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(Citation)
Journal of the Acoustical Society of America,130(3):1411-1419

(Issue Date)
2011-09

(Resource Type)
journal article

(Version)
Version of Record

Acceptable range of speech level in noisy sound fields for young adults and elderly persons

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(Received 10 January 2011; revised 13 June 2011; accepted 17 June 2011)

The acceptable range of speech level as a function of background noise level was investigated on the basis of word intelligibility scores and listening difficulty ratings. In the present study, the acceptable range is defined as the range that maximizes word intelligibility scores and simultaneously does not cause a significant increase in listening difficulty ratings from the minimum ratings. Listening tests with young adult and elderly listeners demonstrated the following. (1) The acceptable range of speech level for elderly listeners overlapped that for young listeners. (2) The lower limit of the acceptable speech level for both young and elderly listeners was 65 dB (A-weighted) for noise levels of 40 and 45 dB (A-weighted), a level with a speech-to-noise ratio of +15 dB for noise levels of 50 and 55 dB, and a level with a speech-to-noise ratio of +10 dB for noise levels from 60 to 70 dB. (3) The upper limit of the acceptable speech level for both young and elderly listeners was 80 dB for noise levels from 40 to 55 dB and 85 dB or above for noise levels from 55 to 70 dB.
 [DOI: 10.1121/1.3609122]

PACS number(s): 43.55.Hy, 43.71.Lz [NX] Pages: 1411–1419

I. INTRODUCTION

Speech information is frequently provided to people through public address (PA) systems in public spaces, such as railroad platforms, airports, shopping malls, and so forth. PA systems for such noisy spaces amplify speech information to make it intelligible. However, speech information in noisy public spaces is often amplified more than necessary, making such spaces less pleasant for users. Therefore, speech loudness should be adjusted to the most comfortable loudness while maintaining maximum intelligibility to optimize the quality of speech information.

The concept of the most comfortable loudness or listening level (MCL) is of good reference in determining speech loudness in public spaces. MCL has been studied for around 60 years and its main application is hearing-aid evaluation[1] and speech audiometory.[2] In general MCL measurement,[2] the listener is asked to indicate the level at which a speech stimulus is most comfortable to listen to as the intensity of the stimulus is varied. There have been some studies on MCL for speech in noise. Richards[3] and Beattie *et al*.[4] measured MCL for monaural speech as a function of noise level. Their results demonstrated that MCL increases with increasing noise level. According to Beattie *et al*., MCL was from 82 to 90 dB in noise from 55 to 85 dB, which was higher than the value obtained by Richards of 65 to 84 dB in the same range of noise level. Van Heusden *et al*.[5] measured MCL (*preferred listening level* in their paper) as a function of noise level for speech radiated from a loudspeaker in a room with a reverberation time of 0.5 s. In their study, the listener asked to adjust the level of speech material as if they were listening to a radio. They obtained a constant MCL of approximately 50 dB (A-weighted) for noise levels of less than 40 dB (A-weighted), and for noise levels of greater than 40 dB (A-weighted) MCL increased by 3.1 dB per 10 dB shift in noise level. Kobayashi *et al*.[6] proposed an optimum speech level based on word intelligibility scores and listening difficulty ratings[7] under listening conditions similar to those used by Van Heusden *et al*. The optimum speech level according to Kobayashi *et al*. was 55 dB (A-weighted) for noise levels of less than 40 dB (A-weighted), and a level satisfies a speech-to-noise ratio of +15 dB for noise levels of greater than 40 dB (A-weighted).

The MCLs for speech in noise in the previous studies cited above are qualitatively consistent but are quantitatively different from each other. The quantitative difference is probably due to the differences in the methods and instructions of listening tests, as pointed out in other studies on MCL.[8–11] Meanwhile, Berger and Lowry[12] suggested that MCL is not a certain loudness but a range of loudness. This aspect of MCL would be a more fundamental reason for the quantitative difference, because it is obvious that this aspect would increase the variability of MCL among listening tests. Considering this aspect of MCL, Sato *et al*.[13] suggested an acceptable range of speech level in quiet and reverberant sound fields. However, the acceptable range of speech level in noisy sound fields has not yet been clarified.

On the other hand, speech information in public spaces is provided to not only listeners with normal hearing but also listeners with hearing loss. Considering that the number of elderly persons with hearing loss due to aging is increasing, an acceptable range of speech level for both young adults and elderly persons is required to optimize the quality of speech information provided in public spaces.

The purpose of the present study is to clarify the acceptable range of speech level in noisy sound fields for both young adults and elderly persons. In the present study, the

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acceptable range of speech level at a particular noise level is defined as the range that maximizes word intelligibility scores and does not cause a statistically significant increase in listening difficulty ratings from the minimum ratings at the noise level.[13] Therefore, in the following section, word intelligibility scores and listening difficulty ratings as a function of speech level for each noise level are obtained, and then statistical analyses are performed to clarify the acceptable range of speech level for each group of listeners. Finally, the acceptable ranges for each group are superimposed to clarify the acceptable range for both young and elderly listeners.

Though sound fields in public spaces have wide varieties of temporal, frequency and spatial characteristics, the present study focused on only the effect of noise level on the acceptable range of speech level to simplify the listening test and to decrease test parameters. This means that application of the present study is limited to within less reverberant sound fields. In addition, considering that interaural cross-correlations of speech and noise do not significantly affect listening difficulty for relatively high speech-to-noise ratios that frequently appear in everyday listening condition,[14] spatial aspects of speech and noise were not treated, in other words, diotic presentation was adopted to simplify the listening test.

