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Psychological impressions and listening score when listening to audio signals composed of monosyllables and words, while subject to meaningless steady noise—introduction of weighted-mean spectral distance

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Abstract

A useful index for evaluating two psychological impressions of annoyance, speech audibility, and the listening score, when listening to audio signals composed of monosyllables and words, while subject to meaningless steady noise is discussed. More specifically, eight evaluation indices (*SN*, *AI*, *SIL*, *WSPD*, etc.) are introduced that reflect the mutual relationships between the spectrum level of the speech peaks and that of the noise. After careful consideration of the relationships between these indices and the psychological impressions/listening score, *WSPD* can be selected as a useful index. Next, prediction problems of the psychological impressions/listening score are considered. The predicted values of the psychological impressions/listening score are compared with experimental data. The predicted values are in good agreement with the observed results.

1. Introduction

One of the most fundamental means of information transmission is direct transfer of speech. For speech to be effective, it is important to have a comfortable sound environment in which the listener can concentrate on the speech without being distracted by external noise. Hence, to design a comfortable sound environment (such as when planning and selecting the sound insulation material for reduction of external noise, or the volume adjustment of an audio signal), it is very important to understand quantitatively the relationship between how audio signals differ from

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external noise and psychological impressions/listening score. The psychological impression of external noise on subjects under the condition of meaningless random noise while listening to an audio signal has been considered [1]. However, two aspects of the psychological impression of the audio signal and the listening score have not been taken into consideration. Regarding the listening score, research on the relationship between syllable articulation (or word/sentence intelligibility) and the characteristics of noise has been carried out by a number of researchers and the results have been reported [2–5]. However, most of this research has placed emphasis on the audio signal from the point of view of perception and understanding, therefore attention has not been directed towards psychological impressions of the noise and audio signal, which play an important role in the creation of a comfortable sound environment.

From these viewpoints, this paper is a further evolution of the discussions already published [1]. The following three aspects were focused on when listening to audio signals composed of monosyllables and words while subject to meaningless steady noise: annoyance caused by noise, speech audibility of the audio signal, and the listening score. A useful index for evaluating the above three aspects simultaneously is discussed. First, the eight evaluation indices (*SN*, *AI*, *SIL*, *WSPD*, etc.) that reflect the mutual relationship between the spectrum level of the speech peaks and that of noise are introduced. Next, estimation and/or prediction problems of the two psychological impressions and the listening score are considered.

It should be noted that the results in the present paper were obtained under the following restricted conditions.

A. The psychological experiment was conducted indoors only.
B. The subjects in the psychological experiment were male and female students in their 20s, with normal hearing.
C. The external noise did not have any significant meaning.

2. Outline of psychological listening experiments

The outline of the indoor listening psychological experiments was as follows.

2.1. Experiment I

Experiment I was conducted to establish the regression function of the psychological impressions of the noise and audio signal, and the listening score.

[I-A] *Location of psychological experiment*: The experiment was conducted in a simple soundproof room on campus having the following dimensions: length 5.1 m, width 3.3 m, and height 2.2 m. The sound pressure level of the background noise was about 37 dB. A-weighted sound pressure level was about 21 dB(A). The sound pressure level in this paper is the value measured by a sound level meter with FLAT response. The reverberation time was 0.08, 0.07 and 0.06 s for octave band-limited white noise with center frequencies of 500, 1000 and 2000 Hz.

[I-B] *Time and date of psychological experiment*: 1:00 p.m.–7:00 p.m. from the end of August to the beginning of September.

[I-C] *Subjects*: A total of 160 subjects, 130 male and 30 female students, all with normal hearing, participated in the psychological listening experiment.

[I-D] *Presented sound*

(I-D-1) Audio signal. A monosyllable list, and a two- or three-syllable word list (a list contained 50 monosyllables or words) from a CD for the evaluation and fitting condition of hearing aids (TY-89) [6] were used. The maximum band levels of speech measured with a sound level meter (RION, type NL-06) and a real-time octave-band analyzer (RION, type SA-30) with FAST dynamic response for each list, are shown in Fig. 1. Maximum band levels were adopted as band levels of speech peaks. The overall sound pressure level of the speech peaks was about 62 dB.

