Influence of sound source characteristics in determining objective speech intelligibility metrics

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Abstract: Sound source characteristics may be one of the main causes of objective speech intelligibility metric inaccuracy. In this study, the influences of the sound source directivity and frequency response were investigated using three typical sound sources: an artificial mouth, a monitor speaker, and a dodecahedral sound source. The results show that, the simultaneous influences of directivity and frequency response on the objective speech intelligibility metric are significant, typically with a variation of 0.147 in speech transmission index (STI); sound source directivity may also result in a noticeable difference in the objective speech intelligibility metric, typically with a variation of 0.123 in STI. In comparison with sound sources with a high directivity index (DI), the measurement results for sound sources with a relatively low DI may be higher when background noise is high, and may be lower when background noise is low. The influence of sound source directivity may also depend on the room acoustic conditions, and at receiver position where reflections are abundant, the influence of sound source directivity may be more significant. Not applying frequency response equalisation resulted in large errors in the values being measured, which deviate from the real values of STI by up to 0.172, depending on the original frequency response characteristics of the sound sources that are used.

Keywords: sound source characteristics; directivity; frequency response; speech intelligibility; objective speech intelligibility metric.

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1. Introduction

Speech intelligibility is an important metric and can be used to evaluate the sound transmission quality of auditorium, public address system and communication system. Attempts for objective evaluation of speech intelligibility began in the 1920s, and the first objective evaluation metric, the articulation index (AI) [1], that was developed into SII (speech intelligibility index) recently [2], was put forward subsequently in the 1940s to 1950s. At the end of the 1970s, other metrics, such as speech transmission index (STI) [3] and articulation loss of consonants (%ALcons) [4], were created. STI and SII are currently the two most commonly used objective evaluation metrics for speech intelligibility, corresponding to two current standards: IEC 60268-16 [5] and ANSI S3.5 [2], respectively.

There are many factors affecting STI and SII measurement results, and one of them is the characteristics of the sound source. For sound sources, directivity and frequency response are important characteristics that can influence the results of STI and SII measurements [6, 7, 8, 9]. In IEC 60268-16 [5], it is specified clearly that STI measurement shall be conducted using a sound source with directivity and radiation pattern similar to those of the average human mouth and an omnidirectional microphone, and there are also corresponding specifications for the frequency response of sound sources. In ANSI S3.5 [2], there is no clear specification for the directivity of the sound sources, and both directional sound sources and omnidirectional sound sources can be used. However, there are some specifications for the frequency response of the sound sources.

Bozzoli and Farina [6] conducted a study on the influence of the directivity of three artificial mouths on STI measurements in different acoustic environments. The study shows that the measurement of STI is not strongly influenced by the directivity of the artificial mouths, for room acoustics applications because of the substantial distance between speaker and receiver, and the presence of numerous reflections. However, in their study the influence of frequency response was not investigated. Another study conducted by Mapp [7] shows that equalisation can significantly affect the intelligibility. However, the study focuses particularly on the influence of sound system equalisation on speech intelligibility, and the influence of directivity was not investigated. Petra and Hongistob [8] compared the STI and SII measurement methods and suggested that loudspeakers possibly have a considerable influence on the STI and SII measurements. Peng et al. [9] evaluated subjective Chinese speech intelligibility using three sources with different directional patterns: an omnidirectional source, a source with directivity similar to a human speaker, and a human speaker in both real and virtual rooms with different reverberation times. The results show that speech intelligibility scores obtained using an omnidirectional source are lower than those obtained using the other two sources. However, the influence of frequency response was not considered. Overall, there is still a lack of study of the systematic and simultaneous influence of frequency response and directivity of sound sources on the intelligibility.

The aim of this study is therefore to systematically investigate the influence of sound source characteristics, including frequency response and directivity in determining objective speech intelligibility metrics. This paper starts with selecting three typical sound sources with different directivities and frequency responses; then the full STI of eight receiver positions, and a total of 32 sound environments in three rooms were measured. Finally, analyses of the results are presented.

2. Methods

2.1 Sound sources

In this study, three typical sound sources were used: (1) An artificial mouth GRAS 44AA with a directivity and radiation pattern similar to those of the average human mouth, which is the standard sound source for measuring STI recommended in IEC 60268-16 [5]; (2) a monitor loudspeaker GENELEC 8020B (cone diameter is 4 inch), which is the alternative sound source for measuring STI recommended in IEC 60268-16 [5]; and (3) a dodecahedral sound source B&K 4292L, which is one of the sound sources that can be used for measuring SII in ANSI S3.5 [2]. Although the three sound sources are recommended or allowed to be used in the standards, they are rather different in acoustic characteristics, having completely different frequency response and directivity patterns.

The relative amplitude in relation to 1000 Hz of the three sources was measured in an anechoic hamber using impulse responses. For the dodecahedral sound source 4292L, because there was no main radiation and the directivity changed with orientations, an average of the 20 frequency responses from the 20 measurement points with solid angles covering the measurement sphere based on ISO 3745 [10] was used as the equivalent frequency response. The results are shown in Figure 1. It can be seen that the frequency response of the monitor loudspeaker 8020B is the best of the three sound sources, and the response is almost flat in the entire frequency range, which also meet the specification in IEC 60268-16 [5] that "over the range 88 Hz to 11300 Hz, the 1/3 octave frequency response of the test signal source is within ±1 dB when measured in a free field" without frequency response equalisation. The frequency response of the artificial mouth 44AA is poor, which is strongest at 1000 Hz but decreases greatly at other frequencies, especially at 125 Hz and as the frequency exceeds 2000 Hz. The frequency response of the dodecahedral sound source 4292L is not good either, which is relatively strong at 125-250 Hz or so, but decreased as the frequency increases once the frequency exceeds 125 Hz.

The relative amplitude in relation to 1000 Hz of the artificial mouth 44AA and the dodecahedral sound source 4292L, after being equalised by inverse filtering of the frequency response, was measured in an anechoic chamber with the same layout for the artificial mouth 44AA and the layout rotating by 180° about the z-axis for the dodecahedral sound source 4292L, and the results are shown in Figure 2. It can be seen that the frequency responses for both the artificial mouth 44AA and the dodecahedral sound source 4292L are almost flat in the entire frequency range, both meet the specification in IEC 60268-16 [5].

In Figure 2, the inverse filters were generated from the sound source frequency response measured in an anechoic chamber by employing the Kirkeby method [11, 12]. For the dodecahedral sound source 4292L, the equivalent frequency response $\bar{H}(f)$ that was used to generate the inverse filter was the average of 20 frequency responses $H_n(f)$ from 20 measurement points with solid angles covering the measurement sphere, which was based on ISO 3745 [10]. $\bar{H}(f)$ can be calculated using Eq.(1):

$$\bar{H}(f) = \left|\bar{H}(f)\right| e^{j\angle\bar{H}(f)} \quad (1),$$

where $\left|\bar{H}(f)\right|$ is the equivalent amplitude response and $\angle\bar{H}(f)$ is the equivalent phrase response. The equivalent amplitude response $\left|\bar{H}(f)\right|$ can be calculated using Eq. (2):

$$\left|\bar{H}(f)\right| = \sqrt{\frac{1}{4\pi}\sum_{n=1}^{N}\Omega_n\left|H_n(f)\right|^2} \quad (2),$$

where $N = 20$ and $\Omega_n = \frac{\pi}{5}$ for equal solid angles ($n = 1$ to 20) in the measurement. The equivalent phrase response $\angle\bar{H}(f)$ can be calculated by integrating the energy-weighted average group delay $\bar{\tau}(f)$, which can be calculated using Eq. (3):

$$\bar{\tau}(f) = -\frac{\mathrm{d}\angle\bar{H}(f)}{2\pi\cdot\mathrm{d}f} = -\frac{1}{4\pi\left|\bar{H}(f)\right|^2}\sum_{n=1}^{N}\Omega_n\left|H_n(f)\right|^2\frac{\mathrm{d}\angle H_n(f)}{2\pi\cdot\mathrm{d}f} \quad (3),$$

where $\angle H_n(f)$ is the phrase response of the n-th solid angle. Using the method above, the equivalent frequency response $\bar{H}(f)$ for the dodecahedral sound source 4292L was obtained and then the inverse filter was generated. The 20 frequency responses measured without frequency response equalisation and after being equalised for the dodecahedral sound source 4292L are shown in Figure 3 and Figure 4. In each figure the relative amplitude is in relation to 1000 Hz of the average amplitude, and the black thick line is the average of the 20 frequency responses. The 20 frequency responses measured in Figure 4 using different solid angles are from those in Figure 3 by rotating by 180° about the z-axis. It can be observed that though great improvement was achieved after the frequency response equalisation was applied, the 20 frequency responses in Figure 4 are still not equal in the high frequency range. However, the average of the 20 frequency responses can meet the IEC 60268-16 [5] specification.

