorous, sweet, gloomy, and composed. All adjectives are for emotional emphasis. Based on the results of the factor analysis shown in Fig. 8, it is possible to identify “active” “pleasant” with high factor loading for “bright” and “sweet”, and “passive comfort” with high factor loading for “composed” and “smooth”.

(1) Active pleasant (an active comfort, an excited, vigorous comfort)

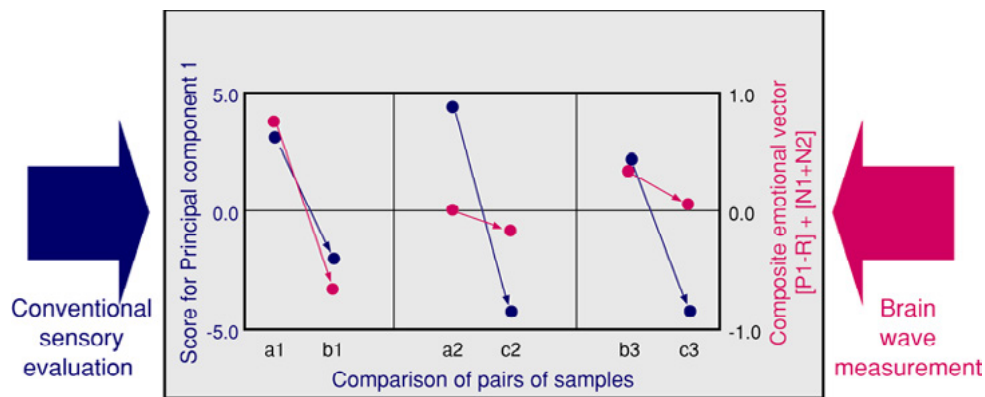


Fig. 7 Comparison between conventional results and results from brain wave measurement

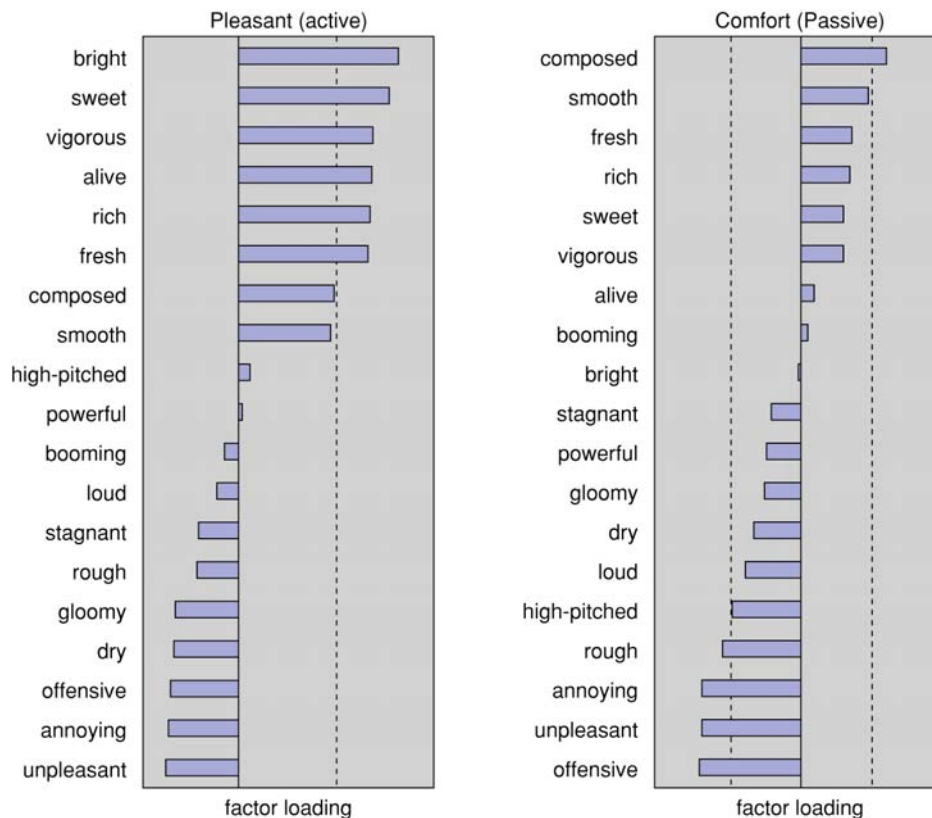


Fig. 8 Differences between active pleasant and passive comfort

- (2) Passive comfort (a quiet comfort, a relaxed, pleasant comfort)

Because passive comfort is deemed to be important in addressing road noise, the analysis of the main tests focused on passive comfort.

