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Technical Notes

Comparison of Two Types of Combined Measures, STI and U_{50}, for Predicting Speech Intelligibility in Classrooms

Young-Ji CHOI

Department of Architectural Engineering, Kangwon National University
1 Kangwondaehak-gil, Choncheon-si, Kangwon-do, 200-701, Korea; e-mail: youngjichoi@kangwon.ac.kr

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The present study reports on the speech intelligibility as measured by speech transmission index (STI) and useful-to-detrimental sound ratios (U_{50}) in university classrooms. Acoustic measurements were made in 12 quietly occupied university classrooms. The measured impulse responses of the classrooms were used to determine the modulation transfer function, $m(F)$, for the STI calculation according to IEC 60268-16. U_{50} values were determined from both signal-to-noise ratios (SNR) and C_{50} values. The mean STI and frequency-weighted U_{50} values for the 12 occupied classrooms were strongly linearly related. The results showed that classrooms with U_{50} values of about +0.5 dB correspond to STI values of 0.60, indicating 'good' acoustical conditions for speech intelligibility. The results illustrate that the U_{50} measure can be a more practically useful means of assessing and understanding room acoustics conditions for real speech communication in active classrooms.

Keywords: speech intelligibility; speech transmission index; useful-to-detrimental sound ratios; classrooms.
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1. Introduction

Two combined measures, speech transmission index (IEC 60268-16, 2011) and useful-to-detrimental sound ratios (Bradley *et al.*, 1999) can be considered complete predictors of speech intelligibility in classrooms because they include both a measure of room acoustics quality and a measure of speech-to-noise-ratios. Previous studies (Bradley *et al.*, 1999; Bradley, Yang, 2009) have shown that room acoustics and signal-to-noise-ratios (SNR) both influence speech intelligibility in classrooms and hence the combined effect of room acoustics and SNR on speech intelligibility should be measured. The ratio of early-arriving to late-arriving sound (C_{50}) has been used as a measure of the effects of room acoustics on the clarity of speech sounds in classrooms (Bradley, 1986), but this measure cannot estimate the combined effects of room acoustics and background noise.

Useful-to-detrimental sound ratios (U_{50}) are defined as the logarithmic ratio of the useful to the detrimental sound (Bradley *et al.*, 1999). The useful sound is the early-arriving speech energy and the detrimental sound is the sum of the later-arriving speech energy and the ambient noise energy. Useful-to-detrimental sound ratio values (U_{50}) can be determined from both signal-to-noise ratios and C_{50} values; see Eq. (1) (Bradley *et al.*, 1999). The U_{50} measure can explain the combined effects of room acoustics and SNR values on the resulting speech intelligibility. It attempts to correctly include the balance of the importance of the SNR and acoustic clarity of the room.

$$U_{50} = 10 \log \left\{ \frac{E/L_{50}}{1 + (E/L_{50} + 1)N/S} \right\}, \quad \text{dB}, \qquad (1)$$

where N is the ambient noise energy, S is the speech energy, and E/L_{50} is the linear early-to-late arriving sound energy ratio.

The U_{50} measure combines the detrimental effects of late arriving speech and ambient noise relative to the useful direct and early reflected speech sounds and thus being able to achieve the best combination of maximising both clarity (C_{50}) and G values for optimum conditions in classrooms.

Classroom quality was strongly correlated with the background noise level and the related signal-to-noise ratios (Hodgson, 2002), emphasising the need for the design criteria for occupied classrooms (Hodgson, Nosal, 2002). A number of studies (Hodgson *et al.*, 1999; Sato, Bradley, 2008) have reported that the speech and noise levels are quite different from values measured in active classrooms with the influence of noise due to students' activity. They also proposed a method for estimating SNR values in classrooms when they are occupied and in operation. The results of the active classroom acoustics studies (Hodgson *et al.*, 1999; Sato, Bradley, 2008) indicate greater noise levels than recommended in the ANSI standard for classroom acoustics (ANSI S12.60, 2004).

