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Relationship between sound insulation performance of walls and word intelligibility scores

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Abstract

Conversations must be shielded from people in an adjacent room if they include confidential information. Word intelligibility tests were performed in a total of 185 sound fields to examine the relationship between sound insulation performance and the degree of conversation leakage. The parameters of the test sound fields were background noise level in the adjacent room and the level difference between the two rooms. The background noise level was varied from 30 to 50 dB (A-weighted). The level difference was parametrically varied in terms of 8 frequency characteristics and 10 absolute values. The results showed that word intelligibility scores were strongly correlated with the A-weighted speech-to-noise ratio and SNR_{uni32}. Equal-intelligibility contours, which can easily show the weighted level difference and A-weighted background noise level required to achieve a certain level of word intelligibility scores, were obtained from a multiple logistic regression analysis.

Keywords: Speech privacy, Weighted level difference, Word intelligibility score

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1. Introduction

Conversation is one of the essential forms of communication and is frequently conducted everywhere in our everyday life. However, conversations sometimes include confidential information that should be shielded from third persons. Rooms in which people may talk about something confidential, such as consulting rooms in banks, meeting room in offices, hospitals, pharmacies, and so on, should be designed considering the passible leakage of confidential information by speech transmitted through boundary walls and other paths.

The terms “speech privacy” and “speech security” are often used to quantify the leakage of confidential speech. Several studies have examined this topic in detail. Cavanaugh *et al.*[1] performed privacy rating tests using simulated speech sounds transmitted through five types of walls, with additional noise corresponding to NC-35, and demonstrated how the privacy rating is related to the articulation index[2]. Their study indicated that the privacy rating is strongly related to intelligibility scores.

The relationship between intelligibility scores and sound insulation performance has been investigated on the basis of listening tests similar to those used by Cavabaugh *et al.* Gover and Bradley[3] suggested the use of SNR_{uni32}, which is a frequency-weighted average signal-to-noise ratio with uniform frequency weightings, for estimating audibility, cadence, and intelligibility, which are related to speech security performance. Park *et al.*[4] compared speech intelligibility scores with the sound insulation performance expressed in terms of STC (sound transmission class) from the ASTM E413 standard[5] and R_W (weighted sound reduction index) from the ISO 717-1 standard[6], and they demonstrated that SNR_{uni32} was more suitable than STC and R_W for estimating speech intelligibility scores.

The previous studies clearly showed that the speech-to-noise ratio, in other words, the background noise level and sound insulation performance, are important variables for evaluating speech privacy or security performance. Furthermore, the two variables can be controlled in the acoustic design of rooms. Therefore, it will be useful if speech privacy or security performance can be estimated from the two variables. However, the previous studies did not use background noise level as a listening test parameter. Cavanaugh *et al.* varied the background noise level in their preliminary test, but the range was only 10 dB. Gover and Bradley varied the frequency characteristics of background noise, but the background noise level was constant at 45 dB (A-weighted). Accordingly, equations for estimating the speech privacy or security performance including the background noise level as a variable have not yet been proposed.

In the present study, word intelligibility tests were performed to clarify the relationship among sound insulation performance, background noise level, and the degree of conversation leakage. The parameters of the tests were background noise level and the sound pressure level difference between two rooms. The effect of room acoustics was not considered in order to simplify listening tests, on the basis of the results of Bradley *et al.*[7], which indicated that results without considering room acoustics are on the safe side from the viewpoint of evaluating conversation leakage.

2. Methods

2.1. Situation

Figure 1 illustrates the situation considered in the present study. Persons A and B are talking about something confidential. Person C is not an eavesdrop-

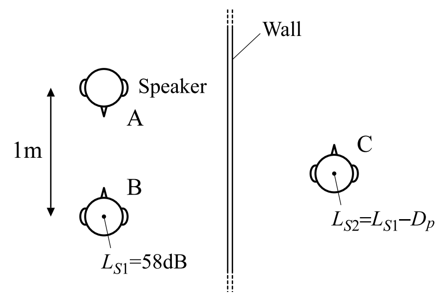

Figure 1: Situation assumed in the present study.

per but can hear speech transmitted through the wall. Person A is speaking with "normal" vocal effort[8], and the speech level at the position of person B is 58 dB (A-weighted). Only speech sound transmitted through the wall reaches person C. The level difference between particular positions (D_P) defined in a normative annex of the JIS A 1417 standard[9] was used as the parameter of sound insulation performance. Equation 1 is the definition of D_P in the present study,

$$D_p = L_{S1} - L_{S2}, \tag{1}$$

where L_{S1} and L_{S2} are the speech levels at the positions of persons B and C, respectively.