II. METHOD

A. Listeners

Two groups of listeners participated in the listening test. The young group consisted of 52 young adults (male: 28, female: 24) in their twenties. The elderly group consisted of 52 elderly persons (male: 25, female: 27). The age of elderly listeners ranged from 65 to 80 yr old, and the average age was 71.3 yr old. The hearing levels for both ears were measured using an audiometer in 5 dB steps in a sound-treated room. Figure 1 shows the mean hearing levels and standard deviations for the ears of each group of listeners, and the estimated mean hearing levels for 20-, 60-, 70-, and 80-yr-old listeners based on ISO 7029.[15]

The mean hearing level for the young group was less than 15 dB at all frequencies and was within the range of the normal hearing level. The mean hearing level for the elderly group showed a rapid increase above 2 kHz, which is a typical tendency of hearing loss due to aging, and the increase was not unusual compared with the mean hearing level for people in their 70s estimated from ISO 7029. Meanwhile, the mean hearing level for the elderly group appeared to be higher than that estimated from ISO 7029 under 1 kHz. However, this result was common to both the young and elderly groups. Therefore, the increase at medium and low frequencies might depend on background noise or the measuring procedure, and does not imply that the hearing level at these frequencies was significantly higher than that for representative young and elderly people. Considering that the background noise level in the test room was 15 dB (A-weighted), hearing levels for high frequencies can be regarded as reliable data.

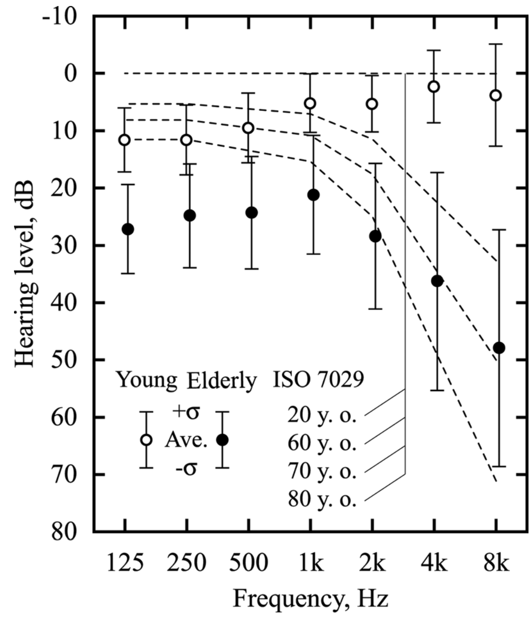

FIG. 1. Mean hearing levels of listeners. Open and closed circles respectively represent the results for the young and elderly groups. Bars represent standard deviations. Dashed lines represent estimated mean hearing levels from ISO 7029 (Ref. 12) for 20-, 60-, 70-, and 80-yr-old people. Estimated mean hearing levels are the average of those for male and female listeners.

B. Test words and test sound fields

A total of 52 Japanese words were used as test words. The test words were selected from familiarity-controlled word lists by Sakamoto *et al.*[16] to be most familiar to both young and elderly people. The test words consisted of four syllables and were spoken by a Japanese female in an anechoic room.

The parameters of the listening test were noise level and speech level. Steady-state random noise with a Hoth spectrum[17] was used as the additional noise. Noise level was measured using a sound level meter (ONOSOKKI, LA-5110). The median level (A-weighted, slow response) was measured at the position of the center of the listener's head. The noise level was set in seven steps of 5 dB from 40 to 70 dB (A-weighted). The speech level, which is the maximum level (A-weighted, slow response) of the test words, was set in nine steps of 5 dB from 45 to 85 dB (A-weighted). The maximum level with A-weighting and slow response was also used as the presentation level of stimuli in the authors' previous studies[6,7,13] because it empirically provides good agreement with loudness. Meanwhile, L_{Aeq} is also used as an approximation for loudness of stimuli. L_{Aeq} for each test word was higher by 2.6 dB than the maximum level averagely. The standard deviation of the differences between the maximum level and L_{Aeq} for each test word was 0.5 dB. Hereafter, the "A-weighted" annotation for the units of the noise level and the speech level is skipped.

Table I shows the test sound fields used in the present study, each of which was represented as a pair consisting of a speech level and a noise level. A total of 52 test sound fields were used. The test sound fields indicated by a circle with an underbar were used as reference sound fields, which were the easiest and severest sound fields of the test sound

TABLE I. Pairs of speech level and noise level for test sound fields. Circles indicate the pairs used in the present study. The pairs indicated by a circle with an underbar were used as reference sound fields.

Noise level, dB	Speech level, dB									Number of sound fields
	45	50	55	60	65	70	75	80	85	
-					$\underline{\bigcirc}$					1
40	○	○	○	○	○	○	○	○		8
45	○	○	○	○	○	○	○	○		8
50	○	○	○	○	○	○	○	○	○	9
55		○	○	○	○	○	○	○	○	8
60			○	○	○	○	○	○	○	7
65				○	○	○	○	○	○	6
70					$\underline{\bigcirc}$	○	○	○	○	5
										Total: 52

fields. The listening difficulty ratings for the reference sound fields were expected to be 0% or 100%; thus the reference sound fields were expected to give listeners criteria for evaluation and improve the reproducibility of listening difficulty ratings.

