INTL JOURNAL OF ELECTRONICS AND TELECOMMUNICATIONS, 2024, VOL. 70, NO. 3, PP. 609-614
Manuscript received June 17, 2024; revised July, 2024. doi: 10.24425/ijet.2024.149586

Crowd noise spectra for the calculation of the speech transmission index for public address systems

Paweł Dziechciński

***Abstract*—Knowledge of interfering noise is necessary for the correct design of a public address system. Noise sound levels can be obtained, for example, from BS 5389-1. It is more difficult to acquire knowledge of the interfering noise spectra, and the spectrum is also important for calculating speech intelligibility. As shown in the paper, for crowd noise, it is possible to determine the spectrum by pairing the level of noise to the speech spectrum for appropriate vocal effort. The error in determining the speech transmission index for public address systems for such selected noise spectra, relative to values for measurement-acquired noise spectra, is acceptable.**

***Keywords*—speech transmission index; STIPA; public address system; interfering noise; noise spectra**

I. Introduction

ONE of the basic factors that affect speech intelligibility is the signal-to-noise ratio (*SNR*). The speech transmission index for public address systems (STIPA) [1], which is currently a commonly used method for the objective evaluation of speech intelligibility in sound systems in Europe, requires the calculation of the *SNR* (and thus knowledge of the spectrum of noise) in the 1/1 octave bands from 125 Hz to 8 kHz. Obtaining this knowledge for existing buildings is possible, for example, by taking measurements. In the case of non-existent or unused buildings, it is possible to obtain data on the basis of similar buildings [2]. In design practise, knowledge of interfering noise is obtained from the literature or predicted. Interfering sound levels can be obtained, for example, from the standard BS 5389-1 [3] on voice alarm systems (VAS). It is more difficult to obtain knowledge about the spectrum of interfering noise. Problems with obtaining such data mean that the spectral aspect of interference is often omitted during design, and, as presented in the paper, the spectrum can be important for speech intelligibility.

In previous work, the author has used mostly the spectrum of pink noise and the long-term male speech spectrum as two extreme cases of interfering noise spectra in public address (PA) systems [4],[5]. However, the differences between the STI values for these cases can be relatively large. In order to properly select the interfering noise spectrum, it is necessary to know its source. One of the most common sources of interfering noise in PA systems is crowd noise. Assuming that the main source of this noise is the human voice, speech intelligibility can therefore be analysed using the long-term speech spectrum as the interfering noise spectrum. This type of interfering noise was considered by French and Steinberg [6], Houtgast and Steeneken [7], or Brachmanski [8]. However, these studies mostly assumed that the spectrum would refer to interfering noise levels typical of direct speech communication. The levels of crowd noise, depending on the public spaces in which they occur, can vary widely. For example, in the case of libraries or classrooms, they can be L_{Aeq} values of 60 dB or less [9],[10], and in the case of noisy sports facilities, they can be greater than 100 dB [11]. With such a wide range of levels, speech intelligibility analyses performed for a long-term speech spectrum of normal vocal effort can lead to an overestimation of the STI values obtained.

The primary goal of the work is to check if it is possible to replace the crowd noise spectrum with a normalized speech signal spectrum to determine the interfering noise spectrum needed for the STIPA calculation. Intuitively, this seems possible if a typical range of noise levels is divided into intervals to which the spectra of the relevant vocal efforts will be assigned. The STIPA values obtained for these representative spectra should be as close as possible, but not greater than for real crowd noise (it is especially important for system designers). The use of white, pink [8] and brown noise [12] is also common in speech intelligibility analyses. For comparison, the paper also shows the effect on STIPA of interfering noise with the coloured noise spectra. The paper does not discuss the problem of modelling the level of crowd noise. Such an overview can be found, for example, in the work of Liu, Ma, and Kang [13].

II. Research design

As will be shown in the paper, the similarity of the normalised and measured interfering noise spectra does not always translate into similar *STIPA* results obtained in both cases. Therefore, the similarity measures of *STIPA*(*SNR*) vectors discussed in this paper were used to evaluate the normalised spectrum. The statistical method from IEC 60168-16 [1] was used to calculate STIPA. The effect of the interfering noise spectrum on STIPA was evaluated by determining the characteristics of *STIPA* as a function of SNR_A defined as:

$$SNR_A = L_{Aeq,s} - L_{Aeq,n} \quad (1)$$

where $L_{Aeq,s}$ is the A-weighted equivalent continuous sound level of speech and $L_{Aeq,n}$ of interfering noise.

According to this algorithm, the changes in *STIPA*(SNR_A) will be the greatest for the reverberation time $T = 0$ s [1],[4]. In this case, the modulation transfer index m_k in the k-th 1/1 octave band depends only on the signal-to-noise ratio in that band SNR_k, while it is independent of the modulation frequency, source-receiver distance and the directional properties of the loudspeaker and is described by (2):

Paweł Dziechciński is with Wrocław University of Science and Technology, (e-mail: pawel.dziechcinski@pwr.edu.pl).