2.2. Level difference between particular positions (D_P)

The frequency characteristics and absolute values of D_P were used as parameters in the listening tests. Figure 2 shows the frequency characteristics of D_P. In the situation assumed in the present study, the frequency characteristics of D_P are equal to those of the sound insulation of the wall. The frequency characteristics from (a) to (g) were determined in order to include a wide variety of the characteristics in realistic range, by reference to the sound insulation characteristics of walls modeled by by Tachibana *et al.*[10] and the sound insulation data from

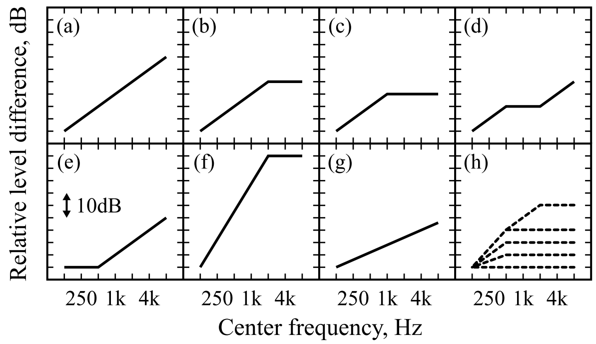

Figure 2: Frequency characteristics of level difference.

the textbook by Maekawa and Lord[11]. The frequency characteristics of (h) are curves used to determine the level difference rank, which is defined in a normative annex of the JIS A 1419 standard[12]. The frequency characteristic of (h) changes depending on its rank (see Fig. 3).

Absolute values of D_P for each frequency characteristic were varied to satisfy 10 level difference ranks from D_r-0 to D_r-45. Figure 3 shows the reference curve for each level difference rank[12]. The curves from D_r-0 to D_r-25 are not included in the original reference curve chart, and are defined in the present study for convenience. The dashed line in Fig. 3 represents D_P with the frequency characteristic of (a), which satisfies rank D_r-25, as an example. In order to satisfy rank D_r-25, D_P in all frequency bands must exceed the reference curve of D_r-25. Eighty types of D_P, which were combinations of 8 types of frequency characteristics and 10 level difference ranks, were used.

2.3. Speech stimuli

A total of 148 Japanese words were used as test words. The test words were selected from the familiarity-controlled word lists developed by Sakamoto *et al.*[13] to be highly familiar to both young and elderly people. The test words consisted

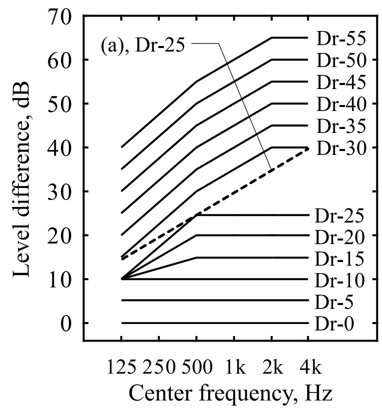

Figure 3: Reference curves of level difference ranks[12]. For example, the dashed line represents the level difference with the frequency characteristics of (a), which satisfies D_r-25. The ranks from D_r-0 to D_r-25 are not included in the original chart.

of four syllables and were spoken by a female Japanese in an anechoic room. Sakamoto *et al.* reported that word intelligibility scores increased with increasing word familiarity. Therefore, from the viewpoint of evaluating confidential information leakage, using the most familiar words provides a safe evaluation. Each test word was filtered to reduce its octave band level for the 80 types of D_P described above and to make speech stimuli that simulate speech sound at the position of person C in Fig. 1.

Listening tests were performed in an anechoic room. Figure 4 shows the loudspeaker arrangement used in the listening tests. The speech stimuli were presented from the loudspeaker directly in front of the listener at a distance of 1.5 m. Table 1 shows the presentation levels of the speech stimuli. The presentation levels were measured using a sound level meter at the position of the center of the listener's head in the absence of the listener. L_{ASmax} for each speech stimulus was measured while the stimulus was played repeatedly.

Table 1: Presentation levels of speech stimuli for each level difference.

