The STI-Matrix – a powerful new strategy to support the planning of acoustically optimized offices, restaurants and rooms where human speech may cause problems.

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Summary
Human speech is one of the most important “noise sources” in open plan offices, restaurants and other rooms where communication between people is important. With existing software techniques it is possible to create computer models of such environments in the planning phase and to apply measures like absorbing surfaces, diffusors and partial screens together with an optimized layout to ensure that disturbance is minimized and intelligibility is optimized according to clear formulated targets. The technique is demonstrated for a planned restaurant, where two conditions should be fulfilled. First in the fully occupied condition the background level with one person speaking at each table should not exceed a given limit and with this background level the speech transmission index STI between all possible combinations speaker-listener at a table – taking into account all tables in the restaurant – should not fall below another minimum limit. Second in the sparsely occupied restaurant with only few people talking quietly the content of the spoken sentences at one table should not be understood at any other table. Proposals for the abovementioned limits are presented and the software-supported optimization process is demonstrated.

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1. Introduction

Complaints about noise in restaurants, offices and other common rooms often originate from the intelligibility of speech. Either persons inside the own communication area are not intelligible enough or the intelligibility of persons from outside this personal communication area is considered as too good.

The Speech Transmission Index STI quantifies the transmission quality of the speech signal between a speaker and a listener position. It allows to assess the intelligibility at every single workplace taking into account the background noise and the emission level of the speaking person according to the situation at hand. The STI describes the reduction of the modulation depth of the speech signal due to the reverberation, taking into account masking effects at high signal levels, the hearing threshold at low signal levels and the masking due to background levels. Therefore, the STI is the right measure to take on situations with potentially disturbing speech signals or if an environment acoustically optimized for a relaxed private conversation it the target. Recently available simulation techniques provide unprecedented possibilities for the planning and assessment of restaurants, offices or any other room where intelligibility is an issue. Here, the basic concept of the STI-matrix is presented. The STI-matrix includes the relations between any pair of workplaces and therefore provides a profound basis for any evaluation.

2. Assessment of the intelligibility based on the STI

The strength of the speech signal emitted by the speaker is the first mayor factor for the assessment of rooms in which human communication is an issue. The sound power levels and the spectral distribution of the speech levels can be found in [1].

After the appropriate sound power level has been assigned to the speaker, the STI can be calculated at the listener position also taking into account the background noise. The STI then can be classified using the scale in table I.

Table I. Intelligibility classification table. Excerpt from Table F.1, DIN EN ISO 9921 [2]

STI	Intelligibility
0,75 to 1,00	very good
0,60 to 0,75	good
0,45 to 0,60	fair
0,30 to 0,45	poor
0,00 to 0,30	bad

In general, there are two cases to consider for the intelligibility between two persons. Either the listener should be able to easily understand the speaker (speaker and listener within the same communication area), or the content of a conversation should not be intelligible to the listener (speaker and listener in different communication areas). These requirements can be considered using the color coding in table II.

Table II. Possible qualification scheme of the intelligibility according to the requirements

Speaker and listener in same communication area		
Range	**Qualification**	**Color**
STI ≥ 0,6	good	green
0,45 ≤ STI < 0,6	fair	yellow
STI < 0,45	bad	red
Speaker and listener in different areas		
Range	**Qualification**	**Color**
STI ≤ 0,2	good	green
0,2 < STI ≤ 0,45	fair	yellow
STI > 0,45	bad	red

However, in cases where a low intelligibility is desired (for examples between different working zones in an office or between different tables in a restaurant), it has to be ruled out that this low intelligibility is caused by an unacceptably high background noise level. Therefore, an additional qualification of the background noise level like proposed in table III is essential.

Table III. Classification of the background noise

Background level for both cases		
Range $L_{ambient}$	**Qualification**	**Color**
$L_{ambient}$ < 35 dB(A)	good	green
35 dB(A) ≤ $L_{ambient}$ < 50 dB(A)	fair	yellow
$L_{ambient}$ ≥ 50 dB(A)	bad	red

It seems reasonable to assess the acoustic quality of the individual areas of the room according to both table II and table III and take the worse score as the final assessment of the area.

The classifications for STI and background level presented in the tables above are suggested for general application cases. Of course, they can be modified to the individual requirements in actual planning scenarios.