Among three types of combined measures (U_{50}, AL_{cons}, STI) for speech intelligibility, U_{50} was the most accurate predictor and explained 97% of the variance in speech intelligibility scores (Bradley *et al.*, 1999). Because the U_{50} measure is based on the same basic concepts and can be calculated from commonly measured parameters (e.g., C_{50} and SNR values), it can be a more practically useful means of assessing and understanding room acoustics conditions for speech. This is the main reason for further exploring the merits of using U_{50} in this study. However, for U_{50} there is no standard procedure for combining information at different frequencies or for the relative importance of signal-to-noise and room acoustics components. Bradley *et al.* (1999) found that both A-weighted and AI frequency-weighted sums of the octave band U_{50} values were well correlated with speech intelligibility scores. Thus these frequency-weighted measures are generally acceptable as broadband measures because they do include effects in all frequency bands of interest. In a recent study (Bradley, 2011), U_{50} values were calculated by combining octave band values following the procedure used in calculating AI and STI values and using the frequency weightings from the STI measure.

Nijs and Rychtáriková (2011) proposed a conversion from measured STI values to quality classification applied to U_{50} values. That is, classifications of STI in 0.15 steps 'bad' to 'excellent' were used for U_{50} in 5 dB steps. But they did not use the frequency weightings from the STI measure (IEC 60268-16, 2011) for calculating U_{50} values. Bradley and Bistafa (2002) proposed a better indication of the general relationship between 1-kHz U_{50} values and mean speech intelligibility scores using a new regression equation. They showed that a 1-kHz U_{50} value of +2 dB is a reasonable goal for conditions that would permit very good speech communication in rooms. A 1-kHz U_{50} value of +2 dB proposed by Bradley and Bistafa (2002) acoustical conditions for speech intelligibility given in Nijs and Rychtáriková's (2011) classification. The results reported in previous studies (Nijs, Rychtáriková, 2011; Bradley, Bistafa, 2002) demonstrate that both measures are highly correlated and essentially describe the same properties of the rooms.

This paper is a follow-up of a previous work (Choi, 2016) that experimentally investigated the effect of occupancy on acoustical conditions in university classrooms. The present study reports on the speech intelligibility as measured by speech transmission index (STI) and useful-to-detrimental sound ratios (U_{50}) in university classrooms. Acoustical measurements were made in 12 quietly occupied university classrooms. The measured impulse responses of the classrooms were used to determine the modulation transfer function, $m(F)$, for the STI calculation according to IEC 60268-16 (2011). U_{50} values were determined from both signal-to-noise ratios (SNR) and C_{50} values. The goal of the present work is to further explore the merits of using U_{50} to measure the combined effects of room acoustics (C_{50}) and SNR values on speech intelligibility in classrooms essentially as accurately as STI values. It is hoped that one can use a linear regression to convert values of one measure to values of the other measure.

2. Measurement procedures

2.1. Measurements of room acoustical qualities in classrooms

Table 1 presents the data describing the 12 university classrooms used for the measurements in a previous paper (Choi, 2016). Of the 12 classrooms, 9 were typical classrooms, and 3 were used for computers, teleconferences, and conferences. Seven classrooms had rectangular shapes with windows on one side and 5 classrooms had non-rectangular shapes. The mean percentage of seats occupied during the measurements was 54%. Speech-reinforcement systems were installed in some larger sized classrooms, but they were not in operation during the measurements. The occupants were allowed to choose where they wished to sit. In the occupied classroom measurements, the students were asked to remain quiet. Thus, the noise measurements did not include significant student activity.

The classrooms varied from small lecture rooms with volumes about 190 m^3, to a large conference hall with a volume of about 2500 m^3. Six classrooms had similar room finishes with reflective surface materials such as: painted concrete walls, terrazzo floors, and were mostly used for small to medium size classes with fewer than 100 occupants. The other 6 classrooms had mostly porous absorbing surface materials. Four of these 6 classrooms were lecture theatres for larger sized classes including up to 240 occupants. The mean mid-frequency T_{30} (500–1000) values for the six occupied and unoccupied reflective classrooms were 0.81 s and 1.32 s. The other 6 classrooms had mostly porous absorbing surface materials and vinyl or fabric covered chairs. Four of these 6 classrooms were lecture theatres for larger sized classes including up to 240 occupants. The mean mid-frequency T_{30} (500–1000) values for the six occupied and unoccupied absorptive classrooms were 0.53 s and 0.60 s. More details of the 12 classrooms are included in Ref. 7.