Rank	Frequency characteristic							
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
D_r-0	47.4	47.4	47.8	49.0	54.9	41.0	50.8	58.0
D_r-5	42.4	42.4	42.8	44.0	49.9	36.0	45.8	53.0
D_r-10	37.4	37.4	37.8	39.0	44.9	31.0	40.8	48.0
D_r-15	37.4	37.4	37.8	39.0	39.9	31.0	40.8	43.6
D_r-20	37.4	37.4	37.8	39.0	34.9	31.0	36.8	39.4
D_r-25	32.4	32.4	32.8	34.0	29.9	31.0	31.8	35.6
D_r-30	27.4	27.4	22.8	19.0	24.9	26.0	22.8	29.2
D_r-35	22.4	22.4	17.8	14.0	19.9	21.0	17.8	24.2
D_r-40	17.4	17.4	12.8	9.0	14.9	16.0	12.8	19.2
D_r-45	12.4	12.4	7.8	4.0	9.9	11.0	7.8	14.2

(L_{ASmax}, dB)

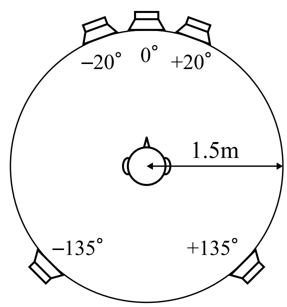

Figure 4: Loudspeaker arrangement.

The constant presentation levels surrounded by solid lines in Table 1 indicate that certain combinations of the absolute value and the frequency characteristic of D_P satisfy more than one rank at the same time. Only the highest rank was applied in the case of such combinations. For example, D_P for rank D_r-10 with the frequency characteristics of (a) also satisfies ranks D_r-15 and D_r-20. In this case, only rank D_r-20 was applied to D_P. Therefore, 68 of the 80 types of D_P were actually used.

2.4. Background noise

To simulate general room noise, steady-state random noise with -5 dB per octave decay in the frequency domain was added to each speech stimulus. The additional noise was presented simultaneously from the five loudspeakers shown in Fig. 4. Five different noise signals, which were uncorrelated with each other but had the same frequency characteristic, were presented from different loudspeakers such that the degree of interaural cross-correlation of the additional noise was close to the theoretical value of the correlation coefficient between two different points (distance: 0.3 m) in a diffuse sound field[14]. L_{Aeq} for the additional noise was measured at the same position as that for the speech stimulus. The additional noise level was set in five steps of 5 dB from 30 to 50 dB. The additional noise of X dB is abbreviated as NX in the rest of this paper. For example, N40 represents an additional noise of 40 dB.

Combinations of D_P and the additional noise level with an A-weighted speech-to-noise ratio ($SNR(A)$: presentation level of speech stimulus minus that of additional noise) from approximately -20 to 0 dB were used in the listening tests. Specifically, the combinations were N50 and D_P with for ranks D_r-0 to D_r-25 (36 conditions), N45 and D_r-5 to D_r-30 (36 conditions), N40 and D_r-15 to D_r-35 (34 conditions), N35 and D_r-20 to D_r-40 (39 conditions), and N30 and D_r-25 to D_r-45 (40 conditions).

2.5. Procedure

Two listening tests were performed. Test I was for the conditions of N30 and N40 (74 conditions), and Test II was for the conditions of N35, N45, and N50 (111 conditions). Each listener was asked to write the speech stimuli using katakana characters (Japanese phonograms) as they listened.

Thirty-seven listeners participated in each test. There was no listener who participated in both tests. The listeners were young adults who had normal hearing levels.

In Test I, each listener listened to 296 speech stimuli that included each test word twice and each condition four times. The combination of the test words and the conditions was different for different listeners. Test I was divided into 8 sessions to listen to 37 speech stimuli. A total of 148 speech stimuli (37 listeners $\times$ 4 times) were presented under each condition after finishing Test I.

In Test II, 111 of 148 test words were used. Each listener listened to 333 speech stimuli, which included each test word and each condition thrice. Test II was divided into 9 sessions to listen to 37 speech stimuli. A total of 111 speech stimuli (37 listeners $\times$ 3 times) were presented under each condition after finishing Test II.

3. Results and discussion

The word intelligibility score, which is the percentage of speech stimuli written down correctly, was calculated from the results for all listeners in Tests I and II.

