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Evaluating room acoustic quality in open-plan offices by adding the distribution of possible source and receiver positions to the simulation

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Abstract

Room acoustics in open-plan offices relies on acoustical and organisational measures. In a theoretical model we show that the number of workstations and the amount of speech are crucial factors for acoustical comfort. Each employee may speak or work quietly, so the acoustical system needs to reflect this multi-source and multi-receiver situation. Target parameters from ISO 3382-3 use a single source, a path of receivers and are hard to optimise. For this reason we propose a systematic approach in which all transfer functions between all user positions are simulated. We use the speech transmission index STI to form a source-receiver matrix, reflecting the whole acoustical system. From this matrix, information on the number of intelligible sources is easily available. From the source-receiver matrix acoustical or organisational improvements can be found quickly, with simple concepts easily explained to project partners.

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1. Acoustics in Open-plan Offices

While open-plan offices are preferred by many project developers over walled offices for their spatial efficiency, the inferior acoustical privacy remains a major point of complaint in those built environments. When users are surveyed on their satisfaction in open-plan offices, the share of highly disturbed users is high, see i.e. data in [1].

Not all irrelevant sounds are equally disturbing. The human voice attracts attention in a special way and appears to be particularly hard to ignore. Persons exposed are not capable of performing cognitive demanding tasks at their best, as parts of the short term memory are vulnerable. It has been shown that the cognitive performance under exposure to irrelevant sounds decreases [2]. The speech transmission index STI has proven to be a useful predictor of how disturbing speech is perceived. Fig.1 gives a rough estimate on expected work conditions based on the speech intelligibility at a given desk. Absorbing, blocking the

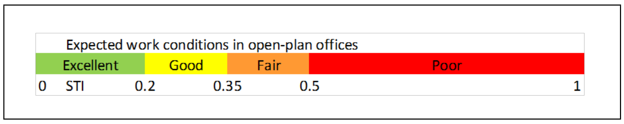

Figure 1. Expected acoustical working conditions with background speech in open-plan offices

propagation path and masking speech by increased background noise levels are common ways to deal with irrelevant speech.

To summarise, particularly sounds of speech cause problems in the open-plan offices which cannot be eliminated purely by room acoustical design.

2. Organisational measures

Acoustical problems can also be addressed by organisational measures. One example is the reading room of a library, where speech is not tolerated. Despite high density of workplaces in reading rooms, the acoustical environment does not hinder the users to work efficiently on different cognitively demanding tasks. There is a high level of absorption in the room (often caused by the books), hardly any shield-

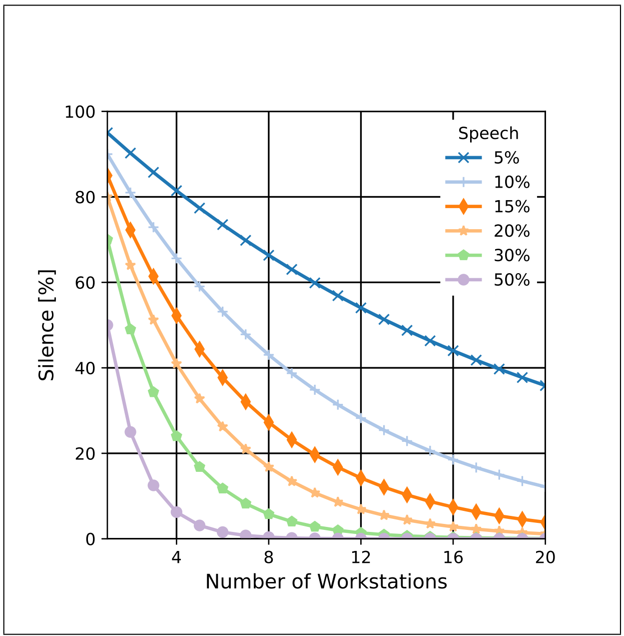

Figure 2. Stochastic share of silence based on different percentages of speech (lines) and the number of workstations in the vicinity of the receiver

ing between the desks and typically a low background noise level. With only a small amount of speech being tolerated, this highly productive environment would cease to exist.
In the sound scape of an open-plan office, the amount of speech is a decisive factor.
Most organisations cannot work without speech communication. However, the power of organisational approaches is high, if they can be implemented by the users. For instance activity based working uses this organisational power by creating a variety of spaces for different tasks. There, silent workstations (WS) can be introduced, as long as users perform their work without speech communication over a period of time. Alternatively, small closed telephone booths near the WS can be used for longer calls and protect colleagues from disturbance. Both approaches have in common that they separate speech based activities and activities without speech. The fundamental dilemma of open-plan offices remains that speech communication and telephone calls are more likely to take place in the same room as the number of desks increases. Organisational approaches require rules, extra resources such as telephone booths and far reaching consent of all users present for them to be effective.

3. Theoretical Considerations

While the fact that silence ceases with the first person speaking is elementary, Fig.2 shows the expected percentage of silence, if there are many users present, each communicating for a fixed percentage (5–50%, see lines) i.e. of the working hours.

From Fig.2 follows:
Firstly, no longer periods of silence are expected in offices with more than 12 WS and communication shares greater the 15%. Both, high numbers of WS and increased communication lead to an non-linear decrease of expected silence.
Secondly, if the number of WS in a room is small and the communication share is low, the likeliness of silence increases sharply. This is in line with a study by Herbig et al. [3].
Fig.2 assumes that speech transmission between all WS assessed is high, i.e. with $STI > 0.5$. For small numbers of WS with little distance between them this is very likely the case.