Table 1. Data for 12 university classrooms used for the measurements including mean (500–1000 Hz) T_{30} values for both occupied and unoccupied cases.

Rooms	Width [m]	Depth [m]	Height [m]	Volume [m^3]	Number of occupants	Mean T_{30} unoccupied [s]	Mean T_{30} occupied [s]
#1	9.0	7.1	3.1	199	15	1.29	0.89
#2	9.1	7.2	2.9	193	11	0.83	0.72
#3	8.9	10.6	3.0	284	22	1.18	0.82
#4	8.8	10.1	2.8	248	13	1.15	0.84
#5	7.9	16.6	2.7	354	62	1.81	0.83
#6	7.4	11.9	2.7	238	46	1.68	0.77
#7	17.5	17.2	4.4	1310	84	0.56	0.55
#8	13.9	15.8	5.6	1227	80	0.74	0.57
#9	17.0	16.2	2.5	690	61	0.44	0.39
#10	6.4	13.1	2.7	226	48	0.31	0.26
#11	16.5	21.1	7.3	2535	53	0.92	0.84
#12	17.5	15.9	3.2	888	74	0.65	0.58
Mean	11.7	13.6	3.6	699	47	0.96	0.67
s.d.	4.4	4.3	1.5	707	27	0.47	0.20
Max	17.5	21.1	7.3	2535	84	1.81	0.89
Min	6.4	7.1	2.5	193	11	0.31	0.26

Room acoustical quantities were determined from the measured impulse responses in occupied classrooms. A logarithmic sine sweep signal was used as the source signal and was radiated into the classroom from a dodecahedron loudspeaker (Norsonic, Nor276). Measurements were made at six to nine receiver positions using 1/2″ free-field microphones (G.R.A.S, Type 46AF) evenly distributed among the seated occupants in each classroom, at a height of 1.2 m. One centre source position at a height of 1.5 m was used.

The reverberation times (T_{30}), the early-to-late-energy ratios (C_{50}), and the strength (G) were measured in accordance with ISO 3382 (2003) using the Dirac software V.6.0 (Brüel & Kjær, 2014). The actual ambient noise levels were measured at each receiver position in each classroom. Useful-to-detrimental sound ratios were calculated using Eq. (1). The octave band energy ratios were weighted with the same frequency weightings as used in the STI measure (IEC 60268-16, 2011) before summing to give the overall U_{50} values.

2.2. Calculation of expected speech levels at each receiver position

An ideal talker was assumed, to be located at the position of the sound source and speaking with a 'raised voice level' according to that specified in ANSI S3.5 (1997). The expected speech levels at each receiver position were calculated assuming the source level at 1 m from the source was the ANSI 'raised voice level' and corresponding source spectrum. The expected attenuation to each receiver position was calculated from the measured G values using the following Eq. (2)

$$\text{Atten} = L_{\text{ss}} - L_{\text{rs}} = -G + 20, \quad \text{dB}, \tag{2}$$

where attenuation is a positive value representing the reduction in level from a distance of 1 m to a distance of r m from the speech source. L_{ss} is the direct speech sound level, 1 m from the source, and L_{rs} is the speech sound level at the receiver position.