3.1. Single number evaluation

$SNR(A)$ and SNR_{uni32}[3] were calculated to compare with word intelligibility scores.

Figure 5 shows the scores as a function of $SNR(A)$. Different symbols represent different frequency characteristics of D_P shown in Fig. 2. The scores began to depart from 0% when $SNR(A)$ exceeded around -15 dB. Then the scores increased close to 100% with increasing $SNR(A)$ up to ±0 dB. The scores seemed

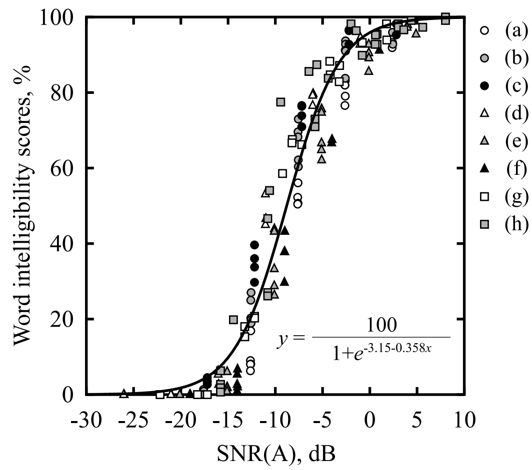

Figure 5: Word intelligibility scores as a function of $SNR(A)$. The solid curve represents a logistic regression curve. The different symbols represent the different frequency characteristics of D_P (see Fig. 2).

to fit along a logistic regression curve, regardless of the frequency characteristics of D_P. Figure 6 shows the relationship between the scores and those estimated from the regression curve shown in Fig. 5. Only the scores in the range from 5 to 95% were used in a linear regression analysis. The two scores were highly correlated with each other (r=0.94). The dashed lines represent 95% prediction intervals. The intervals were approximately ±20%.

Figure 7 shows the scores as a function of SNR_{uni32}. The relationship was very similar to that between the scores and $SNR(A)$, except that the scores for the frequency characteristic of (f) were higher than those for other frequency characteristics. In other words, SNR_{uni32} underestimates the scores for the frequency characteristic of (f). The frequency characteristic of (f) has a slope of 10 dB per octave, which is steeper than that for the other characteristics. This means that the speech-to-noise ratio at high frequencies decreased more rapidly. SNR_{uni32}

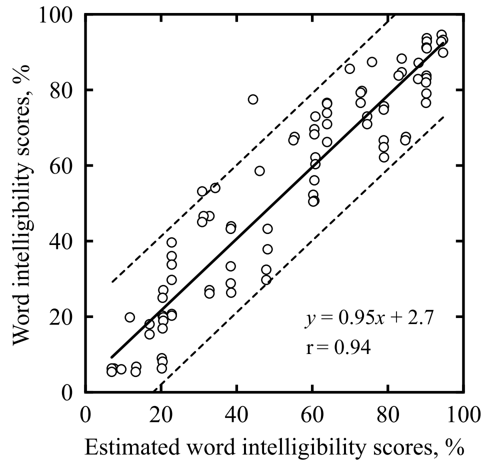

Figure 6: Relationship between word intelligibility scores and estimated scores from the logistic regression curve shown in Fig. 5. The solid line represents a linear regression line between the two scores. The dashed lines represent 95% prediction intervals.

can take into account of the decrease at high frequencies while $SNR(A)$ cannot, because $SNR(A)$ for (f) is mainly determined by mid-frequency components. Accordingly, this result suggested that the scores in the present study were not predominantly affected by the decrease in the speech-to-noise ratio at high frequencies. Meanwhile, Gover and Bradley[3] concluded that SNR_{uni32} is more suitable than $SNR(A)$ for estimating intelligibility scores. The result obtained here is different from that obtained by Gover and Bradley. The difference might be related to the difference between the importance of high frequency components to the intelligibility of Japanese speech and that of English speech.