$$m_k = \frac{1}{1+10^{-SNR_k/10}} \quad (2)$$

As reference noise spectra, standardised spectra for individual vocal efforts were used, or in their absence, spectra well documented in the literature. Vocal efforts are typically classified in 6 dB steps. The typical range of speech levels $L_{S,A,1m}$ (A-weighted speech levels at 1 m distance in front of the mouth) [14] is 36-96 dB, giving 11 categories of vocal effort [15]. Treating speech as a source of interfering noise in the design of typical sound systems, this range can be limited to levels of 54-84 dB, corresponding to vocal efforts from “relaxed” to “shouted” [14],[16]. In this paper range of levels is limited to vocal efforts for which 1/1 octave bands spectra are available in standards or literature. Such spectra have been described in a number of publications [17],[18], including languages other than English [19], including Polish speech [20],[21]. Standardised spectra were used wherever possible. For normal vocal effort, these include the spectra used for STI measurements - for male speech from IEC 60268-16:2020 [1], female speech from ISO 9921 [14], unisex from ISO 3382-3 [22], BB93 [23] based on ANSI 3.5 [16] and ITU-T P.50 [24]. For Polish speech, spectrum of the paper of Majewski, Rothman and Holien was used [21].

For higher vocal efforts, such spectra are described in ANSI 3.5. In this study, they were extended to include the 1/1 octave band of 125 Hz by reducing the values from the 250 Hz band by 6 dB (according to BB93 and ISO 3382-3). The “relaxed” vocal effort is defined in ISO 9921 as an $L_{S,A,1m}$ = 54 dB, but it does not define a spectrum for this. Consequently, the spectrum for vocal effort “relaxed” was chosen from the spectra of vocal efforts defined as “casual” in Pearsons, Bennett, Fidell [16], and “hushed” in Cushing, Cox, Worrall Jackson [18]. The spectra of the reference noises are shown in Fig. 1, Fig. 2, Table I and Table II.

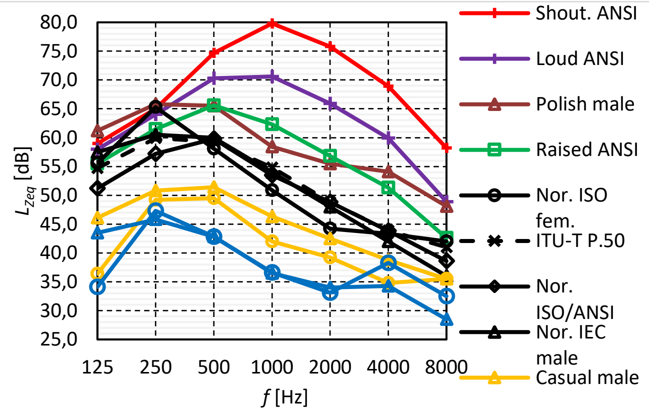

Fig. 1. Speech spectra for different vocal efforts.

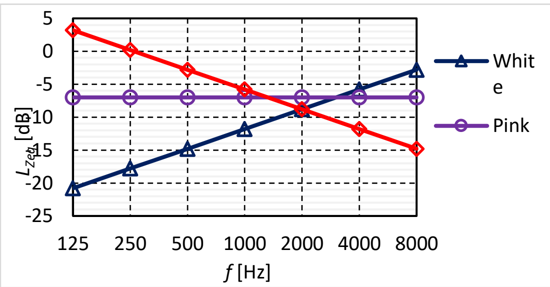

Fig. 2. Coloured noise spectra normalized to L_{Aeq} = 0 dB.

TABLE I
REFERENCE NOISE SPEECH SPECTRA

Vocal effort	L_{Zeq} [dB]							L_{Aeq}
f [Hz]	125	250	500	1000	2000	4000	8000	[dB]
Hushed male [18]	43.5	45.8	42.8	36.5	34.0	34.3	28.5	44.3
Hushed female [18]	34.1	47.3	42.8	36.6	33.1	38.3	32.5	45.3
Casual male [17]	46.1	50.8	51.4	46.3	42.5	38.8	35.5	52.1
Casual female [16]	36.4	49.2	49.5	42.0	39.2	34.8	35.5	49.4
Normal IEC male [1]	57.5	60.5	60.0	54.0	48.0	42.0	36.0	60.0
Normal ISO female [14]	55.6	65.3	58.1	50.9	44.2	43.3	42.0	60.0
Normal ISO/ANSI [22]	51.2	57.2	59.8	53.5	48.8	43.8	38.6	59.5
ITU-T P.50 [24]	54.7	59.9	59.3	54.8	48.8	43.9	41.0	60.0
Polish male [19]	61.2	65.8	65.5	58.4	55.5	54.1	48.1	65.8
Raised ANSI [16]	55.5	61.5	65.6	62.3	56.8	51.3	42.6	66.5
Loud ANSI [16]	58.0	64.0	70.3	70.6	65.9	59.9	48.9	73.7
Shouted ANSI [16]	59.0	65.0	74.7	79.8	75.8	68.9	58.2	82.3

TABLE II
REFERENCE COLOURED NOISE SPECTRA NORMALIZED TO L_{AEQ} = 0 DB

Noise	L_{Zeq} [dB]							L_{Aeq}
f [Hz]	125	250	500	1000	2000	4000	8000	[dB]
White noise	-20.8	-17.8	-14.8	-11.8	-8.8	-5.8	-2.8	0
Pink noise	-7.0	-7.0	-7.0	-7.0	-7.0	-7.0	-7.0	0
Brown noise	3.2	0.2	-2.8	-5.8	-8.8	-11.8	-14.8	0

In this paper, the $STIPA(SNR_A)$ relationship was calculated for SNR_A in the range from 5 to 15 dB, which corresponds to typical values used in PA systems. In the first stage of the study, representative spectrum was selected for the "relaxed" and "normal" vocal efforts on the basis of the $STIPA(SNR_A)$ relationship (Fig. 3). On the basis of preliminary comparative analyses with measured crowd noise spectra and as the worst case is often assumed in design, the spectrum for which the smallest $STIPA$ values were obtained was considered as such. For the “relaxed” vocal effort, this was the hashed male speech spectrum [18], and for the “normal” ISO/ANSI [16],[22],[23].