C. Procedure

The listening test was performed in an anechoic room. The speech level and noise level were adjusted by changing the amplitude of the digitized sound files for each test word and the additional noise. Then the test word and additional noise were mixed in monaural to make the stimuli. The stimuli were presented from a loudspeaker (Fujitsu Ten, TD512) at a distance of 1 m in front of the listener. The frequency characteristics of the loudspeaker were flat within ±5 dB in the range from 100 Hz to 10 kHz.

A total of 2704 stimuli (52 test words × 52 test sound fields) were prepared in advance. The stimuli were divided into 52 different sets of stimuli, which consisted of 52 different stimuli, not to duplicate the test word and the test sound field in each set. Specifically, the combinations of the test words and the test sound fields for a set of stimuli were rotated in order to make another set of stimuli, and the rotation was repeated 51 times to make 52 different sets of stimuli. Thus each set of stimuli included all test words and test sound fields.

Listeners participated in four trials of the listening test. Each listener listened to a set of stimuli per trial, and the set was different in different trials. The sets of stimuli were assigned to each listener as follows: the sets from 1 to 4 for listener 1, the sets from 2 to 5 for listener 2, and the sets 52, 1, and 2 for listener 52. The assignments were the same for each group of listeners. Thus each set of stimuli was presented four times to each group of listeners. This means that all test words were presented four times for each test sound field, and the phonetic balance for each test sound field was uniform after finishing over the entire listening test. Stimuli were presented in random order in each trial, except for the first and second stimuli. The first and second stimuli were the reference sound fields where listening difficulty ratings were expected to be 0 and 100%, respectively.

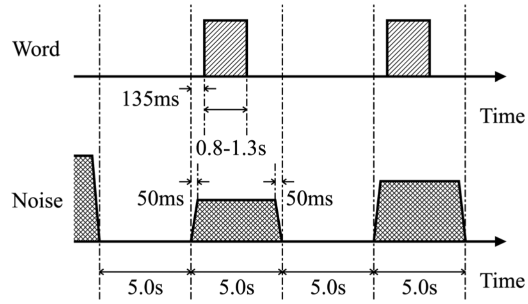

FIG. 2. Time sequence of presentation of speech signals (words) and additional noise.

Figure 2 shows the time sequence of the presentation of stimuli. The delay time between the onset of the additional noise and that of the test words was 135 ms. The duration of the additional noise was 5 s, and 50 ms fade-in/out was applied to the onset/offset of the additional noise. The interval between stimuli was 5 s. The duration of the test words varied from 0.8 to 1.3 s.

The method of evaluating listening difficulty was the same as that proposed by Morimoto *et al*.[7] Each listener was asked to write down stimuli as they listened using katakana characters (Japanese phonograms) and to simultaneously rate listening difficulty into one of the four categories shown in Table II. Before the listening test, each listener was trained using twenty stimuli. The stimuli for training were not used in the listening test. The training was repeated using the same stimuli until the listener could continually evaluate the listening difficulty within the interval.

III. RESULTS

A. Word intelligibility score

The word intelligibility score is the percentage of test words written down correctly. Figure 3 shows word intelligibility scores as a function of speech level for each noise level and each group of listeners. The scores were obtained from all responses (N = 208) for each group.

1. Young group

For the young group, word intelligibility scores were almost 100% for all speech levels, except for the sound fields with a speech-to-noise ratio of −5 dB and a noise level of 50 dB and above, where the score decreased to approximately 90%.

A one-way repeated measures analysis of variance was performed for each noise level to clarify whether the effect of the speech level on the scores was significant or not. The scores for each trial were calculated, and the analyses were performed assuming that the scores for each speech level

TABLE II. Categories of listening difficulty (Ref. 5).

1	Not	Difficult
2	A little	Difficult
3	Fairly	Difficult
4	Extremely	Difficult

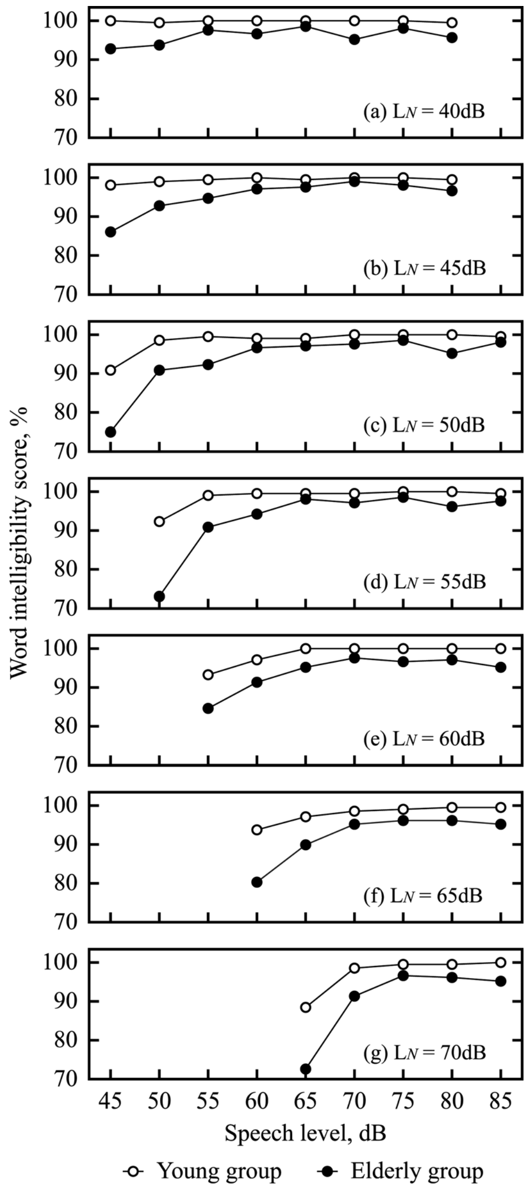

FIG. 3. Word intelligibility scores as a function of speech level. (a)–(g) The scores for noise levels (NL) from 40 to 70 dB, respectively. Open and closed circles represent the scores for the young and elderly groups, respectively.

were measured four times. For noise levels of 40 and 45 dB, the main effect of the speech level was not significant ($p > 0.05$), whereas for noise levels of 50 dB and above, the main effect of the speech level was significant ($p < 0.01$).