Figure 8 shows the relationship between the scores and those estimated from the regression curve shown in Fig. 7. Although the correlation coefficient (r=0.92) was lower than that for $SNR(A)$, the two scores were highly correlated with each other. The regression analysis without the frequency characteristic of (f)

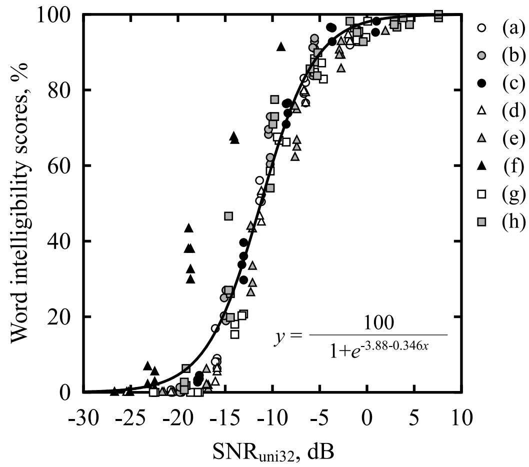

Figure 7: As for Fig. 5, but for SNR_{uni32}.

showed that the correlation coefficient between the scores and those estimated from SNR_{uni32} was 0.97, which was higher than that for $SNR(A)$ (r=0.95).

It is concluded that the prediction accuracies for $SNR(A)$ and SNR_{uni32} are high and not significantly different from each other in most cases. However, $SNR(A)$ can be used regardless of the frequency characteristics of D_P whereas SNR_{uni32} should not be used for frequency characteristics with a steep slope, such as 10 dB per octave, at least for Japanese speech.

3.2. Evaluation from sound insulation performance and background noise level

Being able to estimate word intelligibility scores from a number of variables that can be changed is useful for assessing or designing speech privacy or security in a confidential room. Regression analyses were performed to obtain an equation for estimating word intelligibility scores using sound insulation performance and background noise level as independent variables. The level difference rank between particular positions ($D_{P,r}$) and the weighted level difference between par-

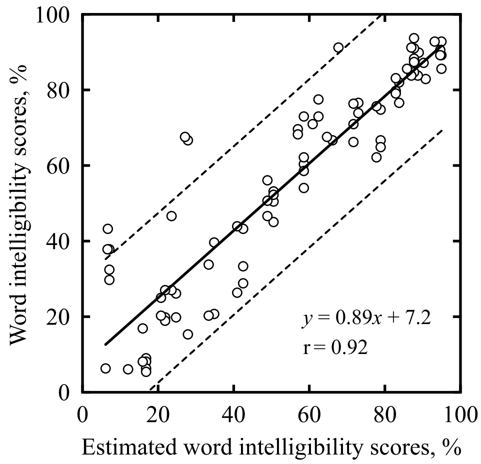

Figure 8: Same as Fig. 6, but for SNR_{uni32}. The estimated scores were obtained from the logistic regression curve shown in Fig. 7.

ticular positions ($D_{P,W}$) were studied as to whether they are suitable as variables of sound insulation performance in estimating word intelligibility scores. Both $D_{P,r}$ and $D_{P,W}$ are defined in the JIS A 1419-1 standard[12]. $D_{P,W}$ is basically equal to R_W defined in the ISO 717-1 standard[6], except $D_{P,W}$ is obtained from the level difference between particular positions.

Figure 9 shows the word intelligibility scores as a function of $D_{P,r}$ for each L_N. Different symbols represent different frequency characteristics of D_P. The scores for each value of $D_{P,r}$ exhibited broad ranges regardless of L_N. This result shows that $D_{P,r}$ is unsuitable as a variable for estimating the scores. Meanwhile, the scores for a value of $D_{P,r}$ that satisfies $L_N + D_{P,r} = 75$ were close to 0% with a few exceptions. Therefore, the expression of $L_N + D_{P,r} \geq 75$ could be used as a rough guideline for designing zero-intelligibility conditions.

$D_{P,W}$ was obtained using the 1/1 octave method, and the reference curve was moved in 0.1 dB steps to increase the resolution of sound insulation performance.

Figure 10 shows the word intelligibility scores as a function of $D_{P,W}$. Solid curves represent logistic regression curves obtained for each L_N. β_0 and β_1 are the intercept and the regression coefficient of $D_{P,W}$, respectively. The word intelligibility scores were fitted in logistic regression curves for each L_N, regardless of the frequency characteristic of D_P and L_N. This means that $D_{P,W}$ is suitable as a variable for estimating the scores.