The measured G values can be used to determine the attenuation of sound from the source position to that expected at each receiver position simply by correcting G values to be relative to a reference level at 1 m rather than 10 m. They should precisely predict the effect of the measured sound attenuation on the source levels and therefore give the correct expected speech levels at each receiver position using the following Eq. (3):

$$L_{\text{rs}} = L_{\text{ss}} - \text{Atten} = L_{\text{ss}} + G - 20, \quad \text{dB}. \tag{3}$$

2.3. Calculation of speech transmission index

The measured impulse responses of the classrooms were also used to determine the modulation transfer function, $m(F)$, for the STI calculation according to IEC 60268-16 (2011). The modulation transfer function at modulation frequency F, ($m(F)$), can be calculated from room impulse responses and the effective signal-to-noise ratio, S/N (in dB), using the following Eq. (4) (Schroeder, 1982):

$$m(F) = \frac{\left|\int_0^\infty h^2(t) e^{-2\pi F t}\,\mathrm{d}t\right|}{\int_0^\infty h^2(t)\,\mathrm{d}t} \cdot \frac{1}{1 + 10^{\frac{-S/N}{10}}}, \tag{4}$$

where F is a modulation frequency, $h(t)$ is an impulse response, and S/N is the speech signal-to-noise ratio in dB. The STI value is calculated from a weighted average of modulation transfer index (MTI). The IEC 60268-16 (2011) describes this calculation and also considers masking effects and the absolute threshold of masking for the calculation of the revised speech transmission index.

3. Results and discussion

3.1. The combined effect of room acoustics and background noise

It is well known that good acoustical design for speech communication requires one to maximise the signal-to-noise ratio and provide optimum room acoustics conditions in classrooms This process is to find an optimum reverberation time that maximises the 'useful' components (the combination of the direct and early-reflected sound) of the speech sounds relative to the 'detrimental' (the sum of the late-arriving speech sounds plus the ambient noise) components. For example, in very quiet conditions the ambient noise levels will be much lower than the late-arriving speech sound energy and hence the amount of late-arriving energy will predominate for the detrimental components. For such conditions varying the reverberation time will have large effect on achieving optimum room acoustics conditions in classrooms.

In this study, U_{50} values were calculated by averaging octave band values from 125 to 4000 Hz and using the frequency weightings from the STI measure following the procedure used in Bradley's study (2011). Using a non-frequency weighted calculation of U_{50} values is not appropriate because this would overemphasise the importance of the low frequencies when the intention is to predict expected speech intelligibility. Table 2 compares the results of linear regression fits of various broadband useful-to-detrimental sound ratio measures to STI values. For example, U_{50} (A, 125–4000) indicates U_{50} values obtained from A-weightings of the octave band C_{50} and speech and noise levels and averages of the octave band values from 125 to 4000 Hz. The U_{50} (STI, 125–4000) values, obtained from STI-weighted averages of the octave band values from 125 to 4000 Hz, were best correlated with the STI values and led to an R^2 value of 0.968 shown in Table 2. They showed a slightly better correlation than the U_{50} (STI, 500–4000) values averaging over the four octave bands from 500 to 4000 Hz (R^2 value of 0.953). The frequency-weighted U_{50} values seem to be more reliable as a broadband measure because they appear in all frequency bands of interest.

Table 2. Results of linear regression fits of various broadband useful-to-detrimental sound ratio measures to STI values.

Measure	R^2
U_{50} (125–4000)	0.961
U_{50} (500–4000)	0.952
U_{50} (A, 125–4000)	0.948
U_{50} (A, 500–4000)	0.952
U_{50} (STI, 125–4000)	0.968
U_{50} (STI, 500–4000)	0.953

Figure 1 plots the calculated mean, frequency-weighted, U_{50} (STI, 125-4000) values versus the measured mean C_{50} values for the 12 occupied classrooms. The mean overall U_{50} and C_{50} values for the 12 occupied classrooms in Fig. 1 show a good fit to the linear regression line with a small amount of scatter ($R^2 = 0.944$ and the standard deviation about the regression line, $\sigma = 0.015$). Only two classrooms deviate much from the linear regression line. These were classrooms #1 and #8 where measurements included air conditioner noise. The increased noise for these rooms leads to lower U_{50} values for similar C_{50} (125–4000) values. For example the results for classroom #8 deviate 9.8 dBA below the regression line indicating lower SNR values than for the main trend. The results in Fig. 1 indicate that U_{50} values are mostly related to the corresponding C_{50} values except for rooms #1 and #8 where the increased ambient noise levels further reduce the U_{50} values. A C_{50} value of +1 dB or greater has been suggested (Bradley, 1986) to be required for good conditions for speech communication, which corresponds a frequency-weighted U_{50} value of +0.11 dB or greater from the regression line in Fig. 1.