4. Main Tests

4.1. Method

In order to understand passive comfort through brain wave measurements, the results of the preliminary tests formed the basis of the main tests. A total of 21 subjects (average age: 23.6) are tested. The brain wave measurement method that is used in the preliminary tests is used without modification in the main tests, and the analysis is conducted by calculating the emotion spectrum and the composite values. In addition, typically pleasant noises and uncomfortable noises that are not road noises are added to the sample noises.

The sample noises are all binaural recordings that are played back to the subjects through headphones. A breakdown of the sample noises follows:

- (1) Road noise samples: Recordings made from the passenger seat in ten stock cars while driving on a rough road surface
- (2) Reference noises for discomfort: Recordings made from the passenger seat while driving on an extremely rough road surface, the roar of a waterfall at Nikko Yutaki, the sound of scratching on frosted glass
- (3) Reference noises for comfort: A gentle breeze in the woods in Kirifuri Kogen, a small stream, the sound of a waterfall with the sound pressure reduced and with AM modulation applied to produce a more calming effect
- (4) Reference noise for each stage: Pink noise

A total of 18 noises are used. (Refer to Table 4.)

Sample noises are played back in the following manner: ten seconds of pink noise (for stabilization), 45 seconds of the sample noise, ten seconds of silence. In order to eliminate any possible effect caused by the sequence of the sample noises, the noises are played in a random order.

Table 4 Sample noises

No.	group	content
1	Road noise	A Medium
2		B Medium
3		C Compact
4		D Compact
5		E Medium
6		F Entry
7		G Compact
8		H Entry
9		I Executive
10		J Executive
11	Criteria noise	K Rough road
12		Waterfall
13		Waterfall AM
14		A gentle breeze in wood
15		Stream
16		Scratch of a nail on frosted glass
17		Pink noise

The following the four emotion spectrum composite values:

- (1) N1 + P1: Combines an increase in mental alertness and an increase in good feeling, and is interpreted as a pleasant feeling
- (2) N2 + R: Combines a decrease in mental activity and a decrease in good feeling, and is interpreted as a gloomy feeling
- (3) N1 + N2: Combines an increase in mental activity and a decrease in good feeling, and is interpreted as an irritated feeling
- (4) P1 + R: Combines a decrease in mental activity and an increase in good feeling, and is interpreted as a comfortable feeling

After the measurement of brain waves is completed, a sensory evaluation is conducted using the same sample noises. Passive comfort is then evaluated by the Semantic Differential method using a seven grade scale for each of 16 tone factors.

As shown in the analysis flow in Fig. 9, the validity of each of the brain wave measurement results and sensory evaluations is verified and then each pair is compared.

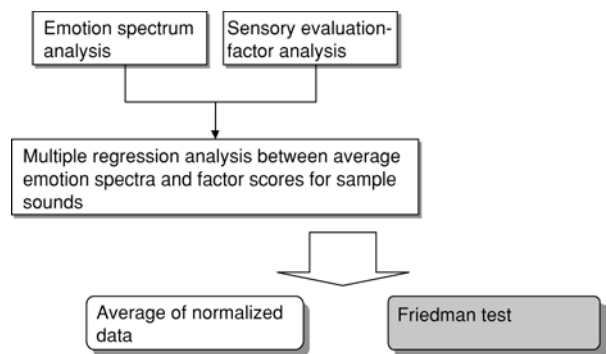


Fig. 9 Analysis flow

4.2. Results of Emotion Spectrum Analysis

Table 5 shows the results of statistical verification of the emotion spectrum and the composite values calculated from the brain wave measurements taken during the playback of the sample noises for all of the subjects. Verification is accomplished by using the Friedman test to determine the significance of the ranking of the 21 subjects for the 18 sample noises; those items with 1% significance are marked by ** in the table. Aside from a few cases, such as N1 Anger, the table shows that the emotion vectors demonstrate significant response to the sample noises. Figure 10 shows the results for R Relax for each sample noise.