In Figure 5 the horizontal and vertical directivity patterns of the three sources at 250, 500, 1000, 2000, 4000, and 8000 Hz are shown, where the manufacturer provides the data for the monitor loudspeaker 8020B, the data for the dodecahedral sound source 4292L are based on the product description [13], and the data for the artificial mouth 44AA are obtained through measurements in this study in an anechoic chamber. The octave band directivity index (DI) for the three sources is also listed in Table 1.

Table1. The octave band DI for the three sound sources.

Frequency band (Hz)	125	250	500	1000	2000	4000	8000
B&K 4292L (dB)	0	0	0	0	0	0	0
GRAS 44AA (dB)	0.6	1.2	1.3	1.7	3.9	4.8	6.3
GENELEC 8020B (dB)	1.2	0.9	3.3	5.7	8.1	9.3	9.1

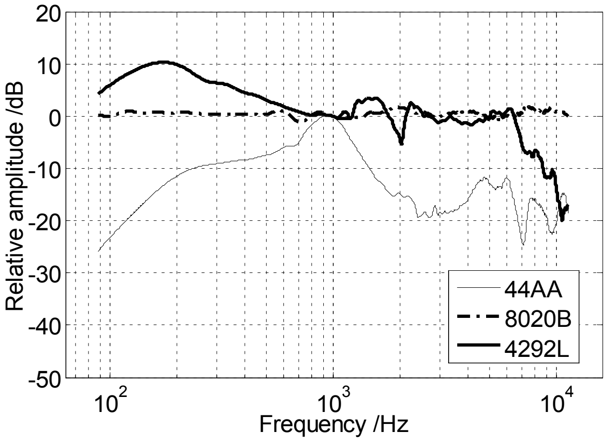


Fig. 1. The relative amplitude in relation to 1000 Hz of the three sound sources, measured in an anechoic chamber.

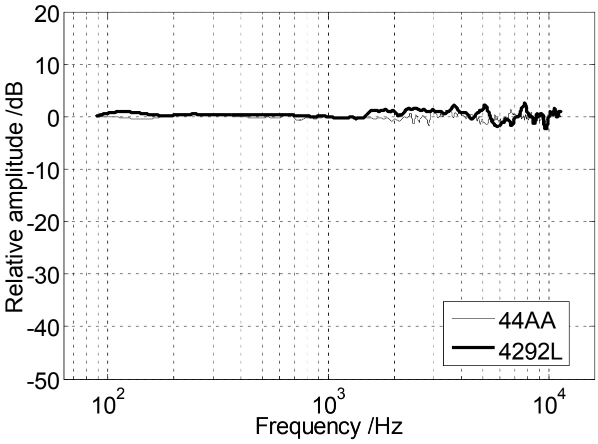


Fig. 2. The relative amplitude in relation to 1000 Hz of the artificial mouth 44AA and the dodecahedral sound source 4292L after being equalised by inverse filtering of the frequency response, measured in an anechoic chamber.

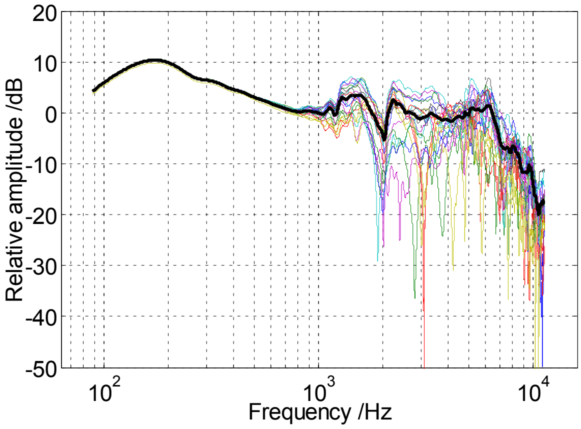


Fig. 3. The 20 frequency responses for the dodecahedral sound source 4292L measured without frequency response equalisation, and an average of the 20 frequency responses. The relative amplitude is in relation to 1000 Hz of the average amplitude. The thin lines indicate the 20 frequency responses, and the thick black line indicates an average of the 20 frequency responses.

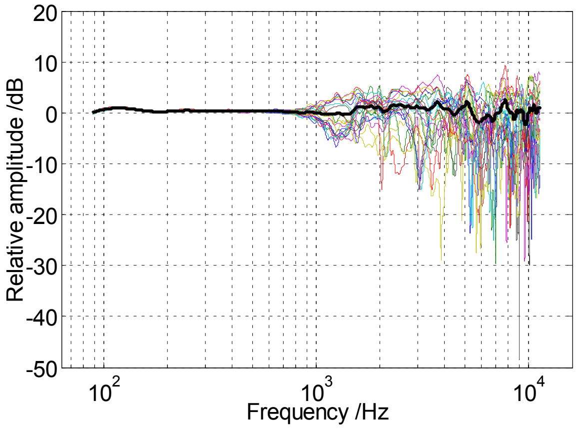
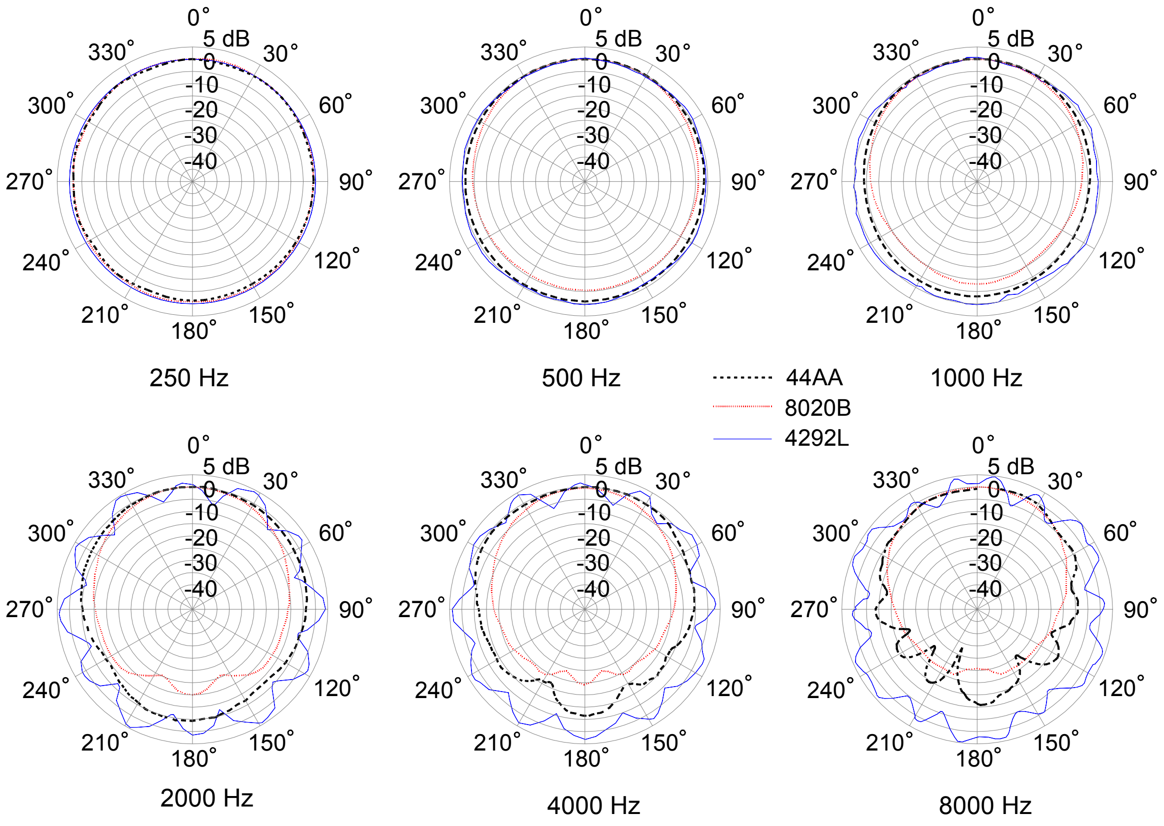
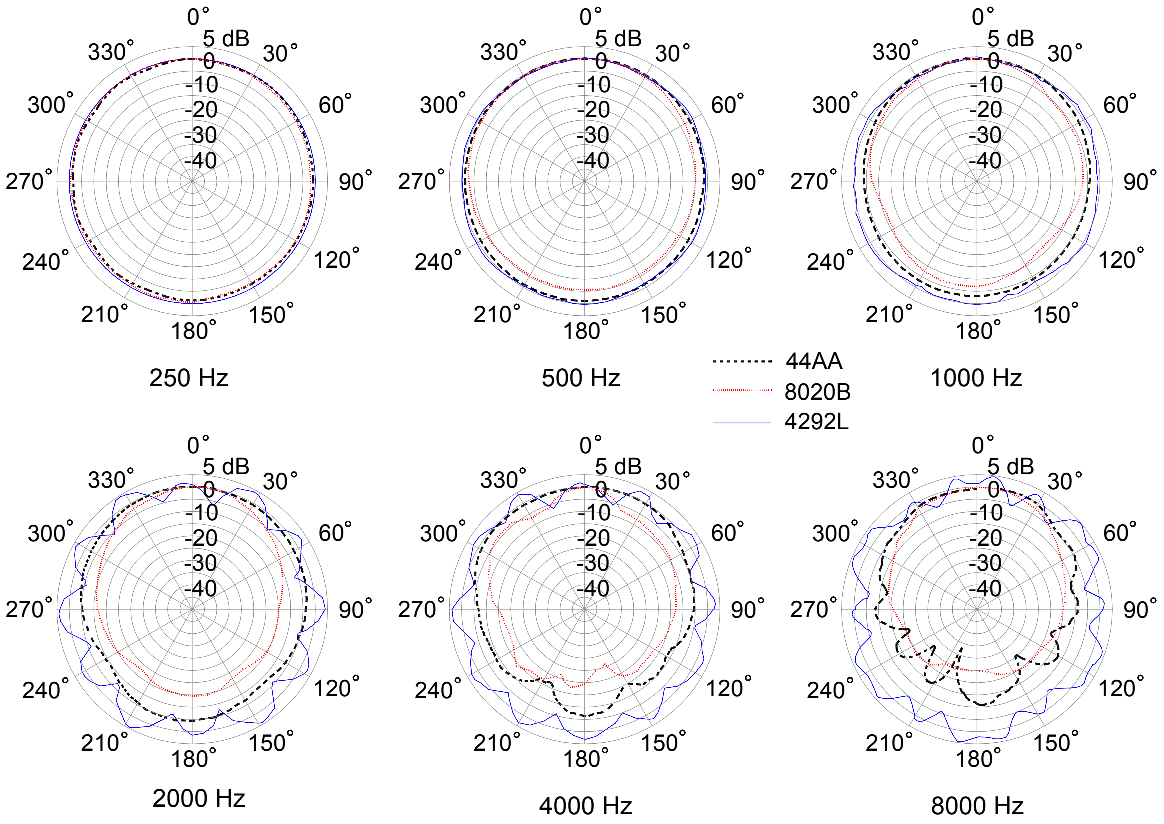