The effect of the reference noise spectra on $STIPA$ for $L_{Aeq,n}$ = 60 dB is shown in Fig. 4. The most difficult for speech intelligibility is pink noise. On the contrary, the least degrading spectrum for intelligibility are the “normal” and “raised” effort. When choosing the wrong interfering noise spectrum, the error of the $STIPA$ calculations can be large. For example, for interfering noise with a "normal" female speech spectrum (Fig. 3) $STIPA$ can be as much as 0.15 greater than for pink noise spectrum (Fig. 4).

For speech interfering noise, the smallest $STIPA$ values are obtained for spectra corresponding to the extreme different vocal efforts, "relaxed" and "shouted", with the "relaxed" spectrum being the more difficult case, especially for low SNR_A. In the analysis range, an increase in the SNR_A value obviously results in an increase in the $STIPA$ value. However, the slope of the $STIPA(SNR_A)$ characteristic is different for the individual interfering noise spectra. The average slope for white noise is 0.019/dB and for brown noise, 0.030/dB. For speech interfering noise, the slope differences are smaller, ranging from 0.025/dB for “shouted” effort to 0.030 for “relaxed”.

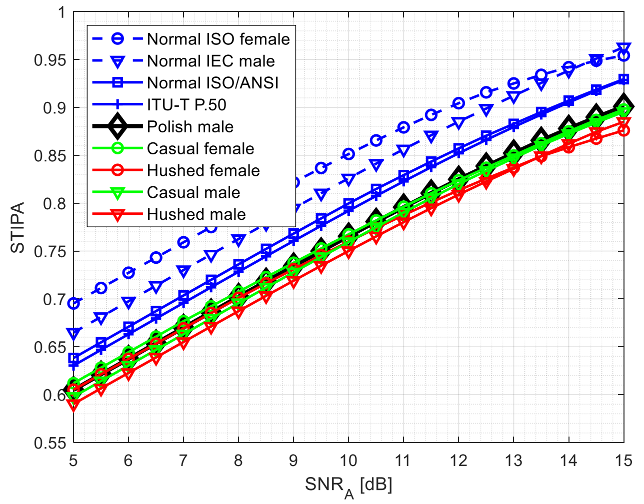

Fig. 3. *STIPA*(SNR_A) for relaxed and normal speech noise spectra of $L_{Aeq,n}$ = 60 dB.

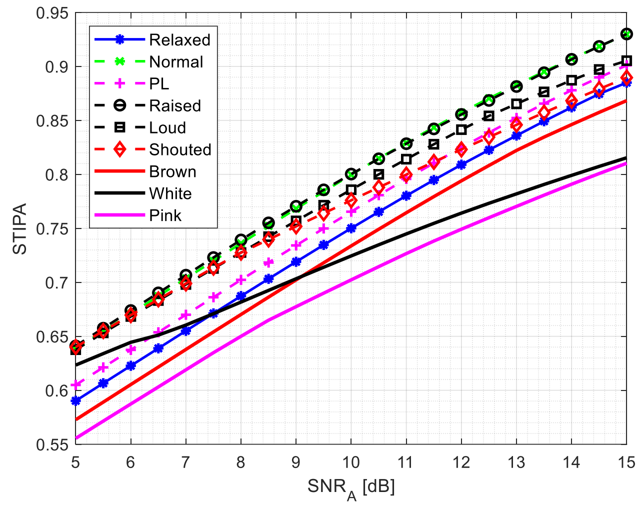

Fig. 4. *STIPA*(SNR_A) for speech and coloured noise spectra of $L_{Aeq,n}$ = 60 dB.

The spectrum for the "rised" vocal effort was abandoned for analysis due to its high similarity to the "normal" spectrum (Fig. 5) and virtually the same effect on *STIPA*(SNR_A) (Fig. 4).

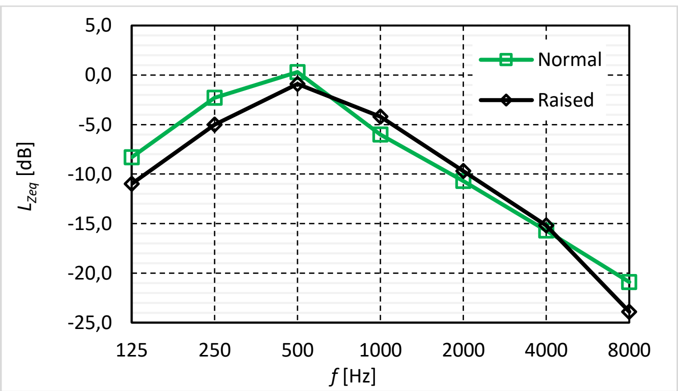

Fig. 5. Speech spectra normalized to $L_{Aeq,n}$ = 0 dB for "normal" and "rised" vocal effort.