Table 5 Significant difference of emotion spectra for sample noises **expresses 99% reliable

Emotion spectrum	Significant difference
N1 Anger	—
P1 Joy	**
N2 Sadness	**
R Relaxation	**
α band power percentile	**
PCA Concentration	**
N1+P1	—
N2+R	—
N1+N2	**
P1+R	**

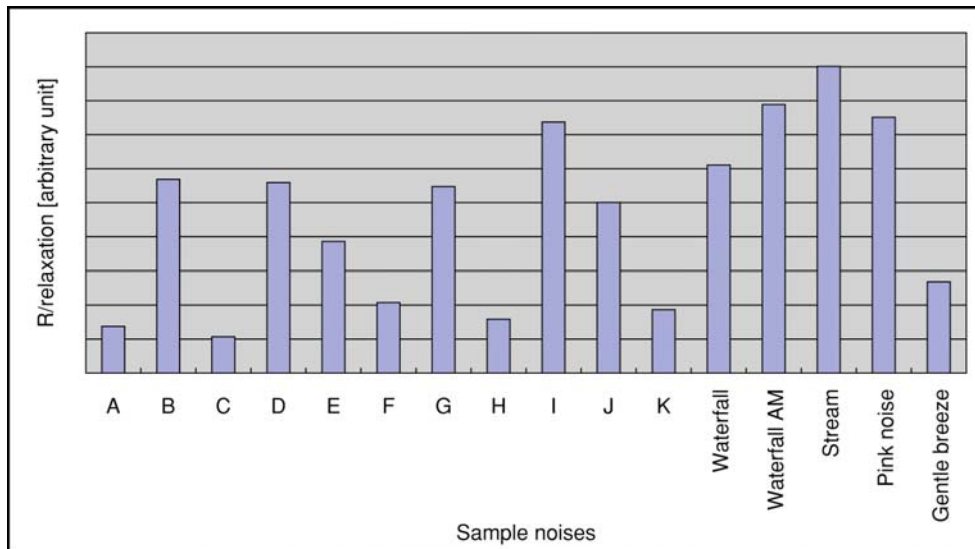


Fig. 10 Emotion spectra of sample noises

4.3. Results of Factor Analysis

After the brain wave measurements, the same sample noises are used in a sensory evaluation using the Semantic Differential method with a seven grade scale for 16 adjectives. Table 6 shows the factor analysis of the results. As shown in the table, three factors are derived: comfort-discomfort, roughness-smoothness, and silence-noise.

Of these, comfort-discomfort expressed passive comfort (feeling comfortable and at ease) and active discomfort (irritated and uncomfortable), a pairing that demonstrated its usefulness for the evaluation of road noise in the preliminary tests. In addition, in this factor analysis the comfort-discomfort factor (passive comfort factor) has a high

contribution rate of 42.6%, so that the passive comfort component in this sensory evaluation should have high reliability and be expressed vividly. Figure 11 shows the passive comfort factor scores for each sample noise.

4.4. Comparison of the Emotion Spectra and the Passive Comfort Factor

The emotion spectra that are derived from the brain wave measurements demonstrated significant response to the sample noises. In addition, the first factor for the same sample noises is the passive comfort factor. In regards to how to express comfort-discomfort in response to the road noise through the brain wave measurement results, the passive comfort factor score for each sample noise is set up as the criterion variable, and a multiple regression analysis is performed for each subject with the emotion spectra N1, P1, N2, and R for that sample noise as the explanation variables. However, the coefficients of the emotion spectra in the multiple regression equation differ considerably for each subject; the correlation coefficient for all of the subjects is only 0.2, making it difficult to specify consistent coefficients. The decision is made to reflect the results of the brain wave

Table 6 Results of factor analysis

No.	Name	Factor contribution rate (%)	Factor cumulative contribution rate (%)
1	Comfort	42.6	42.6
2	Roughness	13.4	56.0
3	Silence	10.9	66.9