Fig. 4. The 20 frequency responses for the dodecahedral sound source 4292L measured after being equalised, and an average of the 20 frequency responses. The relative amplitude is in relation to 1000 Hz of the average amplitude. The thin lines indicate the 20 frequency responses, and the thick black line indicates an average of the 20 frequency responses.



(a) Horizontal directivity patterns of 44AA, 8020B and 4292L



(b) Vertical directivity patterns of 44AA, 8020B and 4292L

Fig. 5. Horizontal and vertical directivity patterns of the three sound sources.

2.2 Experimental arrangement

As two important objective measurement metrics of speech intelligibility, STI and SII have many things in common [8]. In view of the better representativeness of STI for speech intelligibility, only STI is measured in this study. Three rooms were used for measurement, an office, a lab and a multimedia lecture hall, and their characteristics, including the mean absorption coefficient $\bar{\alpha}$ for the three rooms are shown in Table 2, where the early decay time (*EDT*), reverberation time (T_{30}) and clarity (C_{50}) for the average of 500 Hz and 1000 Hz octave band are also shown with the source being the dodecahedral sound source 4292L. There are two receiver positions in the office, three receiver positions in the lab, three receiver positions in the multimedia lecture hall, and the layout of the receiver positions and the sound sources is shown in Figure 6. In the three rooms, the height of all of the receivers is 1.2 m, and the height of all of the sound sources is 1.5 m. In Figure 6, S_1 indicates the signal sound sources (including the artificial mouth 44AA, the monitor loudspeaker 8020B and the dodecahedral sound source 4292L), S_2 indicates a noise source, and R_1-R_8 are receiver positions.

To obtain a wide range of STI, a noise source (PYRITE dodecahedral sound source) was arranged at a distance of 0.5 m from the signal sources to reproduce interference noise at four different sound pressure levels (SPL) so that each receiver position in the three rooms would correspond to four different test environments. The noise source reproduces a males spectra [5] shaped pink noise. In accordance with IEC 60268-16 [5], the SPL at 1 m right ahead of the signal sound source (on the main radiation axis of the artificial mouth GRAS 44AA and the monitor loudspeaker GENELEC 8020B) was set at 60 dBA in an anechoic chamber. At the same time, the SPL of the noise source was adjusted to make the positions at 1 m away from the two sound sources correspond to four different relative background noise levels (RBNLs): 5 dB, 0 dB, -10 dB, and -20 dB (the SPL at 1 m right ahead of the PYRITE dodecahedral sound source was set as 65 dBA, 60 dBA, 50 dBA, and 40 dBA, respectively. The RBNL equals the SNR in a noiseless anechoic chamber; however, due to the influence of different reflections and perhaps environmental noise, the RBNL does not equal the actual SNR at the R_1-R_8 receiver positions). After that, the signal source and the noise source pre-set in the anechoic chamber were placed in the corresponding sound source positions in the test rooms, and during the measurement, the signal sound sources always pointed towards the receiver, the acoustic output microphone always pointed towards the signal sound sources, then measurements were performed at each receiver position in turn. There are two types of signal used for the artificial mouth 44AA and the dodecahedral sound source 4292L, one without frequency response equalisation and the other equalised according to the frequency response of the two sound sources. For the monitor loudspeaker 8020B, only signals without frequency response equalisation were used. The interference noise signal was equalised. The signal used for the SPL calibration of the three sound sources in an anechoic chamber was a compound signal of seven half octave-band carriers without frequency modulation including the male spectrum described in IEC 60268-16 [5]. The male spectrum described in IEC 60268-16 [5], the spectrum of the signal used for calibration, the spectrum of the reproduced calibration signal and noise signal recorded at 1 m in front of the three signal sources and the interference noise source with and without equalisation in an anechoic chamber, after the octave band levels are normalised to an A-weighted level of 0 dB, are shown in Table 3. Considering that the SPL for the dodecahedral sound source 4292L varies with the orientation, the SPL in Table 3 is an average of the three SPLs measured from three representative specific orientations, and the STI used for the dodecahedral sound source 4292L in this paper is also an average of the three STIs measured from the three specific orientations. Figure 7 shows the three specific representative orientations. In an anechoic chamber, the equalisation and calibration for the PYRITE dodecahedral sound source were simpler than 4292L. Only a fixed orientation was selected to be pointed towards the receiver, and this fixed orientation always pointed towards the receiver during STI measurements.

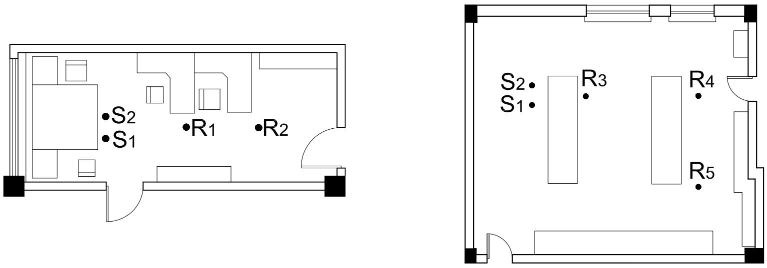
The STI values of the three sources were measured at eight receiver positions, considering that each receiver position will correspond to four different RBNLs, resulting in a total of 32 measuring conditions in the office, the lab and the multimedia lecture hall.

Table 2. Characteristics of the three test rooms.