(I-D-2) External noise. Band-limited pink noise with the following frequency bandwidths which included the auditory sensation area was used.

(I-D-2-1) [44.2, 354], [88.4, 707], [177, 1410], [1410, 11300] Hz. The sound pressure level was adjusted to 62 dB.

(I-D-2-2) [354, 2830], [707, 5660] Hz. The sound pressure level was adjusted to 56, 59, 62, 65, 68, 71, 74, 77 dB. The band levels of external noise were measured with the apparatus mentioned above (I-D-1). The power spectrum forms in the external noises of [44.2, 354], [88.4, 707], [177, 1410], [354,2830], [707, 5660], [1410, 11300] Hz (62 dB) are shown in Fig. 2.

[I-E] *Measurement of psychological impressions and listening score*: Both the audio signal and the noise were presented from a speaker to eight subjects to allow assessment of the psychological impressions and the listening score while listening to the audio signal. It was confirmed ahead of time that there was no difference in the sound pressure levels at the subjects' ears. To quantify the

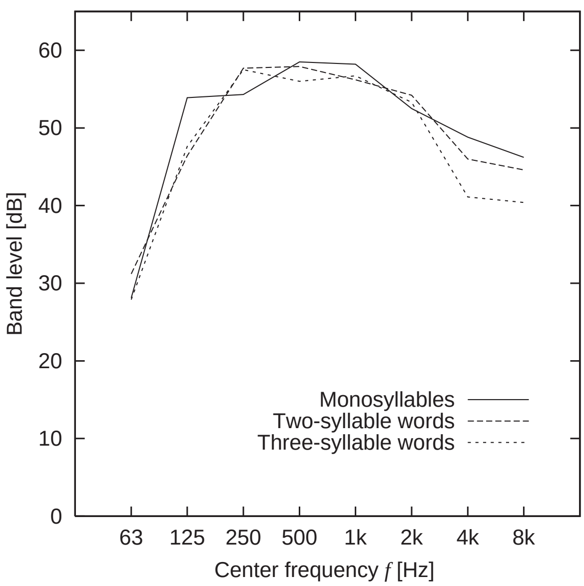

Fig. 1. Spectrum level of speech peeks.

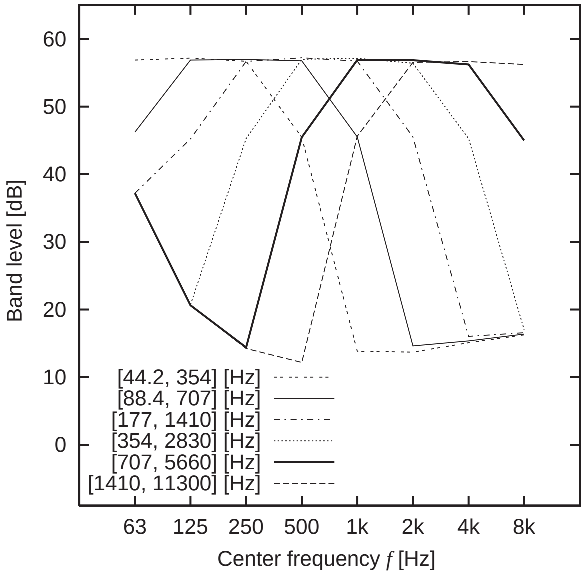

Fig. 2. Spectrum level of external noise (Experiment I).

psychological evaluation of the noise, various psychological evaluation scales for external noise were conceivable. Here, the seven categorized psychological impressions F_i $(i = 1, 2, \ldots, 7)$ of annoyance proposed by Furihata [7] were adopted: F_1, not at all annoying; F_2, not annoying; F_3, not too annoying; F_4, slightly annoying; F_5, annoying; F_6, very annoying; F_7, extremely annoying. On the other hand, the scale for the psychological evaluation of the audio signal adopted the seven categorized psychological impressions A_i $(i = 1, 2, \ldots, 7)$ of speech audibility [8]: A_1, very inaudible; A_2, quite inaudible; A_3, slightly inaudible; A_4, medium; A_5, slightly audible; A_6, quite audible; A_7; very audible. Eight subjects participated simultaneously in the listening psychological experiment. They listened to the audio signal and completed a response sheet reporting exactly what they heard. In addition, they made the above two psychological evaluations, F_i $(i = 1, 2, \ldots, 7)$ of the noise, and A_i $(i = 1, 2, \ldots, 7)$ of the audio signal. This operation was carried out with the same subjects for an external noise condition. The subjects were given sufficient rest to avoid fatigue.