The variation in individual noise spectra does not carry over directly to differences between the *STIPA* values obtained. For example, for the most spectrally different white and brown noise for SNR_A = 10 dB, the *STIPA* value differs by 0.01, whereas for very similar spectra corresponding to female speech and ISO/ANSI for the "normal" effort, the difference can be as high as 0.06. Therefore, the similarity of the normalised noise spectrum to the noise spectrum of a typical application was only a preliminary selection criterion. The similarity of the *STIPA*(SNR_A) benchmark result vector **r** determined for the spectrum of a given reference signal and the test vector **x** determined for noise spectra of a given type acquired by measurement or from the literature was chosen as the main criterion. The similarity of a given vector **r** and **x** was assessed using the Chebyshev distance [25] $d_C(\mathbf{x}, \mathbf{r})$:

$$d_C(\mathbf{x}, \mathbf{r}) = max_i|x_i - r_i| \tag{3}$$

allowing the maximum error to be evaluated, and the Gower distance [25] $d_G(\mathbf{x}, \mathbf{r})$:

$$d_G(\mathbf{x}, \mathbf{r}) = \frac{1}{n}\sum_{i=1}^{n}|x_i - r_i| \tag{4}$$

allowing the average error to be assessed. In addition, a critical index c_D was proposed:

$$c_D(\mathbf{x}, \mathbf{r}) = min_i(x_i - r_i) \tag{5}$$

which, if negative, indicates that the use of the reference interfering noise spectrum will result in an underestimation of *STIPA* relative to the test spectrum. For the set of test vectors, the maximum value d_{Cmax}, the average value d_{Gav}, and the minimum value c_{Dmin} were calculated from the results obtained, respectively.

The tested noise spectra were taken from the literature and the results of measurements carried out by the Acoustic Testing Laboratory of the Wrocław University of Technology and Sciences (spectra given in tables without literature references). These spectra are presented in the chapter with test results. For the purpose of analysis, the levels for a given group of spectra were normalised to the value given in the description. After preliminary analyses, it was decided to do research for three ranges of crowd noise levels:

1) group #1 for $L_{Aeq,n} \leq 70$ dB,
2) group #2 for 70 dB < $L_{Aeq,n}$ < 90 dB,
3) group #3 for $L_{Aeq,n} \geq 90$ dB.

Group #1 are the levels of interfering noise, which are assumed in the design of PA systems for building areas such as waiting rooms and concourses of railway stations and airport terminals, classrooms, banks, courtrooms, libraries, museums, galleries, and quiet: cafeterias, food courts, and shopping malls. Group #2 are the levels that occur, e.g. in noisy: sports halls, offices, cafeterias, and restaurants. Group #3 are the levels of interfering noise that occur mainly in stadiums and halls for loud ball games [3].

III. Results

In group #1, two cases were selected for analysis for five building areas: concourse of the railway station, departure hall of the airport [26],[27], food court, shopping mall, classroom [9],[10] (noise of student activity). The interfering noise spectra for these areas are shown in Table III and in Fig. 6. The spectra for the "relaxed" and "normal" vocal efforts were used as references. The results of the analyses are presented in Fig. 7 and Table IV.

TABLE III
TESTED CROWD NOISE SPECTRA – GROUP #1, $L_{AEQ,N} \leq 70$ DB

Building area		L_{Zeq} [dB]							L_{Aeq}
Symbol	f [Hz]	125	250	500	1k	2k	4k	8k	[dB]
RS1	Railway station 1	59.6	59.6	60.1	58.4	56.7	49.4	41.0	63.2
RS2	Railway station 2	60.4	59.7	60.4	57.8	54.5	49.5	42.9	62.5
AT1	Airport 1 [26]	62.0	60.0	60.0	57.0	53.0	49.0	45.0	62.0
AT2	Airport 2 [27]	64.1	63.5	63.7	60.0	57.2	51.9	44.2	65.3
FC1	Food court 1	63.6	62.1	63.2	59.9	56.8	52.0	45.4	64.9
FC2	Food court 2	63.1	65.7	68.1	64.8	61.1	55.3	47.1	69.5
SM1	Shopping mall 1	63.7	61.3	61.3	58.0	54.7	49.9	43.7	63.1
SM2	Shopping mall 2	61.7	63.8	66.3	63.7	59.8	54.2	45.1	68.0
SA1	Classroom 1 [9]	57.5	61.8	57.2	54.2	52.0	46.4	38.1	60.0
SA2	Classroom 2 [10]	55.0	56.0	57.0	52.5	49.0	44.0	37.0	57.9

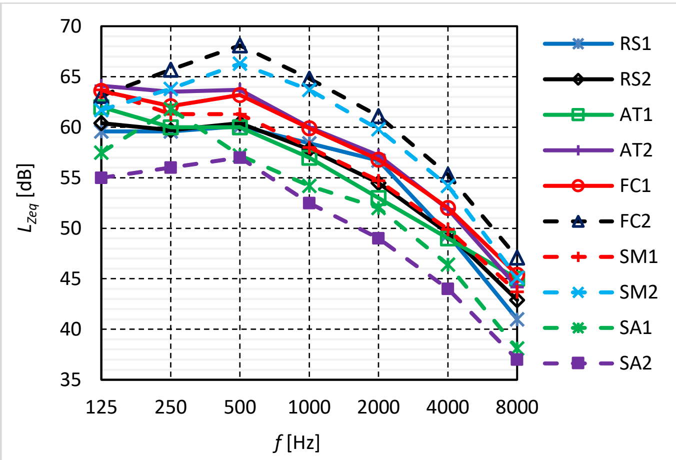

Fig. 6. Tested crowd noise spectra – group #1 ($L_{Aeq,n} \leq 70$ dB)