Tukey's honestly significant difference (HSD) test[18] was employed for *post hoc* comparisons between the scores. The HSD for each noise level ($p < 0.05$) was 2.5, 2.8, 2.0, 4.1, and 4.2% for noise levels from 50 to 70 dB, respectively. For noise levels of 50 dB and above, the scores for a speech-to-noise ratio of −5 dB significantly decreased from the maximum score for each noise level. For a noise level of 60 dB, the score for a speech level of 60 dB, in other words, that for a speech-to-noise ratio of ±0 dB also significantly decreased from the maximum. However, the score was 97%, close to 100%, in contrast to the scores for a speech-to-noise ratio of −5 dB that varied from 88 to 93%. Therefore, the significant decrease can be ignored.

It is concluded that the lower limit of the speech level required to maximize word intelligibility scores for the young group is the level with a speech-to-noise ratio of over ±0 dB for noise levels from 50 to 70 dB. For noise levels of 45 dB and below, a speech level of 45 dB is still sufficient to maximize word intelligibility scores for the young group.

2. Elderly group

The scores for the elderly group qualitatively showed the same tendency as those for the young group, that is, the scores increased with increasing speech level, and kept the maximum when the speech level exceeded a certain level. However, the scores for the elderly group were lower than those for the young group for all sound fields. The maximum scores were not close to 100% and were approximately 95% for noise levels of 60 dB and above.

For a noise level of 40 dB, the score did not show an obvious decrease for a lower speech level. For a noise level of 45 dB, the score decreased to approximately 85% for a speech-to-noise ratio of ±0 dB. For noise levels of 50 dB and above, the scores apparently decreased for speech-to-noise ratio of −5 dB, and the minimum scores were around 70% for noise levels of 50, 55, and 70 dB.

The effect of the speech level on the score was tested using a one-way repeated measures analysis of variance for each noise level. The main effect of the speech level was significant ($p < 0.01$) except for at the noise level of 40 dB ($p = 0.06$).

HSDs ($p < 0.05$) were calculated for noise levels of 45 dB and above. Table III shows the HSDs and the pairs of speech levels which showed a significant difference in the score for each noise level. Although there are a few exceptions, it can be concluded that for noise levels of 50 dB and above, the score significantly decreases when the speech-to-noise ratio is −5 dB, and for a noise level of 45 dB, the score significantly decreases when the speech-to-noise ratio is ±0 dB and less.

Therefore, the lower limit of the speech level required to maximize word intelligibility scores for the elderly group is the same as that for young group, that is, the level with a speech-to-noise ratio of over ±0 dB for noise levels from 50 to 70 dB. However, for a noise level of 45 dB, a speech level

TABLE III. Pairs of speech levels that showed a significant difference in word intelligibility scores for the elderly group based on Tukey's HSD post-hoc test ($p < 0.05$). The parenthetic numbers such as (A, B-C) indicate that the score for the speech level of A dB is significantly different from each of the scores for the speech level from B to C dB.

Noise level, dB	HSD, %	Pair of speech level, dB
45	5.4	(45, 50-80), (50, 70)
50	7.5	(45, 50-85), (50, 75)
55	8.2	(50, 55-85)
60	8.3	(55, 65-85)
65	8.2	(60, 65-85)
70	7.3	(65, 70-85)

of 45 dB is not sufficiently high to maximize the score. Sato *et al.*[13] reported that the lower limit of the speech level that maximizes word intelligibility scores for an elderly group in a sound field without additional noise and reverberation sound is 45 dB. This means that the lower limit is at least 45 dB. Considering this and the results of the present study, the lower limit should gradually decrease from 50 to 45 dB with decreasing noise level from 50 to 40 dB and remain constant at 45 dB for noise levels of less than 40 dB.

B. Listening difficulty rating

The listening difficulty rating is the percentage of the sum of the responses rated listening difficulty from 2 to 4 in Table II. Figure 4 shows listening difficulty ratings as a function of speech level for each noise level and each group of listeners. The ratings were obtained from all responses ($N = 208$) for each group.