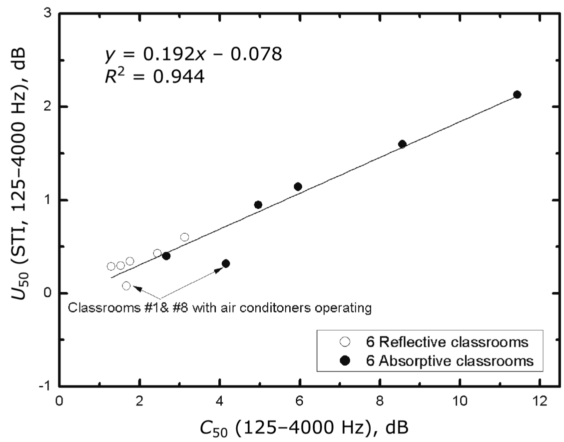

Fig. 1. Calculated mean frequency-weighted U_{50} (STI, 125–4000) values versus measured mean C_{50} values averaged of the octave bands 125 Hz to 4000 Hz for the 12 occupied classrooms.

The frequency-averaged C_{50} and U_{50} results show the more general trends of how the SNR values would affect the intelligibility of speech sounds in the groups of classrooms. The 6 more absorptive classrooms (symbols for filled circles) having decreased later arriving reflection energy lead to increased C_{50} values by about 4.3 dB relative to the results for the 6 more reflective classrooms (symbols for empty circles). However, shorter reverberation times led to larger reductions in speech levels and hence decreased SNR values. This resulted in a larger reduction in U_{50} values for the more absorptive classrooms in Fig. 1. Overall the U_{50} values indicate that the negative effect of reduced speech levels was greater than the positive effect of increased clarity.

3.2. Comparison of predictors of speech intelligibility

The results for both measures are compared in Fig. 2 which is a plot of STI values versus U_{50} (STI, 125–4000) values. The measured SNR values were included in the calculation of both STI and U_{50} values. The data in Fig. 2 show that the 6 more reflective classrooms (symbols for empty circles) have lower STI values even if the SNR values are more than 15 dBA. That is, the effects of room acoustics are more predominant than the SNR values in these reflective classrooms (T_{30} (500–1000) > 0.7 s). For such conditions, the amount of late-arriving energy will predominate for the detrimental components and hence decrease speech intelligibility. However, the results for two absorptive classrooms (T_{30} (500–1000) < 0.7 s) show that the SNR component is more critical for obtaining close to optimum conditions for speech. If the classrooms have more ideal reverberation times for speech (typically 0.5–0.7 s) (Yang, Bradley, 2009), the SNR component is more important for obtaining close to optimum conditions. Similarly decreasing reverberant sound would also decrease speech intelligibility because at some point decreasing reverberation leads to decreased early-arriving sound.

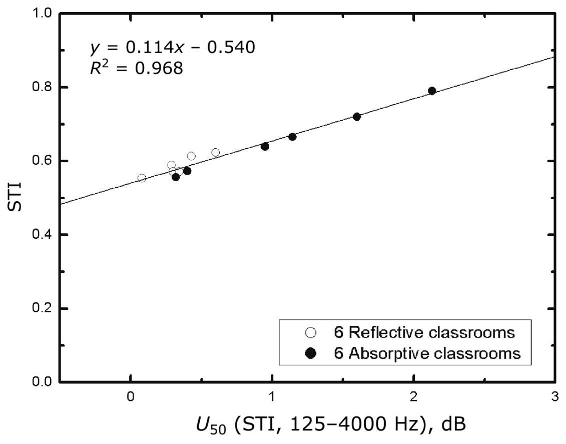

Fig. 2. Calculated STI values versus mean frequency-weighted U_{50} values from 125 Hz to 4000 Hz for the 12 occupied classrooms.