2.2. Experiment II

Experiment II was conducted to compare the predicted values of the two psychological impressions and the listening score with the observed values.

[II-A] *Location of experiment*: The same location as Experiment I.

[II-B] *Time and date of experiment*: 1:00 p.m.–7:00 p.m. from the beginning to the end of September.

[II-C] *Subjects*: A total of 112 people, 100 male and 12 female students, all with normal hearing participated in the psychological experiment. They were different from the subjects of Experiment I.

[II-D] *Presented sound*

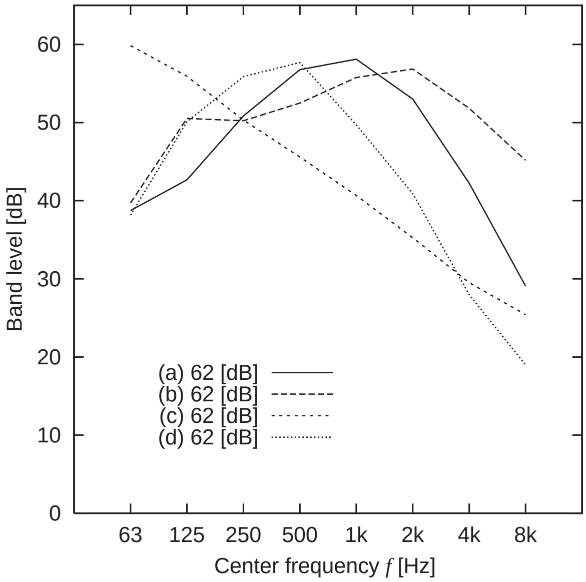

Fig. 3. Spectral level of external noise (Experiment II).

(II-D-1) Audio signal. The same audio signals as Experiment I.

(II-D-2) External noise. Following external noises that appeared realistically and contained many low-, middle-, or high-frequency components were used.

(a) Pseudo-voice noise. Pseudo-voice noise from a CD for the evaluation and fitting condition of hearing aids (TY-89). The sound pressure level was adjusted 62 dB.

(b) Pseudo-road traffic noise. This consisted of pink noise whose power spectrum closely resembled that of actual road traffic noise recorded in advance over about 2 h at the side of the road. The sound pressure level was adjusted to 62 dB.

(c) Pseudo-HVAC noise. This consisted of pink noise whose power spectrum closely resembled that of actual HVAC noise [9] The sound pressure level was adjusted to 62 and 67 dB.

(d) Meaningless voice noise. Multi-talker noise from a CD for the evaluation and fitting condition of hearing aids (TY-89). The sound pressure level was 62 and 67 dB.

(e) No external noise. The power spectrum forms in the external noises of (a)–(d) are shown in Fig. 3. The specific method of the psychological experiment was the same as that used in Experiment I.

3. Selection of the most useful index

The most useful index for evaluating the psychological impression and the listening score when listening to audio signals composed of monosyllables and words while subject to meaningless steady noise is discussed. Hereupon, the differences between the spectrum level of the speech peaks and that of the noise are considered.

3.1. Introduction of indices

From the purpose of deciding the most useful index for evaluating the psychological impression and listening score, it was rational to use not only traditional indices such as the well-known signal-to-noise ratio (SN, SN_A), articulation index (AI) [10] (which is a measure of the speech-communication system's potential intelligibility), and speech interference level (SIL) [11] (which indicates the required intensity of the speech signal at the listener's ears for a given noise condition to be heard reliably), but also the newly set up indices with various frequency bandwidths and frequency responses. Therefore, four indices to express the relative relationships between speech and noise (amplitude/frequency response) were introduced experimentally.