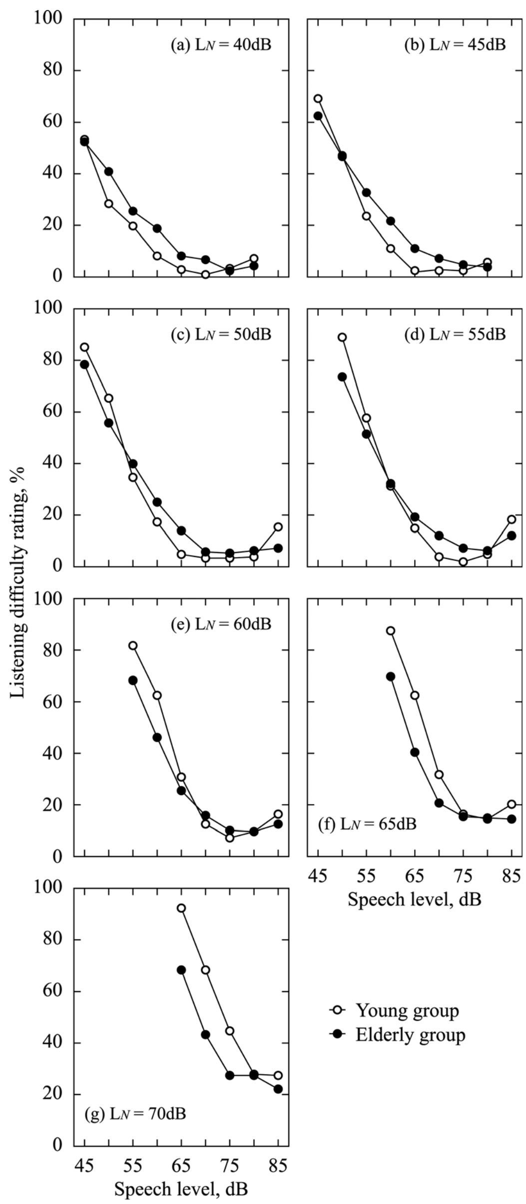

FIG. 4. As for Fig. 3, but for listening difficulty ratings.

1. Young group

The listening difficulty ratings for the young group were more strongly affected by the speech level than the word intelligibility scores. The rating decreased with increasing the speech level until it reached a minimum value, then increased when the speech level increased further. The minimum listening difficulty rating was higher than 0% when the noise level exceeded 60 dB. This means that a sound field for which no one experiences listening difficulty can only be achieved for noise levels of 55 dB and less.

A one-way repeated measures analysis of variance was performed in the same way as that for the word intelligibility scores. The main effect of the speech level was significant for all noise levels ($p < 0.01$). Table IV shows the results for *post hoc* comparisons using HSD ($p < 0.05$). The results for the young group are shown above the diagonal line in each table. The speech level with a background color of gray indicates the level that minimized the ratings for each noise level. For example, the ratings for the young group for a noise level of 40 dB [see Table IV(a)], were minimized for a speech level of 70 dB, and the rating for 70 dB was significantly different from the ratings for 45, 50, and 55 dB.

For noise levels of 40 and 45 dB, the lower limit of the speech level that did not cause a significant increase in the ratings from the minimum value was 60 dB. The upper limit was unclear, but it is considered to not be higher than those for higher noise levels.

For noise levels of 50 and 55 dB, the lower limits of the speech level were 65 and 70 dB, respectively. In other words, the lower limits were the levels with a speech-to-noise ratio of +15 dB. Meanwhile, the ratings significantly increased for a speech level of 85 dB. Therefore, both the lower and upper limits were determined. The ranges were from 65 to 80 dB and from 70 to 80 dB for noise levels of 50 and 55 dB, respectively. Considering that the upper limit for noise levels of 50 and 55 dB was 80 dB, the upper limit for noise levels of 40 and 45 dB is also considered to be 80 dB.

For noise levels from 60 to 70 dB, the lower limits of speech level increased with increasing noise level, and they were 70, 75, and 80 dB for noise levels of 60, 65, and 70 dB, respectively. The lower limits maintained a speech-to-noise ratio of +10 dB, less than that for noise levels of 50 and 55 dB. The ratings did not significantly increase for a speech level of 85 dB, therefore the upper limit was unclear.

2. Elderly group

The effect of the speech level on the listening difficulty ratings for the elderly group was larger than that on the word intelligibility scores, similar to the young group. The ratings decreased with increasing speech level, and then remained at the minimum value. The increase in the ratings due to over amplification was less than that for the young group and such an increase only appeared for noise levels of 55 and 60 dB. For noise level of 55 dB and above, the minimum ratings for each noise level increased from 0%.

The ratings for the elderly group were not always higher than those for the young group. For a speech-to-noise ratio of −5 dB, the ratings for the elderly group were lower than

TABLE IV. Results of multiple comparisons ($p < 0.05$) between listening difficulty ratings for each speech level. (a) to (g) show the results and HSDs for the young (HSDY) and elderly (HSDE) listeners for noise levels from 40 to 70 dB. The results for the young and elderly groups are shown above and below the diagonal line in each table, respectively. Asterisks indicate a significant difference between listening difficulty ratings. The speech level with a background color of gray is the level that minimized the ratings for each noise level.

(a) $L_N = 40$ dB

$HSD_Y = 13.8\%$, $HSD_E = 14.5\%$

	45	50	55	60	65	70	75	80	85
45		*	*	*	*	*	*	*	-
50				*	*	*	*	*	-
55	*	*			*	*	*		-
60	*	*							-
65	*	*	*						-
70	*	*	*						-
75	*	*	*	*					-
80	*	*	*						-
85	-	-	-	-	-	-	-	-	

(b) $L_N = 45$ dB

$HSD_Y = 11.7\%$, $HSD_E = 12.3\%$

	45	50	55	60	65	70	75	80	85
45		*	*	*	*	*	*	*	-
50	*		*	*	*	*	*	*	-
55	*	*		*	*	*	*	*	-
60	*	*							-
65	*	*	*						-
70	*	*	*	*					-
75	*	*	*	*					-
80	*	*	*	*					-
85	-	-	-	-	-	-	-	-	

(c) $L_N = 50$ dB

$HSD_Y = 11.5\%$, $HSD_E = 14.3\%$

	45	50	55	60	65	70	75	80	85
45		*	*	*	*	*	*	*	*
50	*		*	*	*	*	*	*	*
55	*	*		*	*	*	*	*	*
60	*	*	*		*	*	*	*	
65	*	*	*						
70	*	*	*	*					*
75	*	*	*	*					*
80	*	*	*	*					*
85	*	*	*	*					