Room Type	Capacity (m^3)	$\overline{\alpha}$	Receiver position	*EDT* (S)	T_{30} (S)	C_{50} (dB)
Office	108	0.14	R_1	0.61	0.63	3.82
			R_2	0.65	0.63	2.65
Lab	238	0.08	R_3	1.70	1.56	0.63
			R_4	1.51	1.59	-2.89
			R_5	1.48	1.59	-2.04
Multimedia lecture hall	1674	0.41	R_6	0.66	0.72	4.49
			R_7	0.72	0.71	4.13
			R_8	0.66	0.75	3.30

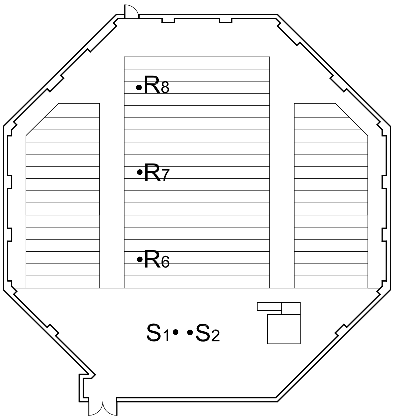
Table 3.The male spectrum described in IEC 60268-16 [5]; the spectrum of the compound signal used for calibration; the spectrum of the reproduced calibration signal and noise signal recorded at 1 m in front of the three signal sources and the interference noise source, with and without equalisation in an anechoic chamber. The octave band levels have been normalised to an A-weighted level of 0 dB.

Frequency band (Hz)	125	250	500	1000	2000	4000	8000	L_A
male spectrum in IEC 60268-16 (dB)	2.90	2.90	-0.80	-6.80	-12.80	-18.80	-24.80	0
Spectrum of the calibration signal (dB)	2.84	2.84	-0.86	-6.85	-12.85	-18.81	-24.83	0
Spectrum of the reproduced calibration signal for 8020B (dB)	3.07	2.75	-0.81	-7.21	-12.20	-18.39	-24.42	0
Spectrum of the reproduced calibration signal for 44AA (without equalisation) (dB)	-10.32	-0.76	-2.70	-2.12	-22.19	-27.81	-36.28	0
Spectrum of the reproduced calibration signal for 44AA (with equalisation) (dB)	3.11	2.62	-0.78	-6.81	-13.00	-18.39	-24.35	0
Spectrum of the reproduced calibration signal for 4292L (without equalisation) (dB)	7.25	5.67	-2.56	-11.84	-17.53	-23.36	-37.77	0
Spectrum of the reproduced calibration signal for 4292L (with equalisation) (dB)	3.30	2.83	-0.88	-7.23	-12.24	-17.97	-25.42	0
Spectrum of the reproduced noise signal for PYRITE (without equalisation) (dB)	7.11	5.66	-2.55	-11.19	-18.84	-23.83	-36.85	0
Spectrum of the reproduced noise signal for PYRITE (with equalisation) (dB)	3.20	2.63	-1.08	-6.57	-12.22	-17.98	-24.93	0



Office

Lab



Multimedia lecture hall

Fig. 6. Source and receiver locations in the office, the lab, and the multimedia lecture hall.

Ori. 1 Ori. 2 Ori. 3

Fig. 7. The three specific representative orientations of the dodecahedral sound source 4292L used for the measurement of STI.

2.3 Measurement of STI

There are two STI measurement methods recommended by IEC 60268-16 [5], namely a direct method based on signal modulation and an indirect method based on impulse response. The two methods use different ways to obtain the envelope of signals, but they are almost the same for later-stage data time-consuming, and the resulting data processing has relatively high requirements for the hardware. Most significantly, it is more difficult to measure full STI, though usually used in scientific research in accordance with the suggestion in IEC [5]. To reflect the authentic STI measurement method recommended by IEC 60268-16 [5], the full STI test signals and the computing programs of the direct measurement method were compiled in this study.

During measurement, there may be inaccuracies caused by the measurement system, such as inaccuracies in calibration of the SPL of the sound source, the generation of measuring signals and the later-stage processing. To reduce such inaccuracies, a standardised measurement system was used, and the measurement process followed the requirements strictly. The measurement systems used in this experiment include signal sources (GRAS 44AA, GENELEC 8020B and B&K 4292L), interference noise source PYRITE, power amplifier B&K 2734B (corresponding to B&K 4292L), power amplifier AMPHION (corresponding to PYRITE), and audio interface B&K ZE-0948, microphone B&K 4189 (power supply is B&K 1704), and sound recording software Audition 3.0. Loop calibration was performed for the entire system before measurement to make sure it is a linear time-invariant (LTI) system without harmonic distortions. All of the sound sources used in the experiment were calibrated in the anechoic chamber. The SPL of all of the signals being measured are controlled accurately at the beginning of signal generation by filtering.

The effectiveness of the measurement program is also the key to the reliability of the measurement results. A measurement signal whose modulation depth is 0.8 has been generated according to the standard, and it is processed (loop calibrated) directly as a received signal. After loop calibration, 98 modulation transmission values obtained will not be 0.8. There are many factors to consider. For example, the pink noise is a pseudo-random signal, filtering and modulation is required during signal generation, and filtering and envelope extraction are also required after the signal is received, which may cause loss of signals and result in inaccuracy. To evaluate these inaccuracies, a one-sample T test statistical method was used to check whether there is significant difference between the population mean of the 98 figures and the designated value of 0.8. It was shown that the p-value is 0.819, indicating that there is no significant variation. Ninety-eight modulation transmission values whose modulation depth is 0.8 and 98 modulation transmission values after passing the loop are also input into the program to calculate the STI simultaneously. The STI difference under the two conditions is only 0.001, far smaller than a JND (Just Noticeable Difference, which is approximately 0.03) [17]. This shows that the inaccuracy brought about by the measuring program is very small.

3. Results

This section first considers simultaneous influence of frequency response and directivity, and it then investigates the influence of directivity. The section subsequently examines the influence of frequency response equalisation. Appendix A lists the STI values at eight receiver positions, with a total of 32 sound environments for the three sound sources. Appendix B lists the operational speech level using test signals with and without frequency response equalisation for the three sound sources at eight receiver positions; it also lists the background noise levels under four RBNLs.

3.1 Simultaneous influence of frequency response and directivity

The STI values of the three sources without frequency response equalisation are shown in Figure 8. Under such conditions, both the directivity and the frequency response have an effect on the measurement results. The figure shows that the result of the artificial mouth 44AA is the lowest, except when the RBNL is -20 dB at receiver position R_3 and when the RBNL is 5 dB at receiver positions R_4 and R_5. The result of the monitor loudspeaker 8020B is the highest, except when the RBNL is 5 dB at receiver position R_4 and when the RBNL is 5 dB and 0 dB at receiver position R_5. The result of the dodecahedral sound source 4292L is in the middle, except when the RBNL is -20 dB at receiver position R_3 and when the RBNL is 5 dB and 0 dB at receiver position R_5. Corresponding to the four RBNLs, 5 dB, 0 dB, -10 dB, and -20 dB, the average STI differences between the dodecahedral sound source 4292L and the artificial mouth 44AA at eight receiver positions are 0.023, 0.057, 0.051, and 0.013, and the largest difference that is reached, 0.093, occurs when RBNL is -10 dB at receiver position R_5. The average STI differences between the dodecahedral sound source 4292L and the monitor loudspeaker 8020B of eight receiver positions are -0.021, -0.042, -0.058, and -0.063, and the largest difference reached is -0.125 when RBNL is -20 dB in receiver position R_6. The average STI differences between the monitor loudspeaker 8020B and the artificial mouth 44AA of eight receiver positions are 0.044, 0.098, 0.109, and 0.077, and the largest difference that is reached, 0.147, occurs when RBNL is -10 dB in receiver position R_6. The STI differences between different sources under four RBNLs at eight receiver positions are listed in Appendix C. These differences above are considerable, may reflect the simultaneous influence of directivity and the frequency response on the measurement results, and are consistent with Petra and

Hongistob's research [8] that loudspeakers may have a considerable influence, though their conclusion comes only through an inference based on measurement results, without accurate measurement and analysis. Our measured differences are also similar to Mapp's result [7], though the influence of directivity was not involved in his study, and are greater than Bozzoli and Farina's result [6]. However, in Bozzoli and Farina's study, the influence of frequency response was excluded by calibrating the three artificial mouths in an anechoic room to fit ITU recommendations [18].