A. Signal-to-noise ratio (SN).
B. Signal-to-noise ratio with A-response (SN_A).
C. Articulation index (AI). In this paper, the octave-band method [10] with center frequency f_i ($f_1 = 63, f_2 = 125, \ldots, f_8 = 8000$ Hz) was adopted.
D. Speech interference level (SIL). SIL was calculated as an arithmetic-mean of the A-weighted band levels of the noise with center frequency f_i ($f_4 = 500, f_5 = 1000, \ldots, f_7 = 4000$ Hz) [11].
E. Signal-to-interference-noise ratio (SI). Focusing on the four octave band with center frequency f_i ($f_4 = 500, f_5 = 1000, \ldots, f_7 = 4000$ Hz) which is required to compute the SIL, SI was calculated by

$$SI = \frac{1}{4}\sum_{i=4}^{7}[L_{SA}(f_i) - L_{NA}(f_i)], \tag{1}$$

where $L_{SA}(f_i)$ and $L_{NA}(f_i)$ denote A-weighted band level with center frequency f_i ($i = 4, 5, \ldots, 7$) of the speech peaks and of the noise, respectively. This index did not use weight which considered the contribution to speech intelligibility [10] but A-response.
F. Weighted-mean spectral distance ($WSPD$). In the study of AI [10], experiments show that only frequency band [200, 6100] Hz contributes to speech intelligibility. It has also been possible to determine 20 frequency bands, which seem to contribute equally to intelligibility. Therefore, based on these 20 frequency bands, eight weightings a_i for the octave bands were calculated. Further, $WSPD$ was calculated as follows:

$$WSPD = \sum_{i=1}^{8} a_i[L_S(f_i) - L_N(f_i)], \tag{2}$$

$$\begin{aligned} &a_1 = 0.000000 \quad a_2 = 0.000000 \quad a_3 = 0.063794 \quad a_4 = 0.140096,\\ &a_5 = 0.226255 \quad a_6 = 0.319855 \quad a_7 = 0.227360 \quad a_8 = 0.022640, \end{aligned} \tag{3}$$

where $L_S(f_i)$ and $L_N(f_i)$ denote band level with center frequency f_i ($f_i = 63, 125, \ldots, 8000$ Hz) of the speech peaks and of the noise, respectively.

$WSPD$ was modified AI, AI was calculated from the spectrum of the speech and that of the noise which may have been present. Concretely, weighted differences in decibels between the spectrum level of the speech peaks and that of the noise over the range of frequency bands that contribute to speech intelligibility were summarized. Whenever the difference between the spectrum level of the speech peaks and that of the noise was zero or less, zero was assigned to that difference; whenever the speech exceeded the noise by 30 or more decibels, 30 was assigned to that difference. Further, it was regularized so that the magnitude was taken to vary between zero and unity. In the calculation of *WSPD*, the difference between the band level of the speech peaks and that of the noise can be zero or less, and can exceed 30 dB because it was not regularized. The above mentioned was different from *AI*.

G. Arithmetic-mean spectral distance (*ASPD*). *ASPD* was calculated by

$$ASPD = \frac{1}{8}\sum_{i=1}^{8}[L_S(f_i) - L_N(f_i)]. \quad (4)$$

This index included neither weight which considered the contribution to speech intelligibility nor A-response.

H. Arithmetic-mean spectral distance with A-response ($ASPD_A$). $ASPD_A$ was calculated by

$$ASPD_A = \frac{1}{8}\sum_{i=1}^{8}[L_{SA}(f_i) - L_{NA}(f_i)]. \quad (5)$$

Though this index used A-response as well as *SI*, the focused bandwidth of the frequency was different.

3.2. Relationship between index and psychological impressions

In this paper, in order to select the most useful index, the observed data obtained by Experiments I and II were used. Also, using these data, the relationships between the eight indices explained above and the psychological impressions regarding annoyance caused by the noise and speech audibility of the audio signal were considered. Since these relationships had to be understood, the following types of model describing regression between them were adopted.