When the mean STI values are plotted versus the mean frequency-weighted U_{50} (STI, 125–4000) values for the 12 occupied classrooms in Fig. 2, they show a very good fit to the linear regression line with a very small amount of scatter ($R^2 = 0.968$ and the standard deviation about the regression line of $\sigma = 0.007$). The present results agree well with the results reported in previous studies (Bradley *et al.*, 1999; Nijs, Rychtáriková, 2011). Figure 2 shows a 0.114 increase of STI values per 1 dB increase of U_{50} values. The results in Fig. 2 show that classrooms with U_{50} values greater than +0.5 dB will have STI values of about 0.60 or higher, which indicates 'good' acoustical conditions for speech intelligibility. That is, both measures provide approximately the same information and one can use the linear regression in Fig. 2 to convert values of one measure to values of the other measure.

A U_{50} value of +0.5 dB is 1.5 dB and 1 dB lower than the values in two previous studies by Bradley and Bistafa (2002) and Nijs and Rychtáriková (2011), respectively. This is mainly because there is no standard procedure for including how to combine information at different frequencies and weightings to obtain U_{50} values. In the present study, the frequency-weighted U_{50} values averaged from 125 to 4000 Hz were used, while Njis and Rychtáriková used the frequency-averaged U_{50} values from 63 to 4000 Hz and Bradley and Bistafa used a 1 kHz U_{50} value for predicting speech intelligibility. It is not well established how to combine information at different frequencies for U_{50} best and what is the most optimal way to combine room acoustics and SNR components.

3.3. Practical application to the classroom acoustical design

The design of classrooms for achieving high speech intelligibility is definitely an optimisation problem. One must understand that the optimisation process is to minimise ambient noise levels to achieve acceptable speech-to-noise ratios. The SNR component is the most critical for obtaining close to optimum conditions for speech communication. One should realise that achieving an optimum reverberation time is of secondary importance because the optimum reverberation time varies when speech and noise levels are changed (Yang, Bradley, 2009). Either too short or too long reverberation time will decrease speech intelligibility.

The speech and noise levels measured in active classrooms (Hodgson *et al.*, 1999; Sato, Bradley, 2008) were quite different from values measured in quietly occupied classrooms. In most cases, the ideal goal of a +15 dB S/N ratio seems to be rarely achieved in active classrooms (Hodgson *et al.*, 1999; Sato, Bradley, 2008). There is a clear need for more representative data and complete understanding of speech and noise levels in occupied classrooms with teaching activities. Although both measures, STI and U_{50}, appear to be very different in a basic concept, the two measures are highly correlated and essentially assess the same characteristics of the rooms (Bradley *et al.*, 1999; Nijs, Rychtáriková, 2012). It is difficult to measure the STI values using amplitude-modulated noise during active speech communication in classrooms. On the other hand, U_{50} values can be easily obtained from both signal-to-noise ratios and C_{50} values in classrooms during speech communication. It is more difficult to measure these parameters in occupied classrooms and hence being able to predict values of these acoustical parameters for real speech communication is a great asset for achieving acoustically successful classrooms. The U_{50} measure can be more practically useful means of assessing and understanding room acoustics conditions for real speech communication.

4. Conclusions

The results illustrate that useful-to-detrimental sound ratios (U_{50}) can be used to measure the combined effects of room acoustics (C_{50}) and SNR values on speech intelligibility in classrooms essentially as accurately as STI values. However, all details of a standard procedure for combining information at different frequencies to obtain U_{50} should be determined and evaluated from a wide range of conditions in real classrooms. Further investigations could include the investigation of relationships between U_{50} values and speech intelligibility scores. Because the U_{50} measure is based on the same basic idea as other room acoustics parameters, such as C_{50} values, it can be a more practically useful means of assessing and understanding room acoustics conditions for speech.

The mean STI and frequency-weighted U_{50} (STI, 125–4000 Hz) values for the 12 occupied classrooms were shown to be highly correlated with U_{50} values and essentially describe the same properties of the rooms. The present results show that for classrooms with U_{50} values greater than 0.5 dB STI values are about 0.60, which indicates ‘good’ acoustical conditions for speech intelligibility.

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