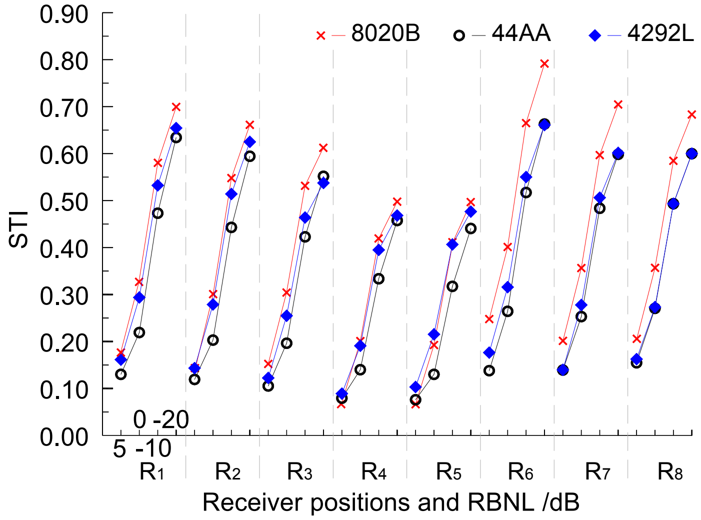


Fig. 8. STI of the three sound sources without frequency response equalisation(note: results are not compliant with the IEC standard due to missing source equalisation).

3.2 Influence of directivity

The STI values of the three sources, with frequency response equalisation, are shown in Figure 9. Under such conditions, the sound source can be deemed to only be subject to the influence of directivity. It can be observed from the figure that the result of the dodecahedral sound source 4292L with the small DI is the highest when RBNLs are 5 dB and 0 dB, and is the lowest when RBNL is decreased to -20 dB except at receiver positions R_5. The result of monitor loudspeaker 8020B with the large DI is the lowest when RBNLs are 5 dB and 0 dB, and when RBNL is decreased to -20 dB, it becomes the highest at receiver positions R_3, R_6, R_7 and R_8. The result of the artificial mouth 44AA with the middle DI is in the middle when RBNLs are 5 dB and 0 dB, and when RBNL is decreased to -20 dB, it is still in the middle at receiver positions R_3, R_5, R_6, R_7 and R_8. These results are reasonable because at the eight receiver positions, the received sound signals for the three sound sources are all composed of direct and reflected sound. As the three sound sources are calibrated in an anechoic chamber, and the SPL at 1 m right ahead of the three sound sources are exactly the same, the SPLs for the direct sound of the three sound sources at each receiver position should also be the same, while the SPLs from the reflected sound of the three sound sources at each receiver position are different due to the different sound source directivities. At a given receiver position, the sound energy for the reflected sound of the monitor loudspeaker 8020B with the large DI may be the lowest, and the dodecahedral sound source 4292L greatest, with the small DI. According to IEC 60268-16 [5], the modulation transfer function $m_k(f_m)$ can be calculated using Eq. (4):

$$m_k(f_m) = \frac{\left| \int_0^\infty h_k(t)^2 e^{-j2\pi f_m t}\, \mathrm{d}t \right|}{\int_0^\infty h_k(t)^2\, \mathrm{d}t} \cdot \left[1 + 10^{-SNR_k/10} \right]^{-1} \tag{4}$$

(4),

where k is the octave band; $h_k(t)$ is impulse response of octave band k; and f_m is the modulation frequency; SNR_k is the signal-to-noise ratio (SNR) in dB. The contribution of reflected sound to STI can be considered in two ways. Firstly, all the reflections measured can increase SNR, which will increase the STI correspondingly. However, when background noise is low, the influence of this SNR variation on

STI would be less significant, which means that when RBNL is decreased to -20 dB, the influence of the SNR variation from the extra sound energy of the dodecahedral sound source 4292L in comparison with that of the monitor loudspeaker 8020B or the artificial mouth 44AA on STI may be negligible. Secondly, when background noise is not taken into account, all the reflections measured can result in the reduction of the modulation depth, thus more reflections can change the pattern of early sound energy decay, which may result in more decrease of modulation depth of the test signal and thus decrease the STI. The interaction of these two aspects results in the results above, namely, when background noise is high, the SNR variation caused by the extra sound energy may influence STI more significantly, and thus, the result of the dodecahedral sound source 4292L with low DI is the highest when RBNLs are 5 dB and 0 dB. Conversely, when background noise is low, the influence from changing pattern of early sound energy decay would be more significant, and thus, the result of the dodecahedral sound source 4292L with low DI is the lowest as RBNL is decreased to -20 dB. There are similar tendencies for the monitor loudspeaker 8020B and the artificial mouth 44AA.

To further examine the tendency for the STI differences with the decrease of RBNL, the STI differences between the dodecahedral sound source 4292L and the monitor loudspeaker 8020B, between the dodecahedral sound source 4292L and the artificial mouth 44AA, and between the monitor loudspeaker 8020B and the artificial mouth 44AA for the eight receiver positions, are shown in Figure 10, Figure 11, and Figure 12, respectively. In Figure 10, It can be observed that corresponding to the four RBNLs, 5 dB, 0 dB, -10 dB, and -20 dB, the average STI differences between the dodecahedral sound source 4292L and the monitor loudspeaker 8020B of eight receiver positions are 0.082, 0.072, 0.015, and -0.029, respectively, decreasing with the decrease of RBNL, which reflects the interaction effect of the SNR variation and the changing pattern of early sound energy decay, and the greatest value, 0.123, appears when RBNL is 0 dB at receiver position R_5, larger than one JND. It can also be observed that at receiver position R_3 in the lab, and at R_6, R_7 and R_8 in the multimedia lecture hall, the STI difference between the dodecahedral sound source 4292L and the monitor loudspeaker 8020B is lower than that at receiver positions R_4 and R_5 in the lab, and R_1 and R_2 in the office. This suggests that the influence of sound source directivity may also depend on the room acoustic conditions, and at receiver position where reflections are abundant, the influence of the sound source directivity may be more significant, and the STI difference between the sound sources with different directivities may be greater. This tendency can also be seen in Figure 11, and Figure 12, although at R_3 in Figure 10 and Figure 11, where reflections are also abundant, this tendency is not strong due to the high direct sound energy and also the directivity characterises of the sound sources used for comparison.

In Figure 11, the average STI differences between the dodecahedral sound source 4292L and the artificial mouth 44AA of the eight receiver positions are 0.036, 0.029, -0.001, and -0.020, decreasing with the decrease of RBNL, which also reflects the interaction effect of the SNR variation and the changing pattern of early sound energy decay, and the greatest value, 0.068, appears when RBNL is 5 dB at R_5, larger than one JND. The STI difference between the dodecahedral sound source 4292L and the artificial mouth 44AA is not very high, as the STI used for the dodecahedral sound source 4292L is an average of three STIs measured using three specific orientations. The difference between the three STIs is significant, and the greatest value, 0.043, appears when RBNL is 5 dB at R_3, larger than one JND, suggesting that when dodecahedral sound source like the dodecahedral sound source 4292L is used as the test source for the measurement of STI or SII, the influence of orientations should not be ignored.

In Figure 12, the average STI differences between the monitor loudspeaker 8020B and the artificial mouth 44AA at the eight receiver positions are -0.046, -0.044, -0.015, and 0.009, increasing with the decrease of RBNL, which again reflects the interaction effect of the SNR variation and the changing pattern in early sound energy decay, and the greatest value, -0.065, occurs when RBNL is 5 dB at receiver position R_2, larger than a JND. This result suggests that when using a 4 inch cone diameter monitor loudspeaker like GENELEC 8020B as the test source for the measurement of STI or SII, the influence of the directivity should also be considered. This is different from the result of a previous study [6], where a smaller range of source directivity range was used. Also, due to the differences in room conditions, it is not necessary that a sound source with better directivity will have a higher intelligibility result when background noise is high, as suggested in another previous study [9].

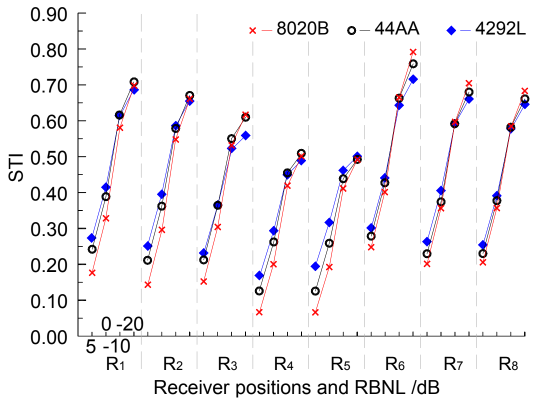


Fig. 9. STI of the three sound sources after frequency response equalisation.