Linear function:

$$y = ax + b. \quad (6)$$

Logistic function:

$$y = \frac{k}{1 + a\mathrm{e}^{-bx}}. \quad (7)$$

Modified exponential function:

$$y = a(1 - \mathrm{e}^{-(x-b)/k}). \quad (8)$$

First, in the case of listening to monosyllables and two or three-syllable words, the relationships between each index and psychological impression of the noise were found. These results are shown in Fig. 4, regarding the special case where *WSPD* was adopted as the index. (Other cases using other indices are omitted.) In Fig. 4, solid lines indicate the regression line selected by akaike information criterion (AIC) [12]. Here, expressions are represented by Eq. (6). This figure reveals the following: when the value of *WSPD* was increased (or decreased), the psychological impression of the noise approached F_1 (or F_7). These relationships were roughly linear. (Results identical to this special case were obtained in other index cases.)

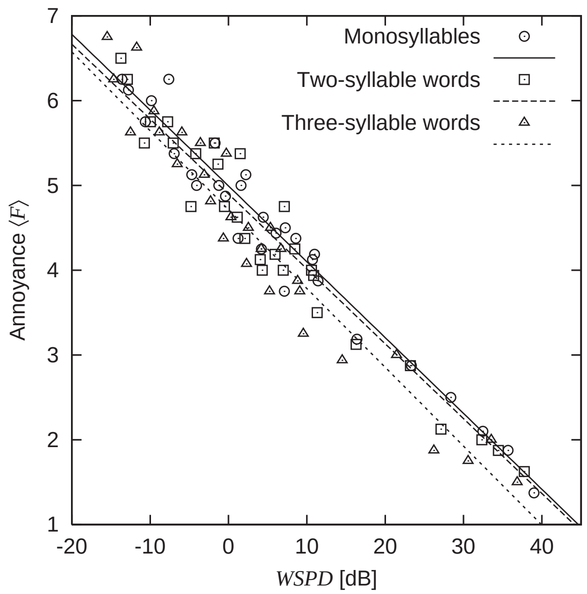

Fig. 4. Relationships between *WSPD* and psychological impression of annoyance.

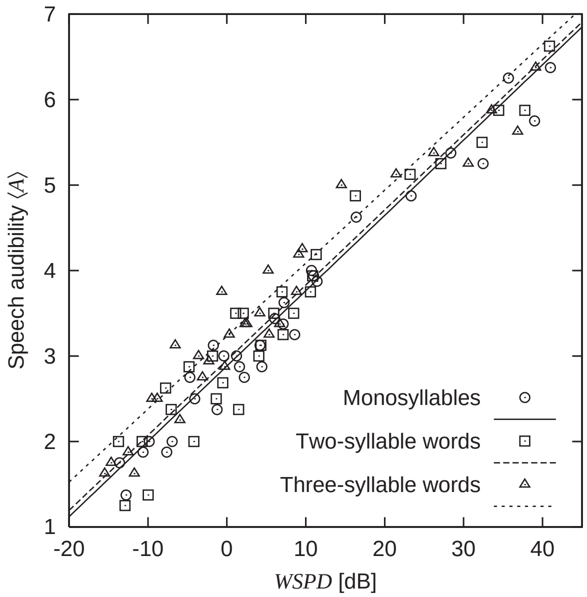

Fig. 5. Relationships between *WSPD* and psychological impression of speech audibility.

Next, Fig. 5 shows the result for the relationships between *WSPD* and speech audibility of the monosyllables and two or three-syllable words. When the value of *WSPD* was increased (or decreased), the psychological impression of the audio signal approached A_7 (or A_1). As regards speech audibility of the audio signal, Eq. (6) was the most suitable. (The same results were obtained in other index cases.)

3.3. Relationship between index and listening score

As mentioned [I-E], subjects noted the monosyllables and two- or three-syllable words exactly as they heard them. Then the number of correct answers was assessed. The listening score was defined as the percentage of correct monosyllables and two- or three-syllable words from the total (50). In the case of listening to monosyllables and two- or three-syllable words, all the observed data of Experiments I and II established the relationship between each index and the listening score. Fig. 6 shows the results in the case of *WSPD*. Here, unlike the case of the two psychological impressions, it is clearly seen that the regression curves are represented with Eq. (7). (The same results were obtained in other index cases.)