(d) $L_N = 55$ dB

$HSD_Y = 12.6\%$, $HSD_E = 14.0\%$

	45	50	55	60	65	70	75	80	85
45		-	-	-	-	-	-	-	-
50	-		*	*	*	*	*	*	*
55	-	*		*	*	*	*	*	*
60	-	*	*		*	*	*	*	*
65	-	*	*				*		
70	-	*	*	*					*
75	-	*	*	*					*
80	-	*	*	*					*
85	-	*	*	*					

(e) $L_N = 60$ dB

$HSD_Y = 12.2\%$, $HSD_E = 10.5\%$

	45	50	55	60	65	70	75	80	85
45		-	-	-	-	-	-	-	-
50	-		-	-	-	-	-	-	-
55	-	-		*	*	*	*	*	*
60	-	-	*		*	*	*	*	*
65	-	-	*	*		*	*	*	*
70	-	-	*	*					
75	-	-	*	*	*				
80	-	-	*	*	*				
85	-	-	*	*	*				

(f) $L_N = 65$ dB

$HSD_Y = 12.9\%$, $HSD_E = 11.1\%$

	45	50	55	60	65	70	75	80	85
45		-	-	-	-	-	-	-	-
50	-		-	-	-	-	-	-	-
55	-	-		-	-	-	-	-	-
60	-	-	-		*	*	*	*	*
65	-	-	-	*		*	*	*	*
70	-	-	-	*	*		*	*	
75	-	-	-	*	*				
80	-	-	-	*	*				
85	-	-	-	*	*				

(g) $L_N = 70$ dB

$HSD_Y = 16.7\%$, $HSD_E = 12.1\%$

	45	50	55	60	65	70	75	80	85
45		-	-	-	-	-	-	-	-
50	-		-	-	-	-	-	-	-
55	-	-		-	-	-	-	-	-
60	-	-	-		-	-	-	-	-
65	-	-	-	-		*	*	*	*
70	-	-	-	-	*		*	*	*
75	-	-	-	-	*	*		*	*
80	-	-	-	-	*	*			
85	-	-	-	-	*	*			

those for the young group, even though the word intelligibility scores for the elderly group were apparently less than those for the young group (see Fig. 3).

The results of a one-way repeated measures analysis of variance showed that the main effect of the speech level was significant for all noise levels ($p < 0.01$). Table IV also shows the results for *post hoc* comparisons using HSD ($p < 0.05$) for the elderly group, which are shown below the diagonal line in each table. The upper limit of the speech level that caused a significant increase in the ratings could not be determined for all noise levels. However, for noise levels of 55 and 60 dB, the ratings were higher for a speech level of 85 dB. Therefore, the upper limit was not much higher than 85 dB. The lower limit was constant at 65 dB for noise levels of 55 dB and below. For noise levels of 60 dB and above, the lower limits were 70, 70, and 75 dB for noise levels of 60, 65, and 70 dB, respectively. This means that the lower limits corresponded to a speech-to-noise ratio of +5 or +10 dB, less than or equal to those for the young group.

C. Acceptable range of speech level

Table V shows a summary of the present study. For the young group, the lower limit of the speech level that maximizes word intelligibility scores was always lower than the lower limit of the speech level that caused a significant increase in listening difficulty ratings, and a decrease in word intelligibility scores due to over amplification was not found in the present study. Therefore, the upper and lower limits of the speech level that caused a significant increase in listening difficulty ratings can be considered as the limits of

TABLE V. Lower limit of speech level that maximizes word intelligibility scores (LL_I), and the lower and upper limits of speech level that do not cause a statistically significant increase in listening difficulty ratings from the minimum ratings (LL_D, UL_D) for each noise level and each group of listeners.

Noise level	Young group			Elderly group		
	LL_I	LL_D	UL_D	LL_I	LL_D	UL_D
40	≤ 45	60	80	45	65	≥ 80
45	45	60	80	> 45	65	≥ 80
50	50	65	80	50	65	≥ 85
55	55	70	80	55	65	≥ 85
60	60	70	≥85	60	70	≥ 85
65	65	75	≥85	65	70	≥ 85
70	70	80	≥85	70	75	≥ 85
						(dB)

the acceptable range of speech level in the present study. This summary also applies to the elderly group.

Figure 5 shows the lower limit of the speech level that maximizes word intelligibility scores and the acceptable range of speech level obtained in the present study. Figures 5(a) and 5(b) show the results for the young and elderly groups, respectively, and Fig. 5(c) shows those for both groups.

The lower limit of the speech level that maximizes word intelligibility scores does not differ between the young and elderly groups, except for noise levels of less than 50 dB. For noise levels of less than 50 dB, that for both the young and elderly groups should be set to that for the elderly group, because the elderly group requires a speech level of at least 45 dB to maintain the maximum word intelligibility score.[13]

The upper limit of the acceptable speech level for the elderly group should be higher than that for the young group, although it could not be clearly determined in the present study. Therefore, the upper limit for both groups is determined by the limit for the young group.