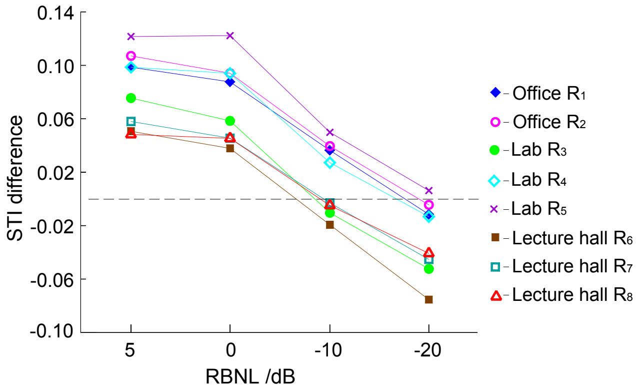


Fig. 10. The difference between STI measured using the dodecahedral sound source 4292L and the monitor loudspeaker 8020B with different RBNL.

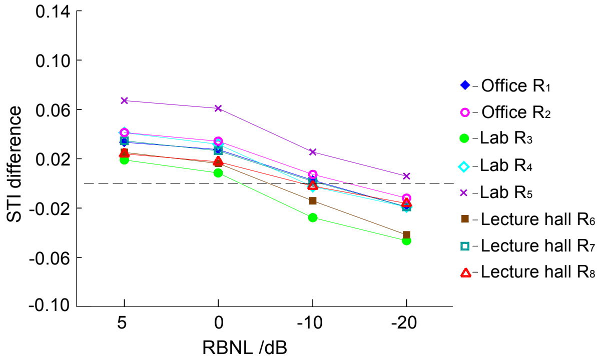


Fig. 11. The difference between STI measured using the dodecahedral sound source 4292L and the artificial mouth 44AA with different RBNL.

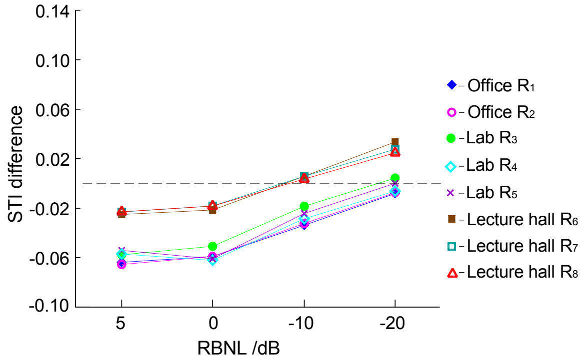


Fig. 12. The difference between STI measured using the monitor loudspeaker 8020B and the artificial mouth 44AA with different RBNL.

3.3 Influence of frequency response equalisation

The STI for the artificial mouth 44AA and the dodecahedral sound source 4292L, with and without frequency response equalisation, are compared in Figure 13. It can be observed that all of the differences are greater than zero, the artificial mouth 44AA has clear improvement after the frequency response equalisation is applied, and the greatest value, 0.172, appears when the RBNL is 0 dB at the receiver position R_1. As a JND is only 0.03 or so, this finding indicates that the artificial mouth cannot be used without a frequency response equalisation, although the artificial mouth is not designed to be the sound source for building acoustic measurements, and its frequency response should include a specific speech spectrum. However, it is not precise to use such a spectrum for accurate STI measurement. The dodecahedral sound source 4292L clearly improves after frequency response equalisation is applied, and the greatest value, 0.124, which exceeded a JND, appears when the RBNL is 0 dB at receiver position R_6. This finding indicates that the dodecahedral sound source 4292L cannot be used without frequency response equalisation. Figure 13 also shows that, for the two sound sources, all maximum STI improvement occurs when the RBNL is 0 dB, and all minimum STI improvement occurs when the RBNL is -20 dB. When the background noise is very high or very low, the influence of SNR variation on the STI will be less significant, while when the SNR is relatively low, the influence of SNR variation on the STI will be clear (the maximum influence will appear when the SNR is 0 dB, which can be derived based on Eq. (4)). In addition, for the two sources, as equalisation-induced SNR variations at each octave band are different, their influences on the STI will be different, even though the overall SNR variation is equal. Moreover, equalisation-induced SNR variations at different receiver positions will still be different due to different reflections, even though the RBNL is equal. These factors will also influence the actual improvement result. For the monitor loudspeaker 8020B, there is no need to perform such a frequency response equalisation. Overall, the results show that the influence of the frequency response equalisation on the sound sources depends on the original frequency response characteristics of the sources.

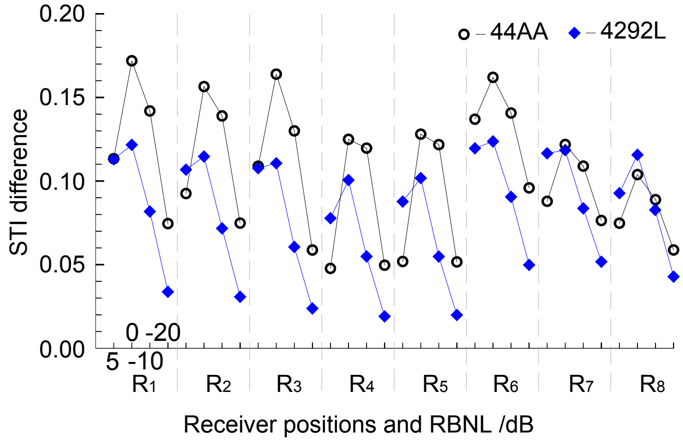


Fig. 13. STI difference between with and without frequency response equalisation of the artificial mouth 44AA and the dodecahedral sound source 4292L.

4. Conclusions

Sound source characteristics may be one of the main causes of objective speech intelligibility metric inaccuracy. In this study, the influences of sound source directivity and frequency response were investigated using three typical sound sources: an artificial mouth, a monitor speaker, and a dodecahedral sound source. It has been revealed that:

1) The simultaneous influences of directivity and the frequency response of the three sound sources are significant: the STI difference between the sound source 4292L and the artificial mouth 44AA reached 0.093, the STI difference between the dodecahedral sound source 4292L and the monitor loudspeaker 8020B reached -0.125, and the STI difference between the monitor loudspeaker 8020B and the artificial mouth 44AA reached 0.147.

2) Sound source directivity may cause noticeable differences in the objective speech intelligibility metric. The STI measured using the dodecahedral sound source 4292L with the small DI is the highest when background noise is high, and may be the lowest when background noise is low; the STI measured using the monitor loudspeaker 8020B with the large DI is the lowest when background noise is high, and may be the highest when background noise is low. The STI difference between them, caused by the sound source directivity, is up to 0.123. The STI difference caused by the sound source directivity between the monitor loudspeaker 8020B and the artificial mouth 44AA is also obvious, and the STI difference between them, is up to -0.065. The influence of sound source directivity may also depend on the room acoustic conditions, and at the receiver position where reflections are abundant, the influence of the sound source directivity may be more significant.

3) Not applying frequency response equalisation resulted in large errors in the values being measured, which deviate from the real values of STI by up to 0.172, depending on the original frequency response characteristics of the sound source. Considering the significant influence of frequency response, careful equalisation of the sound source is always required when performing a STI test according to IEC 60268-16 [5].

Acknowledgements

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Appendix A. STI values at eight receiver positions, with a total of 32 sound environments for the three sound sources, using test signals without frequency response equalisation and after equalised according to the frequency response of the sound sources. Ori. 1, Ori. 2, and Ori. 3 are the three specific representative orientations for the dodecahedral sound source 4292L.