3.4. Consideration of the most useful index

This paper advances the possibility of predicting/estimating the two psychological impressions and the listening score simultaneously, and it seems that one effective means of selecting a useful index using the residual variance from the regression line or curve as a criterion. In the case of listening to monosyllables and two- or three-syllable words, Tables 1–3 show the results of residual variance concerning the psychological impressions of the noise and audio signal, and the listening score for each index. (Smallest values are underlined.) From these tables, the following is clearly seen:

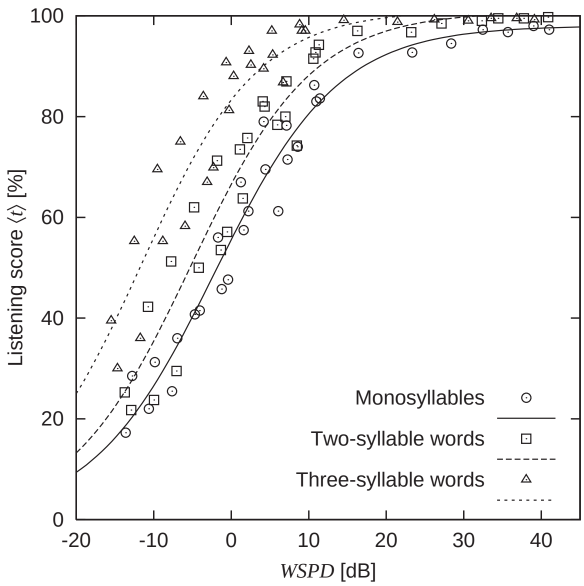

Fig. 6. Relationships between *WSPD* and the listening score.

Table 1
Residual variance (monosyllables)

	Annoyance; linear function	Speech audibility; linear function	Listening score; logistic function
SN	1.18	1.26	321.02
SN_A	0.24	0.32	44.09
AI	0.43	0.26	107.66
SIL	0.27	0.16	43.60
SI	0.27	0.16	43.60
WSPD	**0.24**	**0.15**	**33.80**
ASPD	0.56	0.58	182.86
$ASPD_A$	0.56	0.58	182.86

Table 2
Residual variance (two-syllable words)

	Annoyance; linear function	Speech audibility; linear function	Listening score; logistic function
SN	1.37	1.29	311.47
SN_A	0.34	0.43	61.24
AI	0.49	0.40	177.86
SIL	0.33	0.31	67.90
SI	0.33	0.31	67.90
WSPD	**0.31**	**0.30**	**68.30**
ASPD	0.79	0.78	224.80
$ASPD_A$	0.79	0.78	224.80

Table 3
Residual variance (three-syllable words)

	Annoyance; linear function	Speech audibility; linear function	Listening score; logistic function
SN	1.37	1.30	182.45
SN_A	0.35	0.46	56.04
AI	0.66	0.47	211.63
SIL	0.36	0.28	63.85
SI	0.36	0.28	63.85
WSPD	**0.35**	**0.27**	**68.63**
ASPD	0.82	0.74	159.97
$ASPD_A$	0.82	0.74	159.97

(1) When *WSPD* is used in relation to the two aspects, psychological impressions of noise and audio signal, the difference in the observed data compared to when other indices are used is relatively small.

(2) With regard to the listening score, when *WSPD* is used, the difference is small in the case of listening to monosyllables. When SN_A is used, there is a relatively small difference in the case of listening to two- or three-syllable words, although even if *WSPD* is used, results are still fairly good.

Based on the above results, we can see that it is logical to select *WSPD* as the target index.