3. The concept of the STI-matrix

Assessing rooms by evaluating speech levels and STI values along ideally straight measurement paths along (work)places may be adequate for control measurements after the completion of the construction. For the planning and especially for the assessment of different planning scenarios simulation tools offer more profound concepts. Measurement path according to DIN EN ISO 3382-3 [3] and VDI 2569 [4] can be laid out in different ways, the deduced parameters therefore can be quite inaccurate. Additionally, the measurement paths require the first measurement point not to be positioned behind a screening object. If table partitions are used this causes a lot of restrictions for the allowed paths since the distance between the source and the next screening object is very short.

Instead of assessing the room based on some selected workplaces along the allowed measurement paths the concept presented here takes any pair of workplaces into account. With every workplace as speaker position, the intelligibility at any other workplace as listener position is determined by calculating the STI while also taking into account the appropriate background noise. The appropriate background noise of course depends on the intended use of the room. In offices for concentrated individual work the assumption of a constant background originating from technical equipment like the ventilation system seems appropriate. In restaurants or rooms with similar use the background noise is determined by other person speaking in the same room.

The basic concept of the STI-matrix will be demonstrated using the planning example of a small restaurant described in [1].

For demonstration purposes this example of a small restaurant with only a few tables is chosen. Nevertheless, it can be applied to rooms of any size and any number of places – assuming sufficient computing power. Two planning scenarios – with and without acoustic measures- are compared, visual representations of the small scenario and the acoustic measures can be found in [1] (Figure 22 and Figure 25). The tables (equivalent to the communication areas or communication zones) are numbered from 1 to 6, the seats are numbered from 1 to 30. In total, there are 870 speaker-listener pairs to assess.

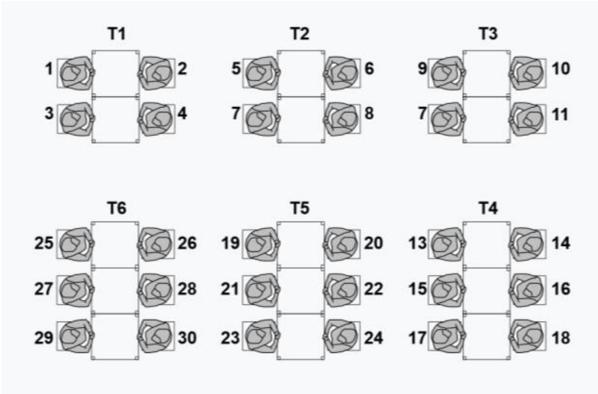

Figure 1. Numbering of the tables (zones) and the seats.

Considering all these 870 “speech channels” goes far beyond any conventional assessment methods and is only possible using appropriate software simulation tools. Any parameter calculated for each pair of speaker to listener - especially the speech levels, the STI and the appropriate background level – are displayed in the matrix format according to figure 2.

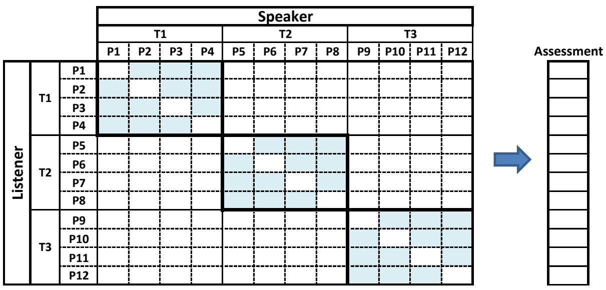

Figure 2. Full matrix displaying the parameter (e.g. speech level, STI-value or background noise) for each pair of speaker to listener (display limited to 3 tables)

This allows to directly review the relations between each individual pair and also contains the information about the table/area or zone of the speaking and listening person. Persons on one table of the restaurant – or also persons within a communication area for collaborative work in an office - are displayed next to each other. This grouping leads to the color coded areas along the diagonal where a good intelligibility is desirable and which are assessed using the upper half of table II. For any other area of the matrix, which means the relations between different tables or zones, the intelligibility should be rather low to allow undisturbed or private conversations (assessment by the lower half of table II).

For restaurants it then makes sense to condense the seat-based format of figure 2 to a table-based format like figure 3. Depending on the specific task this can be achieved by averaging the values of the STI or the background noise level for each combination table A- table B.