It should be noted that the regression coefficients of $D_{P,W}$ (β_1) for each additional noise level were almost equal to each other. The estimated standard errors of β_1 were around 0.01 for all additional noise levels, and *t*-tests based on the estimated standard errors demonstrated that there were no statistically significant differences between any pairs of β_1 ($p<0.05$). This means that the effects of $D_{P,W}$ and L_N on the scores were independent of each other. Therefore, a multiple logistic regression analysis was performed to obtain an equation for estimating the scores from $D_{P,W}$ and L_N, which independently affect the scores. Equation 2 is a regression equation obtained from the analysis:

$$WI = 100/(1 + \exp(-24.0 + 0.354D_{P,W} + 0.336L_N)), \qquad (2)$$

where WI is the word intelligibility score (%).

Figure 11 represents the relationship between the scores and those estimated from Eq. 2. Only the scores in the range from 5 to 95% were used in linear regression analysis. The correlation coefficient ($r=0.95$) was slightly higher than that for $SNR(A)$ ($r=0.94$), and the 95% prediction interval was narrower by around 3% than that for $SNR(A)$ at the average of the estimated scores. It is concluded that word intelligibility scores can be estimated from $D_{P,W}$ and L_N using Eq. 2 with the same or higher accuracy than that of $SNR(A)$, regardless of the frequency characteristic of D_P.

3.3. Equal-intelligibility contours

Figure 12 shows the equal-intelligibility contours based on Eq. 2. This chart enables us to easily estimate the required $D_{P,W}$ and A-weighted background noise level to achieve the desired word intelligibility score in the adjacent room. L_N is replaced by the A-weighted background noise level to generalize it. For example, when $D_{P,W}$ is 30 dB and the A-weighted background noise level is 40 dB, the word intelligibility score in the next room will be 50%. If the score is desired to be reduced to 10%, $D_{P,W}$ should be increased to 36 dB, or the A-weighted background noise level should be increased to 46 dB.

It should be noted that Fig. 12 applies to only L_{S1}, that is, the speech level at the position of person B in Fig. 1, of 58 dB. If different L_{S1} must be assumed, the required $D_{P,W}$ and A-weighted background noise level should be corrected. Figure 13 shows the presentation level of speech stimuli corresponding to the speech level at the position of person C (L_{S2}) in Fig. 1 as a function of $D_{P,W}$. The correlation between L_{S2} and $D_{P,W}$ is very high (r≈-1), and the slope of the regression line was about -1. This means that a 1 dB increase of L_{S2} can be replaced with a 1 dB decrease of $D_{P,W}$. Needless to say, L_{S1} is linked to L_{S2}, and a 1 dB increase of L_{S1} causes a 1 dB increase of L_{S2}. Therefore, the required $D_{P,W}$ should be increased by the same amount as increase of L_{S1} from 58 dB.

Figure 14 shows a modified version of Fig. 9. The ordinate axis is replaced by "$D_{P,W}$ - ΔL, dB", and ΔL is defined as L_{S1} - 58. This chart can be applied to any L_{S1}. The fact that the increase in the vocal effort causes a change in the frequency characteristic of speech would not affect the estimate accuracy in Fig. 14, because the relationship between the scores and $D_{P,W}$ is not affected by the frequency characteristics of D_P, as shown in Fig. 10, and the change in the frequency characteristic of speech can be replaced with that of D_P.

4. Conclusion

In the present study, word intelligibility tests were performed to clarify the relationship among sound insulation performance, background noise level, and the degree of conversation leakage. The difference between the A-weighted speech level and background noise level ($SNR(A)$), and the frequency-weighted average signal-to-noise ratio with uniform frequency weightings (SNR_{uni32}) were tested as single number measures for estimating word intelligibility scores. Additionally, to obtain an equation for estimating word intelligibility scores using sound insulation performance and background noise level as independent variables, the level difference rank between particular positions ($D_{P,r}$) and the weighted level difference between particular positions ($D_{P,W}$) were tested as variables for sound insulation performance. The results of tests and analyses are summarized as follows.

(1) $SNR(A)$ and SNR_{uni32} can be used to estimate word intelligibility scores with high accuracy, regardless of the frequency characteristics and the absolute values of the level difference between particular positions, and background noise level. However, SNR_{uni32} underestimates the scores when the level difference increases by 10 dB per octave with increasing frequency.

(2) $D_{P,r}$ is not suitable as a variable for estimating word intelligibility scores.

(3) Word intelligibility scores can be estimated from $D_{P,W}$ and the A-weighted background noise level with the same or higher accuracy than that of $SNR(A)$.