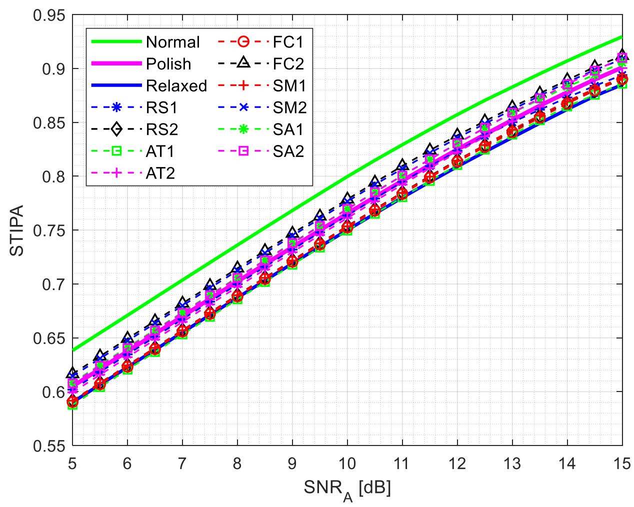

Fig. 7. *STIPA*(*SNR$_A$*) for group #1, $L_{Aeq,n}$ = 60 dB.

TABLE IV
RESULTS FOR CROWD NOISE SPECTRA OF GROUP #1 FOR $L_{AEQ,N} = 60$ DB

Reference vocal effort noise	d_{Cmax}	d_{Gav}	c_{Dmin}
Normal	0.05	0.04	-0.05
Polish	0.02	0.01	-0.02
Relaxed	0.03	0.01	0.00

In group #2, four cases for restaurants [28],[29] and three for noisy situations in stadiums [11] were selected for analysis. The interfering noise spectra for these areas are shown in Table V and in Fig. 8. The spectra for the "normal" and "loud" vocal efforts were used as references. The results of the analyses are presented in Fig. 9 and Table VI. The interfering noise at Hughes Stadium (H), Folsom Field (F) and Invesco Field (I) measured by Egan [11] was divided in relation to on-field events into offence (O), defence (D) and touch down (T). In Tables V and VII, in brackets, the first letter denotes the stadium code given above, and the second the on-field situation.

TABLE V
TESTED CROWD NOISE SPECTRA – GROUP #2, 70 DB < $L_{AEQ,N}$ < 90 DB

Building area		L_{Zeq} [dB]							L_{Aeq}
Symbol	f [Hz]	125	250	500	1k	2k	4k	8k	[dB]
R1	Restaurant 1 [28]	62.0	69.1	71.6	69.4	65.7	58.6	48.3	73.6
R2	Restaurant 2 [29] (B)	68.5	74.0	79.0	75.0	71.0	64.0	54.0	79.7
R3	Restaurant 3 [29] (C)	67.0	73.0	80.0	78.0	73.5	66.0	54.0	81.7
R4	Restaurant 4 [29] (A)	71.0	78.0	84.0	83.0	78.0	71.0	57.0	86.3
S1	Stadium 1 [11] (HO)	61.0	67.5	74.5	74.0	71.0	62.0	53.0	77.6
S2	Stadium 2 [11] (FO)	69.5	73.0	79.5	79.0	74.5	67.0	57.5	82.3
S3	Stadium 3 [11] (IO)	68.0	73.0	83.0	81.0	76.0	69.5	58.0	84.6

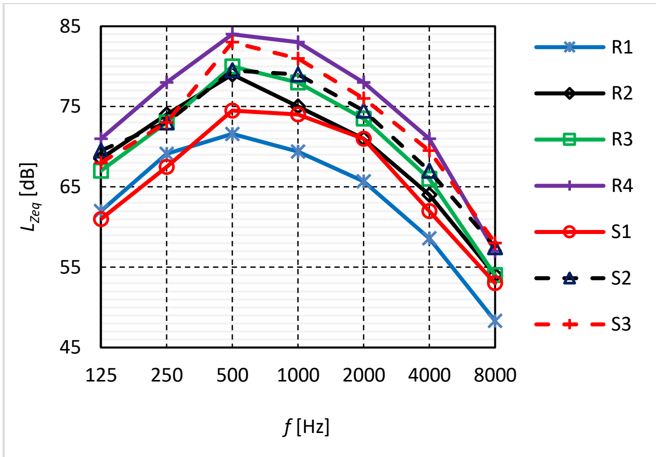

Fig. 8. Tested crowd noise spectra – group #2 (70 dB < $L_{Aeq,n}$ < 90 dB)