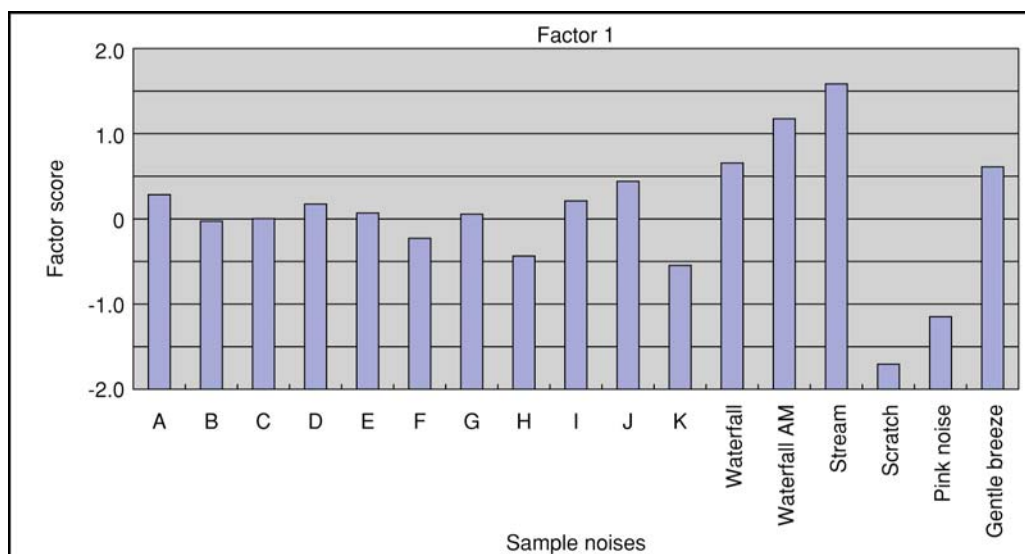


Fig. 11 Factor score of sample noises

measurements by averaging the individual multiple regression scores for all of the subjects. That the average passive comfort score for all subjects, calculated by a multiple regression equation based on this emotion spectrum primary linkage, is significant for the playback of each sample noise is made clear by the Friedman test. (Refer to Table 7.) In other words, it is confirmed that it is possible to use the measured results of brain waves, a physiological response, to express passive comfort in response to noise, including road noise. However, because all of the emotion spectra for joy, anger, sadness and relaxation are used, the interpretation of the regression equation itself is difficult due to individual differences.

Table 7 Significant difference of multi-regression correlation scores **expresses 99% reliable

Factor	Significant difference
Comfort (Factor 1)	**
Roughness (Factor 2)	**
Silence (Factor 3)	**

5. Comparison with Objective Measurements

The multiple regression scores (refer to section 4.4) that reflect the organic response (the results of the brain wave measurements) to each sample noise are expressed through a first order polynomial of physical values and of objective values for psychoacoustic parameters. When deriving the regression equation, the following conditions are maintained:

1. No sign inversions or multi-collinearity.
2. Multiple correlation coefficients of at least 0.9.
3. In analysis of variance of regression fluctuations, a P value of 0.05 or less is significant.
4. In determining the significant difference for partial regression coefficients, significant difference probabilities of 0.05 or less are ignored.

The regression equation that is derived is as follows:

$$\text{Passive comfort-discomfort} = -A * \text{Loudness} + B * \text{Kurtosis} + C * \text{Tonality} + D$$

A, B, C: Partial regression coefficients D: Constant

Multiple correlation coefficients: 0.901

The passive comfort regression equation and the factor scores have a high correlation. (Refer to Fig. 12.) Furthermore, according to the regression equation, the sample noises that are used in these tests are comfortable sounds that have low volume, have small changes in amplitude, and only a few frequency components that stand out.

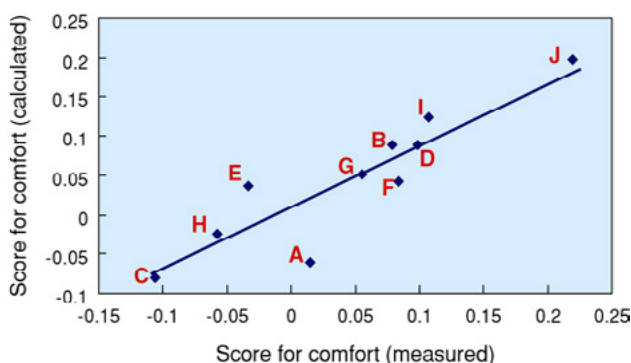


Fig. 12 Comparison of measured and calculated comfort scores

6. Conclusions

The following are the results of this research on objective evaluation of noise through the measurement of organic response (brain waves):

- (1) It was possible to obtain significant results by measuring brain waves in response to the playback of sample noises, including road noise.
- (2) It was discovered that passive comfort, which expresses the comfort-discomfort of road noise by conventional means, can be expressed by emotion vectors determined through brain wave measurement.
- (3) It was possible to derive a regression equation that objectively expressed the multiple regression score that was calculated from the passive comfort of individual subjects using emotion vectors.

An issue that requires further research:

- (4) It is difficult to say definitively that the passive comfort regression equation based on emotion vectors will apply to everyone, due to large individual differences.

The authors wish to acknowledge the assistance of Brain Functions Laboratory Inc. in the measurement and analysis of brain waves.

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