(4) Equal-intelligibility contours that can easily show $D_{P,W}$ and the A-weighted background noise level required to achieve a certain level of word intelligibility scores were obtained. Furthermore, modified contours that can be applied

to any speech level or vocal effort were also suggested.

Acknowledgments

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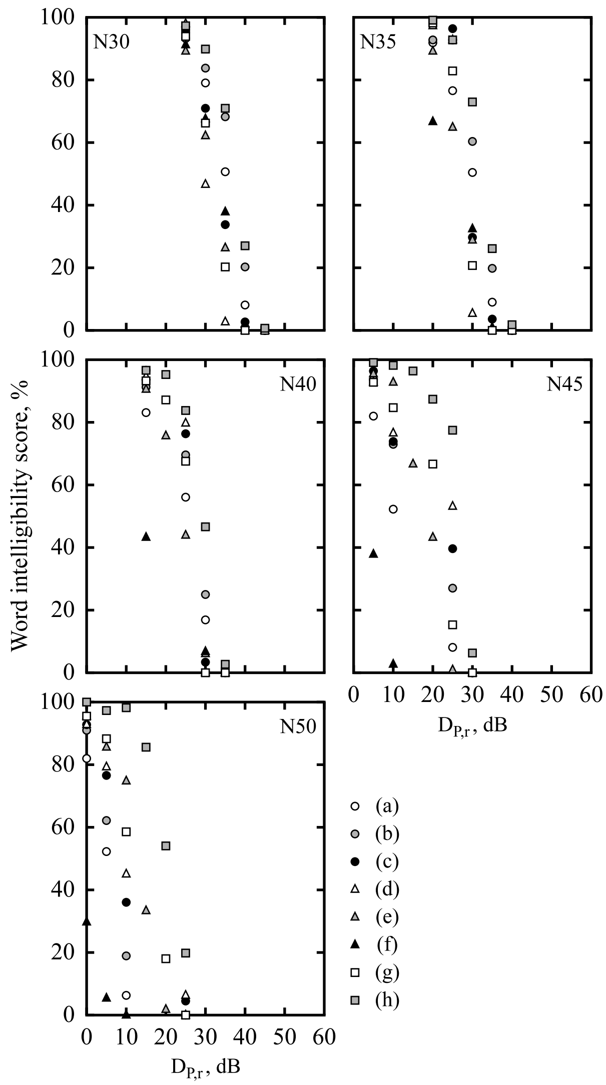

Figure 9: Word intelligibility scores as a function of $D_{P,r}$ for each additional noise level. NX indicates the result for the additional noise level of X dB. Different symbols represent different frequency characteristics of D_P (see Fig. 2).