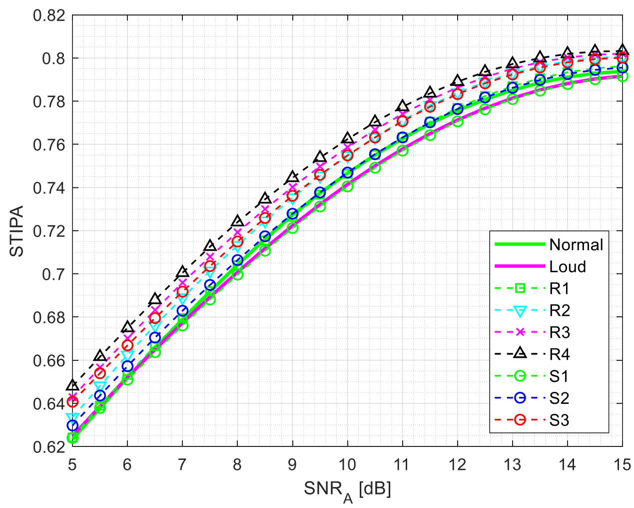

Fig. 9. *STIPA*(*SNR$_A$*) for group #2, $L_{Aeq,n}$ = 80 dB.

TABLE VI
RESULTS FOR CROWD NOISE SPECTRA OF GROUP #2 FOR $L_{AEQ,N}$ = 80 DB

Reference vocal effort noise	d_{Cmax}	d_{Gav}	c_{Dmin}
Normal	0.02	0.02	-0.01
Loud	0.02	0.02	0.00

In group #3, nine cases for loud stadiums [11],[30],[31] and one for a sports hall [11] were selected for analysis. The interfering noise spectra for these areas are shown in Table VII and in Fig. 10. The spectra for the "loud" and "shouted" vocal efforts were used as references. The results of the analyses are presented in Fig. 11 and Table VIII.

TABLE VII
TESTED CROWD NOISE SPECTRA – GROUP #3, $L_{AEQ,N} \geq 90$ DB

Building area		L_{Zeq} [dB]							L_{Aeq}
Symbol	f [Hz]	125	250	500	1k	2k	4k	8k	[dB]
S1	Stadium 1 [11] (HD)	67.0	70.5	85.0	87.5	83.0	77.0	64.4	90.2
S2	Stadium 2	76.7	83.8	87.5	88.7	83.7	74.0	60.2	91.4
S3	Stadium 3 [30] (B)	75.0	81.0	88.0	90.0	85.0	77.0	64.0	92.6
S4	Stadium 4 [11] (HT)	89.0	85.0	87.5	91.5	84.0	77.0	70.0	93.3
S5	Stadium 5 [31]	76.0	81.0	91.0	91.0	86.0	77.0	65.0	93.9
S6	Stadium 6 [11] (IT)	82.0	81.5	90.0	93.0	86.0	79.0	69.0	95.0
S7	Stadium 7 [11] (ID)	83.0	81.0	89.0	95.0	92.0	85.0	69.5	97.8
SH	Sports hall	85.9	90.1	93.7	95.1	90.8	85.3	73.0	98.2
S8	Stadium 8 [11] (FT)	79.0	80.0	90.0	97.0	89.0	81.5	73.0	98.3
S9	Stadium 9 [11] (FD)	78.5	80.0	93.0	98.0	90.5	85.0	72.0	99.6

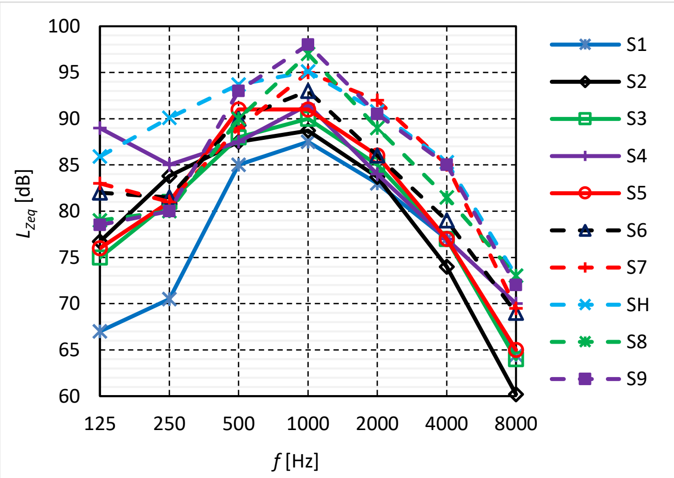

Fig. 10. Tested crowd noise spectra – group #3 ($L_{Aeq,n} \geq 90$ dB)

TABLE VIII
RESULTS FOR CROWD NOISE SPECTRA OF GROUP #3 FOR $L_{AEQ,N}$ = 95 DB

Reference vocal effort noise	d_{Cmax}	d_{Gav}	c_{Dmin}
Loud	0.03	0.02	0.00 (-0.004)
Shouted	0.03	0.02	0.00 (-0.002)

IV. DISCUSSION

The first range of analysed interfering noise is crowd noise with $L_{Aeq,n}$ levels of 50-70 dB. Intuitively, it may seem that a suitable normalised spectrum for these levels would be the spectrum of "normal" or "rised" vocal effort. However, the obtained results (Fig. 7, Table IV) indicate that this approach could give overestimated *STIPA* values (d_{Cmax} = 0.05, d_{Gav} = 0.04, c_{Dmin} = 0.05) relative to the test spectra obtained by measurement. A very safe approach to designing PA systems for such a range of crowd noise levels is to adopt a spectrum defined as "relaxed". For this spectrum, no *STIPA* values were obtained greater than for the tested spectra (c_{Dmin} = 0.00). The average and maximum error obtained for this spectrum (d_{Cmax} = 0.03, d_{Gav} = 0.01) should be considered satisfactory, since for STIPA the maximum deviation for repeated measurements is approximately 0.03.