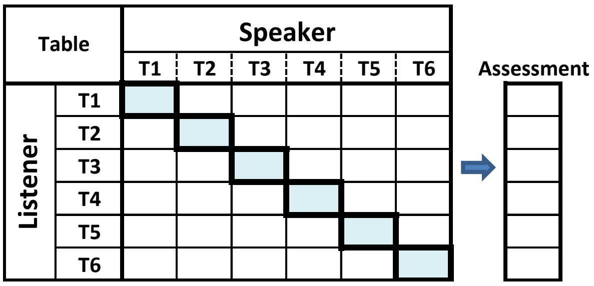

Figure 3. Condensed table-based matrix (including all 6 tables)

For each planning scenario the following steps have to be carried out to generate the parameters displayed in the matrix,

1) Emission of speech from each position and determining the immission at each other position. This results in speech levels and impulse responses from any speaker to any listener position
2) Calculation of the appropriate background noise at each listener position for every speaker position. In the example of the small restaurant the background noise was determined by assuming that one person per table is speaking each table at the same time. At the listener position the speech levels of every person of a certain table are energetically averaged and then these averaged levels per table are summed up for all 6 tables. This procedure is carried out for every listener position
3) Calculating the STI using the impulse response from 1) and background level from 2)

Of course this sequence cannot be performed manually but has to be executed in an automated way.
Depending on the intended use and the operating conditions the input parameters as well as the calculation sequence described above may have to be adjusted. In the case of restaurants, the most important operation condition is the nearly fully occupied restaurant. The speech effort then depends on the kind of restaurant. Usually conversations with “normal relaxed” speech effort are desirable, in wine cellars or beer halls with elongated tables a “normal increased” speech effort seems more appropriate. It has to be noted that the speech emission level itself will not have any effect on the final assessment of room if there are no additional noise sourced or masking effects. Since the speech effort is assigned to any speaker, an overall increased emission level will just result in higher background levels with unchanged intelligibility for the conversation at the tables.
In case of a weakly occupied restaurant the major issue is the lack of privacy since the conversations can be understood at the adjacent tables. The assessment of this operating condition is similar to the fully occupied restaurant but with the following changed assumptions: Since only a few tables are occupied the speech effort will be “very relaxed”. The background noise is not caused by speaking persons at other tables but by technical equipment (e.g. ventilation system), so that the background noise is assumed to be constant in the whole restaurant with a level depending on the particular situation. The STI sis then calculated for any combination of speaker and listener and assessed using the lower part of table II.

4. Application of the STI-Matrix to the planning example without acoustic optimization

For the example for the fully occupied small restaurant the calculations described above result in the following condensed matrix representations for the STI-matrix and the background level matrix.

Table		Speaker					
		T1	T2	T3	T4	T5	T6
Listener	T1	0.42	0.29	0.20	0.18	0.24	0.30
	T2	0.25	0.39	0.29	0.23	0.25	0.21
	T3	0.18	0.30	0.43	0.31	0.26	0.20
	T4	0.17	0.25	0.31	0.42	0.31	0.20
	T5	0.20	0.25	0.24	0.29	0.38	0.28
	T6	0.29	0.24	0.21	0.21	0.20	0.42

Figure 4. Table-based STI-matrix for the scenario without acoustic measures

Table		Speaker					
		T1	T2	T3	T4	T5	T6
Listener	T1	56.1	54.8	55.5	55.5	55.2	54.8
	T2	56.0	57.1	55.8	56.2	56.1	56.3
	T3	56.1	55.3	56.7	55.4	55.7	56.0
	T4	56.0	55.7	55.3	56.6	55.2	56.0
	T5	56.5	55.7	56.3	56.0	57.2	56.0
	T6	55.2	55.6	55.7	55.7	55.8	56.4

Figure 5. Table-based matrix for the background levels in db(A) for the scenario without acoustic measures.

An excerpt of the full STI-matrix for tables 1 to 3 is presented in figure 6.

			Speaker											
			T1				T2				T3			
			P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
Listener	T1	P1		0.41	0.58	0.39	0.30	0.24	0.29	0.24	0.21	0.21	0.20	0.19
		P2	0.38		0.35	0.48	0.41	0.28	0.38	0.27	0.22	0.20	0.20	0.19
		P3	0.50	0.36		0.40	0.27	0.22	0.28	0.22	0.20	0.20	0.19	0.19
		P4	0.34	0.52	0.37		0.37	0.26	0.39	0.26	0.21	0.18	0.21	0.18
	T2	P5	0.27	0.39	0.27	0.37		0.38	0.53	0.34	0.26	0.22	0.26	0.22
		P6	0.17	0.22	0.17	0.22	0.36		0.32	0.47	0.42	0.31	0.39	0.30
		P7	0.24	0.34	0.26	0.37	0.45	0.33		0.36	0.24	0.21	0.24	0.21
		P8	0.16	0.20	0.17	0.22	0.32	0.51	0.34		0.39	0.30	0.40	0.29
	T3	P9	0.15	0.19	0.16	0.20	0.29	0.40	0.28	0.39		0.40	0.53	0.36
		P10	0.18	0.21	0.19	0.20	0.25	0.32	0.25	0.31	0.43		0.38	0.51
		P11	0.14	0.17	0.15	0.19	0.26	0.37	0.27	0.38	0.46	0.35		0.38
		P12	0.16	0.18	0.17	0.19	0.24	0.30	0.25	0.30	0.39	0.55	0.41	