For the lower limit of the acceptable speech level, the limit for both groups is determined by the limit for different groups for different noise levels. For noise levels from 40 to 50 dB, the lower limit for the elderly group is 65 dB, which it is the same or higher than that for the young group. This might be because of a decrease of loudness due to hearing loss. Therefore, the lower limit for both groups should be set at 65 dB. Meanwhile, for noise levels of 55 dB and above, the young group might evaluate listening difficulty more sensitively than the elderly group, and the lower limit of the acceptable speech level for the young group is higher than that for the elderly group. Therefore, the lower limit for both groups is determined by that for the young group, and it is the level with a speech-to-noise ratio of +15 dB for a noise level of 55 dB, and a ratio of +10 dB for noise levels of 60 dB and above.

IV. DISCUSSION

A. Comparison with previous studies

Kobayashi *et al.*[6] reported that the optimum speech level is the level with a speech-to-ratio of +15 dB for noise levels from 40 to 55 dB. The optimum speech level is included in the range of acceptable speech level shown in Fig. 5(a), except for at noise levels of less than 45 dB. The optimum speech level is 5 dB lower than the lower limit of the acceptable speech level for a noise level of 40 dB. A possible reason for this difference might be the effect of reverberation sound. The optimum speech level was measured excluding reverberation sound, and that implies that the speech loudness might be larger than that expected from the optimum speech level because of the enhancement by reverberation sound. Van Heusden *et al.*[5] also reported the preferred listening level as a function of noise level, which they found to be about 50 to 60 dB in the range of noise level from 35 to 70 dB. The preferred listening level is much lower than the acceptable speech level obtained in the present study and the optimum speech level obtained by Kobayashi *et al*. The large difference might be due to the method used to present background noise, and the instruction that specify listening situations. In the present study and Kobayashi's study, background noise was presented from a loudspeaker in front of listeners and listeners were not instructed about listening situations at all. Meanwhile, van Heusden *et al*. used a multispeaker system to produce a diffuse background noise, and instructed listeners to adjust the level of the presented speech as if they were listening to a radio. The preferred listening level could be lower by 10 dB than background noise level while the optimum speech level required speech-to-noise ratio of +15 dB. If the instructed situation did not affect the results, the effect of diffuseness of background noise should be corresponding to increase of speech level by 25 dB at the maximum. However, Licklider[19] reported that the difference between intelligibility scores for

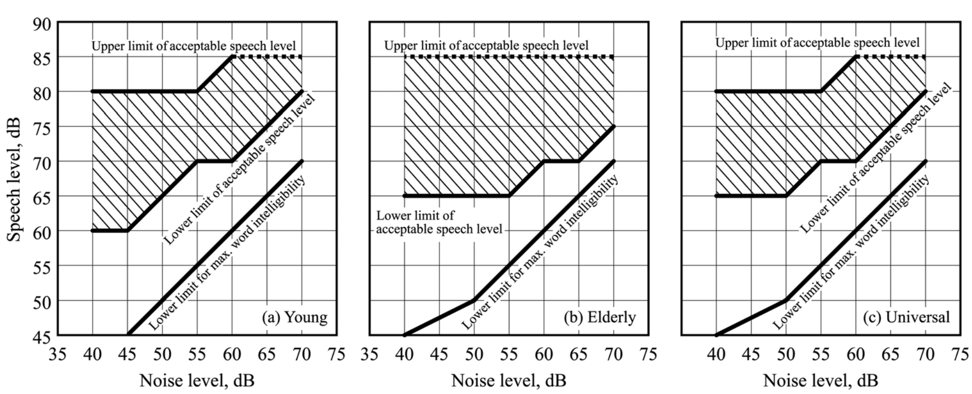

FIG. 5. Lower limits of speech level for the maximum word intelligibility and the range of acceptable speech level obtained in the present study. (a) and (b) The results for the young and elderly groups, respectively. (c) The combined results for both the young and elderly groups obtained by superimposing (a) and (b).

diotic listening condition and those for the condition with speech in phase and noise in random phase was corresponding to the difference of speech-to-noise ratio by around 1 dB at the maximum. Furthermore, the binaural masking level difference where the interfering noise is interaurally uncorrelated is around 3 dB regardless of interaural correlation of signals.[20] These findings indicate that the effect of diffuseness of background noise is not a major reason for the difference between the preferred listening level and the optimum speech level. Because listening to a radio is a personal situation in usual, listeners might prefer small loudness to be polite.

B. Effect of hearing level on acceptable range of speech level

Figure 1 shows that the hearing level for the elderly group has a large standard deviation among listeners. There have been some studies on the effect of the hearing level on MCL, which showed that MCL increased with increasing the hearing level.[21–23] The effect of the hearing level on the acceptable range of speech level was investigated using the results of the present study, focusing on whether the lower limit of the range for both the young and elderly groups [see Fig. 5(c)], which is important for designing public address systems, can be applied to elderly listeners with mild hearing impairments or not.

The elderly group was divided into two groups based on each listener's the pure-tone average (PTA), that is the average hearing level of 500 Hz, 1 kHz, and 2 kHz for both ears. One group had normal hearing ($N=28$) with a PTA of 25 dB or less, and the other group had mild hearing impairments ($N=24$) with a PTA from 26 to 40 dB. There were no elderly listeners with a PTA over 40 dB.

Word intelligibility scores and listening difficulty ratings for each elderly group were obtained from the results in the present study. Word intelligibility scores for both elderly groups were more than 95% at the lower limit of the acceptable range of speech level shown in Fig. 5(c), regardless of the noise level. In other words, the word intelligibility scores for elderly groups with mild hearing impairments were maximized in the acceptable range of speech level shown in Fig. 5(c).