One of the spectra tested was the Wijngaarden and Atsma spectrum [24], which is the average ambient noise spectrum obtained for different areas of the Amsterdam Airport Schiphol. Although this spectrum differs slightly from the "relaxed" spectrum (Fig. 12), the *STIPA*(SNR_A) values obtained for both spectra are virtually the same (Fig. 7).

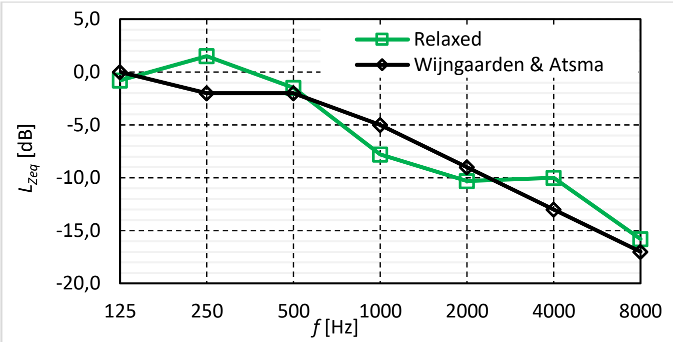

Fig. 12. Speech spectra normalized to $L_{Aeq,n}$ = 0 dB for "relaxed" vocal effort and form Wijngaarden and Atsma [26].

For crowd noise with $L_{Aeq,n}$ levels of 70-90 dB, "no rmal" and "loud" spectra were checked. The results for both spectra (Table VI) yielded the same mean and maximum error (d_{Cmax} = 0.02, d_{Gav} = 0.02). For the "loud" spectrum, no *STIPA* values greater than those for the tested spectra appeared (c_{Dmin} = 0.00). For the "normal" spectrum, c_{Dmin} = -0.01, which means that a spectrum for which smaller STIPA values were obtained appeared among the spectra tested. A safe choice for crowd noise with $L_{Aeq,n}$ levels of 70-90 dB is therefore to use the "loud" spectrum.

For crowd noise with $L_{Aeq,n}$ levels greater than or equal to 90 dB, the "loud" and "shouted" spectra were checked. Using the typical precision of the STI results, both spectra provided the same error (d_{Cmax} = 0.03, d_{Gav} = 0.02, c_{Dmin} = 0.00). However, in Fig. 11, it can be seen that slightly *STIPA* values are obtained for the "shouted" spectrum and closer to the most difficult of the cases tested.

CONCLUSION

As shown in the paper, it is possible to determine the interfering crowd noise spectrum by relating its level to the speech spectrum for the corresponding vocal effort.

On the basis of preliminary analyses, representative spectra were selected for individual vocal efforts. For "relaxed" this was the "hashed" male speech spectrum from the Cushing, Li, Cox, Worrall and Jackson [18], and for "normal" from the ISO 3382-3 standard [22]. For the other vocal efforts, the spectra defined in the ANSI 3.5 standard [16].

As shown in the paper, the use of colour noise spectra to simulate crowd noise leads to an underestimation of STIPA values. For speech interfering noise, the smallest *STIPA* values are obtained for spectra corresponding to the extreme different vocal efforts, "relaxed" and "shouted", with the "relaxed" spectrum being the more difficult case, especially for low SNR_A. For small and medium levels of crowd noise ($L_{Aeq,n} < 70$ dB), the spectrum corresponding to the vocal effort "relaxed" is a suitable spectrum. For high and very high noise levels (70 dB $< L_{Aeq,n} <$ 90 dB), the "loud" spectrum can be used, although for very high levels of crowd noise ($L_{Aeq,n} \geq 90$ dB) a slightly safer approach is to use a "shouted" spectrum. For the spectra selected in this way, a maximum STIPA error of 0.02-0.03 was obtained, which is no more than the maximum deviation for STIPA repeated (0.03).

In the future, similar analyses are planned for other sources of interfering noise such as ventilation, traffic noise, and audio visual equipment.

REFERENCES

[1] IEC 60268-16:2020, "Sound system equipment - Part 16: Objective rating of speech intelligibility by speech transmission index", 2020.

[2] CEN/TS 54-32:2015, "Fire detection and fire alarm systems - Planning, design, installation, commissioning, use and maintenance of voice alarm systems", 2015.

[3] BS 5839-1:2017, "Fire detection and fire alarm systems for buildings. Part 1: Code of practice for design, installation, commissioning and maintenance of systems in non-domestic premises", 2017.

[4] P. Dziechciński, "Effect of Power Amplifier Distortion on the Speech Transmission Index for Public Address Systems", Archives of Acoustics, vol. 47, no. 2, 2022. https://doi.org/10.24425/aoa.2022.141649

[5] P. Dziechciński, "Effect of highpass filtering on the speech transmission index", Vibrations in Physical Systems, vol. 33, no. 3, 2022.