Figure 6. Seat-based STI-matrix for the scenario without acoustic measures.

The color coding in figure 4 and 5 immediately indicates that the acoustic conditions in this restaurant are considered not desirable. The red diagonal elements in figure 4 reveal, that the intelligibility for conversations at each of the 6 tables is not acceptable. The privacy caused by the "not understanding" of the conversations at adjacent tables – indicated through the yellow and green non- diagonal elements – is caused by the very high overall noise level in the restaurant. This then results in a negative assessment according to table III.

5. Application of the STI-matrix to the planning example with acoustic optimization

This for demonstration purposes simple example with already quite dense layout of the tables has been acoustically optimized by adding absorbing screens between the tables, absorbing panels at the walls and a baffle ceiling (details see Figure 25 in [1]). Recalculation of background noise and STI-matrix results in the following table-related representation.

Table		Speaker					
		T1	T2	T3	T4	T5	T6
Listener	T1	0.74	0.28	0.02	0.00	0.16	0.43
	T2	0.23	0.70	0.32	0.09	0.22	0.27
	T3	0.02	0.36	0.74	0.34	0.29	0.08
	T4	0.01	0.18	0.44	0.74	0.32	0.02
	T5	0.12	0.18	0.28	0.21	0.69	0.26
	T6	0.38	0.28	0.05	0.05	0.00	0.70

Figure 7. Table-based STI-matrix for the scenario with acoustic measures

Table		Speaker					
		T1	T2	T3	T4	T5	T6
Listener	T1	45.9	44.3	45.8	45.8	45.3	42.8
	T2	46.2	47.4	45.8	47.0	46.6	46.3
	T3	46.2	44.3	46.3	44.8	45.1	46.1
	T4	45.9	45.4	43.3	46.0	44.3	45.9
	T5	46.9	45.4	46.2	46.5	47.4	46.1
	T6	44.7	45.8	46.9	46.9	47.0	47.1

Figure 8. Table-based matrix for the background levels in db(A) for the scenario with acoustic measures.

The advantages of this assessment taking into account any combination of speaker and listener are obvious. After defining the positions of every seat/workplace and assigning them to the appropriate tables or groups the automated calculation sequence then can be executed for any planning scenario. The acoustic quality then can be assessed using the STI-matrix considering the expected noise levels according to the use and operation condition.
For the planning of offices, the workplace-based matrix like figure 6 also allows to consider typical emission levels at the specific places and varying requirements in different workzones. New improved strategies based on the STI-matrix would also allow to determine room-, zone-, or single workplace-based masking noise level to achieve the desired level of intelligibility or non-intelligibility of speech in the respective areas.

6. Outlook

The workflow presented here was developed for the room acoustic planning based on computer simulations. Especially for complex open plan offices with varying functional areas, staggered layouts and a creative placement of screens and absorbers the STI-matrix delivers a profound basis for the evaluation and the assessment of the intelligibility at each workplace. In general it is useful to include approaches like the STI-matrix in standards and/or guidelines, but before that there still remains some further work to be done to also be able to determine the uncertainty of the predicted parameters and the influence of this uncertainty on the final assessment.

[1] Probst W., Böhm M.: Die Anwendung des Speech Transmission Index (STI) zur Beurteilung von Sprachgeräuschen. Lärmbekämpfung Bd. 12 (2017) Nr. 2 – März

[2] DIN EN ISO 9921: 2004. Ergonomics - Assessment of speech communication. Berlin: Beuth-Verlag, February 2004.

[3] DIN EN ISO 3382-3:2012 „Acoustics - Measurement of room acoustic parameters - Part 3: Open plan offices“, Beuth Verlag

[4] VDI 2569 E:2016 „Sound protection and acoustical design in offices“, Beuth Verlag