Receiver position	RNBL (dB)	Without equalisation						With equalisation				
		44AA	8020B	4292L				44AA	4292L			
				Ori. 1	Ori. 2	Ori. 3	Average		Ori. 1	Ori. 2	Ori. 3	Average
R$_1$	5	0.130	0.180	0.178	0.157	0.156	0.164	0.244	0.297	0.265	0.271	0.278
	0	0.219	0.332	0.315	0.288	0.289	0.297	0.391	0.437	0.406	0.413	0.419
	-10	0.473	0.581	0.555	0.524	0.530	0.536	0.615	0.633	0.605	0.615	0.618
	-20	0.634	0.701	0.671	0.643	0.653	0.656	0.709	0.703	0.678	0.690	0.690
R$_2$	5	0.119	0.147	0.159	0.142	0.139	0.147	0.212	0.267	0.244	0.250	0.254
	0	0.204	0.302	0.295	0.274	0.275	0.281	0.361	0.408	0.386	0.393	0.396
	-10	0.443	0.550	0.527	0.512	0.515	0.518	0.582	0.598	0.583	0.590	0.590
	-20	0.595	0.663	0.633	0.623	0.629	0.628	0.670	0.664	0.654	0.660	0.659
R$_3$	5	0.105	0.157	0.156	0.104	0.117	0.126	0.214	0.269	0.208	0.226	0.234
	0	0.196	0.310	0.292	0.233	0.250	0.258	0.360	0.403	0.343	0.361	0.369
	-10	0.423	0.535	0.499	0.438	0.458	0.465	0.553	0.556	0.502	0.519	0.526
	-20	0.552	0.616	0.572	0.516	0.536	0.541	0.611	0.594	0.542	0.559	0.565
R$_4$	5	0.081	0.072	0.096	0.091	0.092	0.093	0.129	0.175	0.164	0.175	0.171
	0	0.140	0.203	0.199	0.193	0.195	0.196	0.265	0.303	0.291	0.297	0.297
	-10	0.334	0.425	0.402	0.393	0.396	0.397	0.454	0.457	0.448	0.452	0.452
	-20	0.460	0.504	0.477	0.469	0.471	0.472	0.510	0.495	0.487	0.491	0.491
R$_5$	5	0.076	0.074	0.107	0.114	0.104	0.108	0.128	0.189	0.204	0.194	0.196
	0	0.131	0.198	0.215	0.228	0.214	0.219	0.259	0.314	0.330	0.320	0.321
	-10	0.319	0.417	0.408	0.420	0.407	0.412	0.441	0.461	0.474	0.466	0.467
	-20	0.442	0.494	0.477	0.488	0.477	0.481	0.494	0.496	0.507	0.500	0.501
R$_6$	5	0.140	0.252	0.199	0.183	0.168	0.183	0.277	0.320	0.292	0.296	0.303
	0	0.266	0.407	0.337	0.316	0.309	0.321	0.428	0.463	0.433	0.440	0.445
	-10	0.519	0.666	0.575	0.543	0.550	0.556	0.660	0.666	0.628	0.646	0.647
	-20	0.663	0.793	0.689	0.648	0.666	0.668	0.759	0.737	0.695	0.721	0.718
R$_7$	5	0.141	0.206	0.141	0.144	0.155	0.147	0.229	0.257	0.262	0.272	0.264
	0	0.255	0.359	0.280	0.281	0.295	0.285	0.377	0.398	0.402	0.413	0.404
	-10	0.485	0.600	0.509	0.505	0.523	0.512	0.594	0.592	0.591	0.605	0.596
	-20	0.601	0.706	0.607	0.598	0.618	0.608	0.678	0.658	0.654	0.669	0.660
R$_8$	5	0.157	0.209	0.155	0.179	0.155	0.163	0.232	0.243	0.272	0.252	0.256
	0	0.273	0.359	0.269	0.296	0.271	0.279	0.377	0.384	0.411	0.391	0.395
	-10	0.495	0.588	0.492	0.513	0.493	0.499	0.584	0.574	0.594	0.579	0.582
	-20	0.602	0.686	0.597	0.611	0.597	0.602	0.661	0.639	0.653	0.642	0.645

Appendix B. The three sound sources' operational speech levels using test signals with and without frequency response equalisation and the background noise levels under four RBNLs at eight receiver positions. Ori. 1, Ori. 2, and Ori. 3 are the three specific representative orientations for the dodecahedral sound source 4292L.

Receiver position	Frequency bands (Hz)			125	250	500	1000	2000	4000	8000	L_A
R_1	Operational speech level without equalisation (dB)	44AA		50.34	61.57	60.31	60.38	39.70	32.26	22.47	62.60
		8020B		63.21	64.24	60.52	53.50	47.22	38.37	32.36	61.01
		4292L	Ori. 1	67.61	69.31	61.80	51.77	47.54	39.58	25.24	63.58
			Ori. 2	67.77	69.47	61.75	51.30	47.13	38.16	22.69	63.61
			Ori. 3	67.8	69.49	61.71	51.61	46.48	38.32	23.1	63.61
	Operational speech level with equalisation (dB)	44AA		63.69	65.16	62.64	55.63	48.99	42.19	33.95	62.75
		4292L	Ori. 1	63.32	66.17	62.78	55.79	52.27	44.96	36.88	63.38
			Ori. 2	63.38	66.14	62.86	55.59	51.92	43.58	34.18	63.31
			Ori. 3	63.47	66.24	62.74	55.81	51.91	43.64	34.33	63.33
	Background noise level (dB)	RBNL (5dB)		68.55	71.10	67.09	60.43	55.93	48.94	41.19	67.88
		RBNL (0dB)		63.56	66.15	62.14	55.55	51.04	44.03	36.34	62.95
		RBNL (-10dB)		53.67	56.21	52.11	45.70	41.06	34.05	26.61	52.99
		RBNL (-20dB)		44.10	46.31	42.19	35.73	31.34	24.72	18.01	43.11
R_2	Operational speech level without equalisation (dB)	44AA		48.92	59.98	57.91	58.18	38.02	30.16	21.11	60.42
		8020B		60.99	62.83	58.26	50.75	45.33	37.02	29.83	58.96
		4292L	Ori. 1	65.86	66.87	58.44	50.98	47.27	37.09	22.16	61.15
			Ori. 2	65.79	67.02	58.53	51.23	45.12	37.35	22.64	61.18
			Ori. 3	65.76	66.89	58.43	51.21	45.42	36.27	22.29	61.09
	Operational speech level with equalisation (dB)	44AA		61.17	63.51	59.94	53.99	47.15	40.19	31.93	60.60
		4292L	Ori. 1	61.14	63.81	59.82	55.08	51.68	42.53	33.23	61.35
			Ori. 2	61.08	63.81	59.83	55.20	49.29	42.83	33.41	61.12
			Ori. 3	61.07	63.84	59.71	55.33	50.19	41.73	33.33	61.19
	Background noise level (dB)	RBNL (5dB)		69.14	69.69	64.68	59.17	55.08	47.04	39.11	66.25
		RBNL (0dB)		64.09	64.67	59.66	54.06	50.13	42.13	34.19	61.22
		RBNL (-10dB)		54.12	54.70	49.68	44.13	40.22	32.15	24.50	51.26
		RBNL (-20dB)		44.19	44.64	39.74	34.31	30.46	22.97	16.36	41.35
R_3	Operational speech level without equalisation (dB)	44AA		52.16	63.25	58.88	61.46	40.28	32.25	23.27	63.18
		8020B		66.23	66.42	58.99	54.80	47.59	38.73	32.46	61.69
		4292L	Ori. 1	70.56	69.91	60.01	53.66	49.32	39.57	25.56	63.92
			Ori. 2	70.63	69.96	59.83	53.39	47.25	37.71	22.81	63.82
			Ori. 3	70.54	70.15	60.05	53.67	47.48	38.54	23.51	63.99
	Operational speech level with equalisation (dB)	44AA		66.77	66.87	60.91	57.04	48.91	42.71	34.59	63.04
		4292L	Ori. 1	66.61	66.75	61.30	57.84	53.62	44.93	36.95	63.74
			Ori. 2	66.71	66.73	61.14	57.58	52.09	43.00	33.82	63.43