[6] N. R. French, J. Steinberg, "Factors Governing the Intelligibility of Speech Sounds", The Journal of the Acoustical Society of America, vol. 19, no. 1, pp. 90-119, 1947. https://doi.org/10.1121/1.1916407

[7] T. Houtgast, H. J. M. Steeneken, "The Modulation Transfer Function in Room Acoustics as a Predictor of Speech Intelligibility", Acta Acustica united with Acustica, vol. 28, no. 1, pp. 66-73, 1973. https://doi.org/10.1121/1.2016789

[8] S. Brachmański, "Estimation of logatom intelligibility with the STI method for Polish speech transmitted via communication channels", Archives of Acoustics, vol. 29, no. 4, pp. 555-562, 2004.

[9] M. Hodgson, R. Rempel, S. Kennedy, "Measurement and prediction of typical speech and background-noise levels in university classrooms during lectures", The Journal of the Acoustical Society of America, vol. 105, no. 1, pp. 226-233, 1999. https://doi.org/10.1121/1.424600

[10] P. E. Braat-Eggen, A. van Heijst, M. Hornikx, A. Kohlrausch, "Noise disturbance in open plan study environments a field study on noise sources student tasks and room acoustic parameters", Ergonomics, vol. 60, no. 9, pp. 1297-1314, 2017. https://doi.org/10.1080/00140139.2017.1306631

[11] D. Engard, "Noise exposure, characterization, and comparison of three football stadiums", MSc Thesis, Colorado State University, Department of Environmental and Radiological Health Sciences, 2009.

[12] N. Jathar, P. Rao, "Acoustic characteristics of critical message utterances in noise applied to speech intelligibility enhancement", in Proc. 15th Annual Conference of the International Speech Communication Association, INTERSPEECH 2014, Singapore, pp. 2665-2669, 2014.

[13] H. Liu, H. Ma, C. Wang, J. Kang, „Prediction model of crowd noise in large waiting halls", The Journal of the Acoustical Society of America, vol. 152, no. 4, pp. 2001-2012, 2022. https://doi.org/10.1121/10.0014347

[14] ISO 9921:2003, "Ergonomics — Assessment of speech communication", 2003.

[15] H. Lazarus, "Prediction of Verbal Communication is Noise— A review: Part 1", Applied Acoustics, vol. 19, no. 6, pp. 439-464, 1986. https://doi.org/10.1016/0003-682X(86)90039-3

[16] ANSI/ASA S3.5-1997 (R2020), "Methods For Calculation Of The Speech Intelligibility Index", 2020.

[17] K. S. Pearson, R. L. Bennett, S. A. Fidell, "Speech Levels in Various Noise Environments", Office of Health and Ecological Effects, Office of Research and Development US EPA, Washington, 1977.

[18] I. R. Cushing, F. F. Li, T. J. Cox, K. Worrall, T. Jackson, "Vocal effort levels in anechoic conditions", Applied Acoustics, vol. 72, no. 9, 2011. https://doi.org/10.1016/j.apacoust.2011.02.011

[19] D. Byrne, et al., "An international comparison of long-term average speech spectra", The Journal of the Acoustical Society of America, vol. 96, no. 4, 1994. https://doi.org/10.1121/1.410152

[20] W. Jassem, M. Steffen, B. Piela, "Average spectra of Polish speech", In Proceedings of Vibration Problems, vol. 2, pp. 59–71, 1959.

[21] W. Majewski, H. B. Rothman, H. Holien, "Acoustic comparisons of American English and Polish", Journal of Phonetics, vol. 5, no. 3, pp. 247-251, 1977. https://doi.org/10.1016/S0095-4470(19)31138-6

[22] ISO 3382-3:2022, "Acoustics — Measurement of room acoustic parameters — Part 3: Open plan offices", 2022.

[23] BB93, "Guidance on computer prediction models to calculate the Speech Transmission Index for BB93", Version 1.0, Department for Education and Skills, Schools Capital and Building Division, 2004.

[24] ITU-T P.50, "Artificial voices", 1999.

[25] S. H. Cha, "Comprehensive survey on distance/similarity measures between probability density functions", International Journal of Mathematical Models and Methods in Applied Sciences, vol. 1, no. 4, pp. 300-307, 2007.

[26] S. J. van Wijngaarden, R. Atsma, "Ambient noise inside airport terminals: a detailed survey of the background noise at Amsterdam Airport Schiphol", in Proc. InterNoise 2020, Seoul, pp. 1588-1595, 2020.

[27] I. Wilson, "Improving Intelligibility of Airport Terminal Public Address Systems", The National Academies Press, Washington, 2017. https://doi.org/10.17226/24839

[28] T. Wohni, "Method for classification of restaurant acoustics", MSc Thesis, Norwegian University of Science and Technology, Department of Electronic Systems, 2018.

[29] J. H. Rindel, C. L. Christensen, A.C. Gade, "Dynamic sound source for simulating the Lombard effect in room acoustic modelling software", in Proc. InterNoise 2012, New York, 2012.

[30] P. Mapp, R. Hammond, "The effects of spectators on the speech intelligibility performance of sound systems in stadia and other large venues", in Proc. Audio Engineering Society 147th Convention, New York, preprint 10267, 2019.

[31] L. Morales, G. Leembruggen, S. Dance, B. M. Shield, "A revised speech spectrum for STI calculations", Applied Acoustics, vol. 132, pp. 33-42, 2018. https://doi.org/10.1016/j.apacoust.2017.11.008