4. Prediction of psychological impressions and listening score

With regard to the two psychological impressions and the listening score, the definition of the type of model and determination of the regression coefficients were given once again using only the recorded data of Experiment I. The parameters of a regression model based on *WSPD* for the three aspects using the recorded data of Experiment I is follows:

Annoyance

$$\text{Monosyllables}: \quad a = -0.09, \quad b = 4.87 \quad (\text{Eq. (6)}) \tag{9}$$

$$\text{Two-syllable words}: \quad a = -0.09, \quad b = 4.83 \quad (\text{Eq. (6)}) \tag{10}$$

$$\text{Three-syllable words}: \quad a = -0.09, \quad b = 4.65 \quad (\text{Eq. (6)}) \tag{11}$$

Speech audibility

$$\text{Monosyllables}: \quad a = 0.09, \quad b = 2.98 \quad (\text{Eq. (6)}) \tag{12}$$

$$\text{Two-syllable words}: \quad a = 0.08, \quad b = 3.18 \quad (\text{Eq. (6)}) \tag{13}$$

$$\text{Three-syllable words}: \quad a = 0.09, \quad b = 3.23 \quad (\text{Eq. (6)}) \tag{14}$$

Listening score

$$\text{Monosyllables}: \quad a = 0.71, \quad b = 0.13 \quad k = 97.24 \quad (\text{Eq. (7)}) \tag{15}$$

$$\text{Two-syllable words}: \quad a = 0.50, \quad b = 0.13 \quad k = 100.18 \quad (\text{Eq. (7)}) \tag{16}$$

$$\text{Three-syllable words}: \quad a = 0.21, \quad b = 0.13 \quad k = 101.88 \quad (\text{Eq. (7)}) \tag{17}$$

Figs. 7, 8 and 9 show, respectively, the comparisons between the theoretical predicted values of the psychological impressions, the listening score from the above regression model based on *WSPD* for each noise conditions of Experiment II, and values obtained directly from the recorded data. The following findings are revealed by Figs. 7–9: in spite of predicting the psychological impressions and the listening score using the regression models from the psychological experiment in which other subjects participated, in the case of meaningless steady noise with various power spectral level forms, a high level of consistency is seen between the predicted and observed values. As a result of setting both kinds and sound pressure level of the noise considering actual noise environment in Experiment II, the accuracy of the predicted value was discussed by use of limited data.

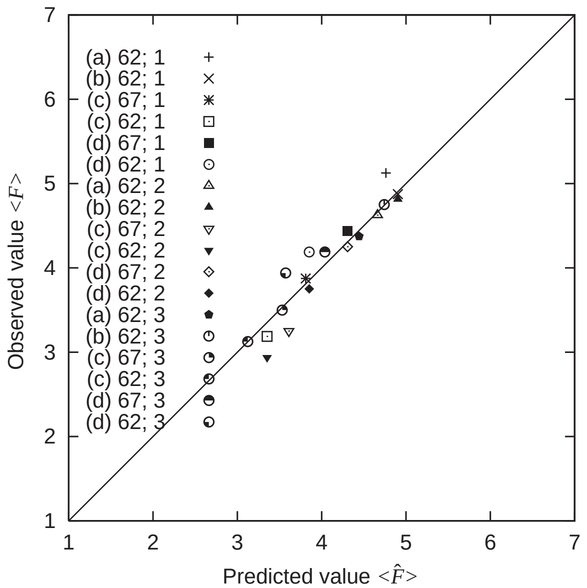

Fig. 7. Comparison between predicted and observed value of $\langle F \rangle$ (index : *WSPD*).

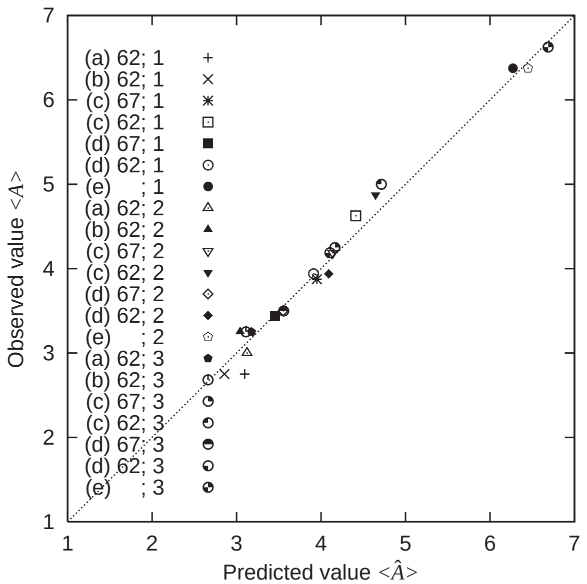

Fig. 8. Comparison between predicted and observed value of $\langle A \rangle$ (index : *WSPD*).