			Ori. 3	66.66	66.77	61.25	57.74	52.20	43.97	34.42	63.53
	Background noise level (dB)	RBNL (5dB)		73.62	71.31	67.73	62.06	56.29	48.26	40.76	68.77
		RBNL (0dB)		68.77	66.20	62.67	57.09	51.25	43.24	35.86	63.74
		RBNL (-10dB)		58.70	56.22	52.72	47.15	41.35	33.35	26.11	53.78
		RBNL (-20dB)		48.89	46.36	42.92	37.39	31.61	23.84	17.56	43.98
R4	Operational speech level without equalisation (dB)	44AA		46.20	59.68	58.27	58.50	37.53	29.19	19.20	60.67
		8020B		60.06	63.19	58.78	51.51	43.89	36.27	27.15	59.31
		4292L	Ori. 1	63.76	66.93	60.71	50.29	45.88	36.89	20.70	61.66
			Ori. 2	63.95	67.02	60.83	50.09	45.74	36.19	20.35	61.74
			Ori. 3	63.79	66.88	60.81	49.99	45.68	36.61	21.29	61.65
	Operational speech level with equalisation (dB)	44AA		60.10	63.79	60.98	53.50	46.92	38.96	29.15	60.99
		4292L	Ori. 1	59.87	63.40	62.03	54.38	50.54	42.46	31.60	61.87
			Ori. 2	59.88	63.63	61.98	54.17	50.33	41.43	31.12	61.82
			Ori. 3	59.91	63.35	61.98	54.05	50.29	42.16	32.26	61.75
	Background noise level (dB)	RBNL (5dB)		68.38	69.37	66.59	59.95	55.14	47.18	38.21	67.02
		RBNL (0dB)		63.40	64.34	61.58	54.97	50.38	42.21	33.24	62.04
		RBNL (-10dB)		53.35	54.34	51.58	44.97	40.40	32.27	23.60	52.04
		RBNL (-20dB)		43.57	44.30	41.60	35.05	30.51	22.74	15.80	42.08
R5	Operational speech level without equalisation (dB)	44AA		50.41	58.60	57.87	57.59	37.61	28.67	19.13	59.91
		8020B		63.28	61.31	58.13	50.76	44.01	35.20	26.72	58.50
		4292L	Ori. 1	67.78	66.36	59.90	51.20	45.82	36.55	20.25	61.46
			Ori. 2	67.78	66.57	60.11	51.19	46.17	36.82	20.92	61.63
			Ori. 3	67.80	66.57	60.13	50.93	45.39	36.54	20.52	61.59
	Operational speech level with equalisation (dB)	44AA		63.48	62.05	60.01	53.13	46.71	39.14	28.52	60.15
		4292L	Ori. 1	63.38	63.13	60.99	55.32	50.26	42.12	31.04	61.59
			Ori. 2	63.29	63.20	61.21	55.38	50.76	42.30	31.80	61.76
			Ori. 3	63.41	63.20	61.39	55.12	50.38	41.90	31.41	61.74
	Background noise level (dB)	RBNL (5dB)		68.86	68.87	65.59	59.10	55.02	46.85	37.70	66.32
		RBNL (0dB)		63.85	63.87	60.62	54.15	50.06	41.90	32.76	61.35
		RBNL (-10dB)		53.87	53.80	50.64	44.19	40.07	31.97	23.17	51.35
		RBNL (-20dB)		43.95	43.99	40.72	34.47	30.34	22.49	15.50	41.53
R6	Operational speech level without equalisation (dB)	44AA		44.39	52.52	49.14	49.37	29.83	22.55	17.72	51.84
		8020B		57.17	55.86	50.82	43.49	39.09	31.12	25.87	52.01
		4292L	Ori. 1	61.27	59.46	50.61	41.82	36.93	30.06	16.08	53.67
			Ori. 2	61.32	59.54	50.74	41.40	37.78	28.29	14.61	53.74
			Ori. 3	61.11	59.52	50.73	41.55	35.59	28.39	16.52	53.65
	Operational speech level with equalisation (dB)	44AA		56.86	55.96	51.43	44.71	38.96	32.30	26.46	52.44
		4292L	Ori. 1	56.82	56.38	51.58	46.01	42.00	35.47	26.57	53.15
			Ori. 2	56.87	56.44	51.73	45.53	42.37	33.67	25.15	53.14

			Ori. 3	56.70	56.46	51.78	45.77	40.48	33.87	27.22	53.03
	Background noise level (dB)	RBNL (5dB)		61.34	59.20	56.31	50.09	44.23	40.09	32.59	57.03
		RBNL (0dB)		56.30	54.14	51.30	45.13	39.29	35.14	27.75	52.03
		RBNL (-10dB)		46.52	44.19	41.28	35.18	29.51	25.35	18.61	42.08
		RBNL (-20dB)		37.48	34.62	31.49	25.46	20.48	16.64	12.94	32.54
R_7	Operational speech level without equalisation (dB)	44AA		43.89	49.02	44.98	45.39	25.81	18.87	16.31	47.92
		8020B		58.02	52.40	46.35	39.51	34.25	25.69	19.71	48.65
		4292L	Ori. 1	62.36	56.22	46.64	37.79	31.29	23.60	11.40	51.15
			Ori. 2	62.46	56.23	46.76	37.47	32.32	23.48	11.78	51.21
			Ori. 3	61.92	56.21	46.62	37.89	32.90	23.18	11.55	51.03
	Operational speech level with equalisation (dB)	44AA		58.03	52.51	47.14	41.03	34.47	26.61	19.35	49.14
		4292L	Ori. 1	58.33	53.29	47.73	42.01	36.00	29.01	21.14	49.86
			Ori. 2	58.41	53.22	47.84	41.57	37.24	28.88	21.63	49.89
			Ori. 3	57.92	53.30	47.72	42.07	37.35	28.60	21.54	49.89
	Background noise level (dB)	RBNL (5dB)		62.89	57.53	52.89	46.22	41.68	34.28	26.69	54.54
		RBNL (0dB)		57.98	52.56	47.91	41.21	36.78	29.36	21.99	49.57
		RBNL (-10dB)		48.00	42.61	37.96	31.34	26.97	19.98	14.56	39.66
		RBNL (-20dB)		38.56	32.84	28.17	21.88	18.56	13.50	11.85	30.22
R_8	Operational speech level without equalisation (dB)	44AA		41.94	49.93	43.35	45.15	25.69	18.31	16.18	47.61
		8020B		53.97	52.89	44.25	38.58	34.24	23.83	17.62	47.54
		4292L	Ori. 1	58.04	57.15	47.72	35.49	29.63	20.37	9.69	50.81
			Ori. 2	58.01	57.19	47.85	35.73	31.96	20.60	9.77	50.90
			Ori. 3	58.12	57.02	47.82	35.89	29.68	19.93	9.91	50.78
	Operational speech level with equalisation (dB)	44AA		53.71	53.32	45.66	40.56	33.96	24.18	17.21	48.33
		4292L	Ori. 1	53.56	54.45	48.53	39.57	34.44	25.73	18.70	49.61
			Ori. 2	53.52	54.37	48.68	39.86	36.89	25.86	18.46	49.79
			Ori. 3	53.51	54.33	48.64	39.96	35.19	25.26	18.95	49.67
	Background noise level (dB)	RBNL (5dB)		57.65	56.36	52.3	45.39	41.33	31.63	24.07	53.22
		RBNL (0dB)		52.73	51.35	47.32	40.39	36.37	26.8	19.55	48.24
		RBNL (-10dB)		42.96	41.45	37.38	30.51	26.61	17.76	13.32	38.36
		RBNL (-20dB)		34.99	32.14	27.7	21.19	18.13	12.87	11.63	29.27

Appendix C. The STI differences (in Section 3.1) of different sources at eight receiver positions under different RNBLs, without frequency response equalisation.

Receiver position	RNBL (dB)	STI difference		
		4292L−44AA	4292L−8020B	8020B−44AA
R_1	5	0.034	-0.016	0.050
	0	0.078	-0.035	0.113
	-10	0.063	-0.045	0.108
	-20	0.022	-0.045	0.067
R_2	5	0.028	0.000	0.028
	0	0.077	-0.021	0.098
	-10	0.075	-0.032	0.107
	-20	0.033	-0.035	0.068
R_3	5	0.021	-0.031	0.052
	0	0.062	-0.052	0.114
	-10	0.042	-0.070	0.112
	-20	-0.011	-0.075	0.064
R_4	5	0.012	0.021	-0.009
	0	0.056	-0.007	0.063
	-10	0.063	-0.028	0.091
	-20	0.012	-0.032	0.044
R_5	5	0.032	0.034	-0.002
	0	0.088	0.021	0.067
	-10	0.093	-0.005	0.098
	-20	0.039	-0.013	0.052
R_6	5	0.043	-0.069	0.112
	0	0.055	-0.086	0.141
	-10	0.037	-0.110	0.147
	-20	0.005	-0.125	0.130
R_7	5	0.006	-0.059	0.065
	0	0.030	-0.074	0.104
	-10	0.027	-0.088	0.115
	-20	0.007	-0.098	0.105
R_8	5	0.006	-0.046	0.052
	0	0.006	-0.08	0.086
	-10	0.004	-0.089	0.093
	-20	0.000	-0.084	0.084