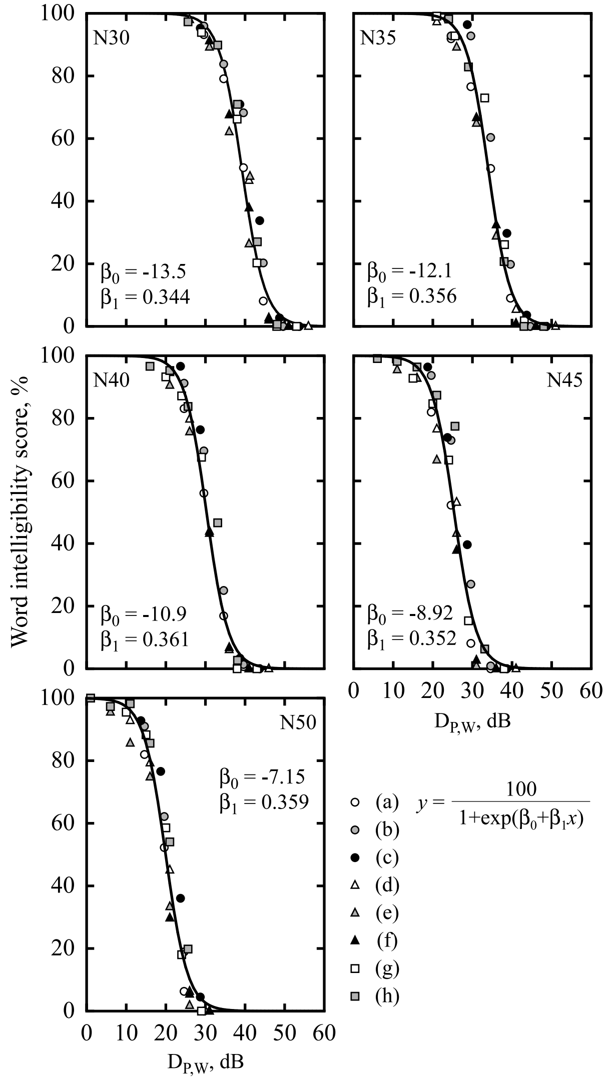

Figure 10: Same as Fig. 9, but for $D_{P,W}$. Solid curves represent logistic regression curves obtained for each additional noise level. β_0 and β_1 are the intercept and the regression coefficient of $D_{P,W}$, respectively.

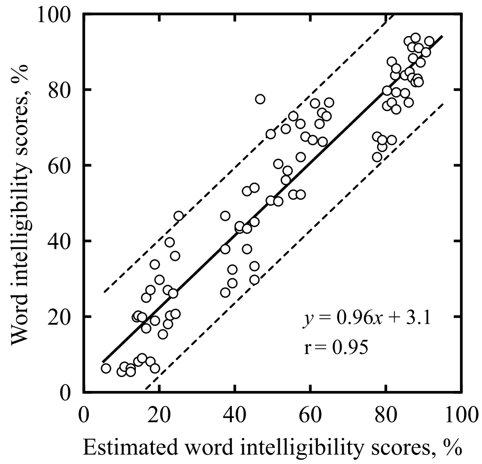

Figure 11: Relationship between word intelligibility scores and estimated scores based on multiple logistic regression analysis (see Eq. 2). The solid line represents a linear regression line between the two scores, and the dashed lines represent 95% prediction intervals.

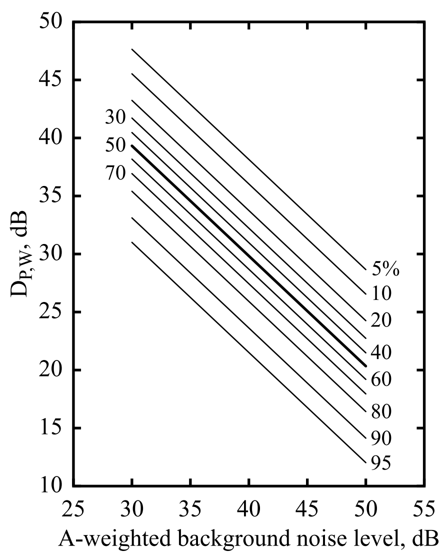

Figure 12: Equal-intelligibility contours as a function of $D_{P,W}$ and A-weighted background noise level.

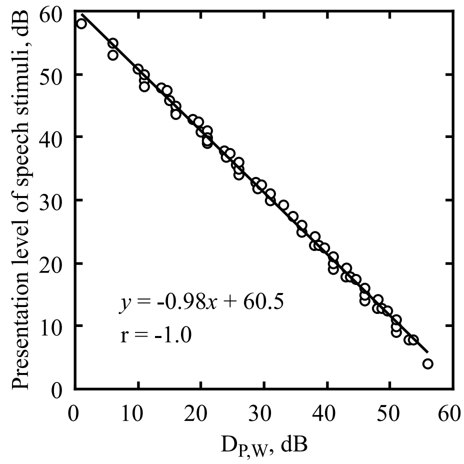

Figure 13: Relationship between the presentation level of speech stimuli and $D_{P,W}$.

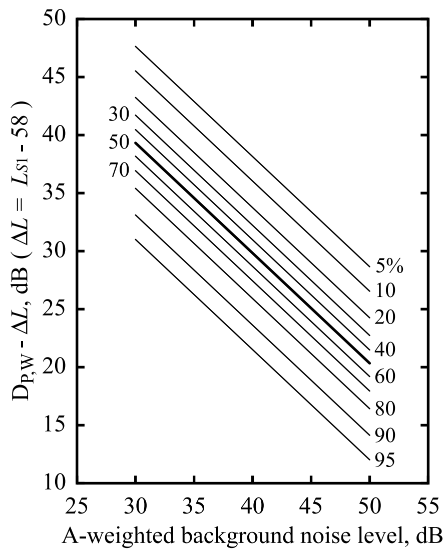

Figure 14: Equal-intelligibility contours modified to be applicable to any L_{S1}.