With respect to the other indices, it was investigated that how the predicted values changed when the above method was used. Table 4 shows the results of the correlation coefficient r between predicted and observed values in terms of the three aspects. Also, the following expression was adopted; $y = x + a$, where y is observed data and x is predicted data, and the bias

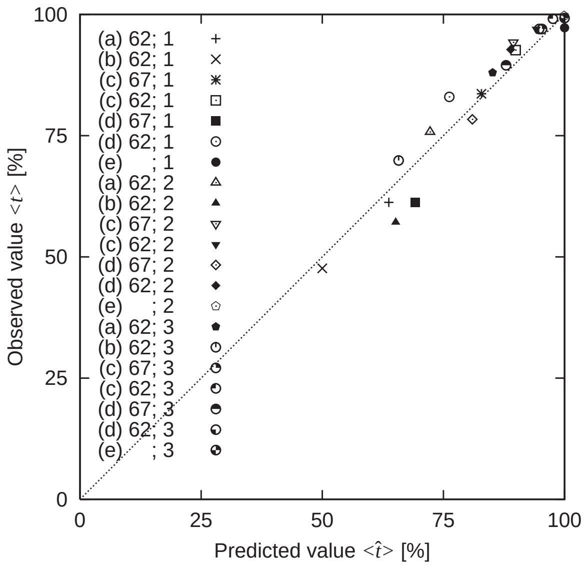

Fig. 9. Comparison between predicted and observed value of $\langle t \rangle$ (index : *WSPD*).

Table 4
Correlation coefficient *r*

	Annoyance	Speech audibility	Listening score
SN	−0.195	0.817	0.247
SN_A	0.919	0.970	0.835
AI	0.921	0.955	0.854
SIL	0.930	0.975	0.884
SI	0.930	0.975	0.884
WSPD	**0.950**	**0.978**	**0.889**
ASPD	0.590	0.907	0.662
$ASPD_A$	0.590	0.907	0.662

a values can be obtained by using the least-square method. Table 5 shows the results of bias *a* values. As can be seen in Tables 4 and 5, in common with the three aspects, it is clear that *WSPD* is better because its estimation error *a* values are smaller than the other indices, and they can systematically predict the psychological impressions and the listening score. From the above results, the usefulness of the index *WSPD* can be recognized for the purpose of predicting/estimating the two psychological impressions and the listening score.

5. Conclusions

In the previous paper, the validity of the evaluation method of the psychological impression of external noise on subjects under the condition of meaningless noise while listening to an audio signal was considered. In this paper, not only the psychological impression of the noise but also

Table 5
Estimation error a

	Annoyance	Speech audibility	Listening score
SN	−0.126	−0.095	5.812
SN_A	0.174	−0.192	2.549
AI	−0.405	0.335	6.375
SIL	−0.326	0.060	3.104
SI	−0.326	0.060	3.104
$WSPD$	**−0.002**	**0.040**	**2.349**
$ASPD$	−1.236	0.093	9.021
$ASPD_A$	−1.236	0.093	9.021

the psychological impression of the audio signal and the listening score have been considered. Also, a useful index that reflects the mutual relationship between the spectral level of the speech peaks and that of noise, for use in evaluating the above three aspects simultaneously when listening to monosyllables and two- or three-syllable words has been discussed. Further, estimation and/or prediction problems of the psychological impressions and the listening score derived by using the most useful index have been considered. Practical consideration of the most useful index has been discussed, and a result, weighted-mean spectral distance ($WSPD$) can be selected as the target index. The validity and the applicability of this index were confirmed experimentally, and reasonable results were obtained.

The primary subjects that should be examined in future studies are listed below:

(1) The discussion in this paper is limited by use of recorded data obtained from psychological experiments with subjects in their 20s. It is necessary to consider how differences in age or hearing loss can affect results.
(2) The applicability of the same method to situations where the external noise is meaningful, such as music and conversation, should be confirmed.

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