Table VI shows listening difficulty ratings at the lower limit of the acceptable range of speech level shown in Fig. 5(c) (D_{LL}), and the minimum ratings (D_{min}) for each noise level and each elderly group. The difference between D_{LL} and D_{min} was up to 14.6% for the group with mild hearing impairments, and it was nearly equal to HSD_E in Table IV. This result implies there is no significant difference between D_{LL} and D_{min} for the group with mild hearing impairments regardless of the noise level. Therefore, the lower limit of the acceptable range of speech level shown in Fig. 5(c) can be applied to people with mild hearing impairments.

The difference in D_{min} between the group with normal hearing and mild hearing impairments was less than 5%. On the other hand, the difference in D_{LL} between the two groups was slightly larger for noise levels of 40, 45, 55, and 70 dB. For noise levels of 40, 45, and 55 dB, DLL for the group with mild hearing impairments was approximately 10% higher than that for the group with normal hearing. This indicates that the lower limit of the acceptable range of speech level might not be ideal for elderly listeners with mild hearing impairment, although the increase in listening difficulty ratings from the minimum values did not appear to be significant. For a noise level of 70 dB, D_{LL} for the group with mild hearing impairments was approximately 10% lower than that for the group with normal hearing. This might be because the increase in listening difficulty ratings due to a loud background noise is less for the group with mild hearing impairments than for the group with normal hearing.

TABLE VI. Listening difficulty ratings for groups of elderly with normal hearing level (PTA $\leq$ 25 dB) and elderly with mild hearing impairments (26 dB $\leq$ PTA $\leq$ 40 dB) for each noise level. DLL represents the ratings at the lower limit of the acceptable range of speech level for both the young and elderly groups [see Fig. 5(c)], and D_{min} represents the minimum ratings for each noise level.

Noise level,	Normal		Mild	
dB	D_{LL}, %	D_{min}, %	D_{LL}, %	D_{min}, %
40	3.6	1.8	13.5	2.1
45	5.4	3.6	17.7	3.1
50	14.3	2.7	13.5	6.3
55	7.1	4.5	18.8	7.3
60	17.0	8.9	14.6	10.4
65	17.0	9.8	13.5	10.4
70	33.0	24.1	20.8	19.8

C. Application to public spaces

The diotic presentation was adopted here to simplify the listening test. Generally speaking, meanwhile, background noise in public spaces is diffused because of reflections and multiple noise sound sources. For example, interaural cross correlation coefficients of background noise in subway stations[24] and underground stations[25] were close to the theoretical value of 2-point cross correlation coefficient in a diffuse sound field.[26] As described in the Sec. IV A, the effect of diffuseness of background noise on intelligibility can be ignored. Sato *et al.*[14] reported that interaural correlations of speech and noise made a significant difference in listening difficulty only for a speech-to-noise ratio of −10 dB, and did not for higher speech-to-noise ratios such as +10 dB. The lower limit of the acceptable speech level was corresponding to a speech-to-noise ratio of +10 dB, and thus the acceptable speech level would not be affected by diffuseness of background noise. Grose *et al.*[27] and Strouse *et al.*[28] reported that the binaural masking level difference for speech was lower for elderly listeners than young listeners. This means that the acceptable speech level for the elderly listeners would also not be affected by diffuseness of background noise.

Temporal and frequency aspects of background noise in public spaces are also differ from those used in the present study. Festen and Plomp[29] reported that the speech reception threshold for steady-state noise was higher by around 5 dB than that for noise with the envelope of speech. This indicates that the acceptable speech level for steady-state noise would be higher than that for fluctuating noise. At least the lower limit of acceptable speech level is applicable to fluctuating noise because it would be on the safe side from the viewpoint of intelligibility. The spectrum of background noise in public spaces is similar to Hoth spectrum used in the present study, which is broad and decreases with increasing frequency, in general. However, the acceptable range of speech level would not be applicable if the spectrum of background noise were narrow or included some tonal components, because the relationship between A-weighted sound pressure level and loudness of background noise could be differ from that in the present study in such cases.[30]

V. CONCLUSION

In the present study, listening tests were performed to clarify the acceptable range of speech level in noisy sound fields for both young adults and elderly persons. The acceptable range of speech level was obtained from word intelligibility scores and listening difficulty ratings. The conclusions of the study are as follows.

(1) Word intelligibility scores were maximized when the speech-to-noise ratio exceeded ± 0 dB for both young and elderly listeners. For elderly listeners, however, a speech level of at least 45 dB was required to maximize word intelligibility scores.
(2) Word intelligibility scores were always maximized for both young and elderly listeners when the speech level was in the range that did not cause a significant increase in listening difficulty ratings from the minimum ratings. This indicates that the range can be regarded as an acceptable range of speech level.
(3) The acceptable range of speech level for elderly listeners overlapped that for young listeners.
(4) The lower limit of the acceptable speech level for both the young and elderly listeners was 65 dB for noise levels of 40 and 45 dB, a level with a speech-to-noise ratio of $+15$ dB for noise levels of 50 and 55 dB, and a level with a speech-to-noise ratio of $+10$ dB for noise levels from 60 to 70 dB.
(5) The upper limit of the acceptable speech level for both young and elderly listeners was 80 dB for noise levels from 40 to 55 dB, and 85 dB or above for noise levels from 55 to 70 dB.
(6) The acceptable range of speech level obtained in this study can be applied for elderly listeners with mild hearing impairments.

ACKNOWLEDGMENTS

This research project was partially supported by the research and development grant of Japan Institute of Construction and Engineering, 03011, 2004, and by Japan Society for the Promotion of Science, Grant-in-Aid for Scientific Research (B), 16360292, 2004–2006.

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