4. Planning tools for open-plan offices

4.1. ISO 3382-3 Parameters

Acoustics in open-plan offices is often described by the parameters of ISO 3382-3 [4]. The standard was designed for acoustical measurement, which means that it samples a limited number of measurement points forming lines from a single sound source (the loudspeaker), called paths. For every measurement point on a path, the speech transmission index STI and the A-weighted sound pressure level of speech $L_{p,A,S}$ are plotted over the distance from the sound source. For those samples a best-fit curve is found. The parameters distraction distance r_D (read from the STI-Plot at $STI = 0.5$) and A-weighted sound pressure level of speech at a distance of 4m $L_{p,A,S,4m}$ as well as the spacial decay rate of speech $D_{2,S}$ (read from the $L_{p,A,S}$-Plot at 4 m, $D_{2,S}$ is the gradient) are found.

Time restrictions in measurement campaigns limit the number of paths and measurement points considered. The parameters found vary, depending on the path chosen and the points included. In most offices there is a large spread between the highest and the lowest parameters measured. This leads to difficulties on how to interpret the results with respect to human perception of sound and overall acoustical quality achieved in the office.

4.2. New Matrix-Method based on Room Acoustical Simulation

In room acoustical simulations, the time limits of measurements do not apply. All established programs can calculate the above mentioned parameters and grids of receivers. The problem in both approaches is that they currently only show the results of one source position at once, which does not reflect the problem. As users in WS can speak or listen, the situation in open-plan offices can be best characterised as a multi-source and multi-receiver scenario. Each seat in the office is treated as source *and* receiver position. So we

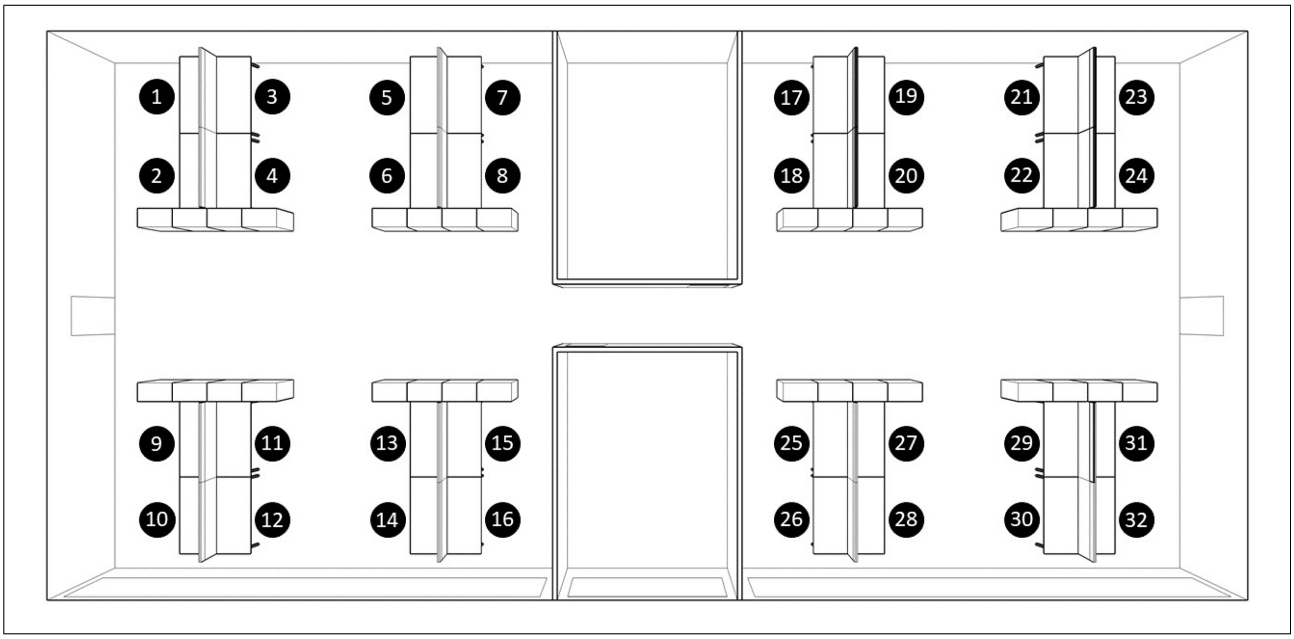

Figure 3. Ground plot of example office with workstations (WS 1–32)

propose a new method in which the number of seats in the open-plan office are the number of simulation sub-jobs required. Each sub-job places the source in the position of a WS and calculates the room impulse response to all other WS. This is repeated for all WS. The impulse response is analysed and the parameters desired calculated to be further processed. With the example in Sec. 5 the process and the benefits of it are explained.

5. Example of new Matrix-Method

Fig. 3 shows the simulated office. All simulation was carried out with the Odeon Auditorium [5]. The room is 25.65 m long and 12.15 m wide, in total an area of 311.6 m². This is a common shape and size for open-plan offices in Germany based on a grid of 1.35 m. There are a total of 32 WS along the façade. Two meeting rooms are placed in the middle, dividing the floor into two areas of 16 WS. Absorptive screens between the desks are 1.60 m high and cupboards (1.20 m high) are placed at the end of each workbench as boundary to the corridor. The ceiling above the corridor is absorptive. The background noise level was set to pink noise of $L_{p,AB}$=38 dB(A).

The acoustical situation is completely described by the matrix of sources and receivers. All room transfer functions between all potential sources and all possible receivers are calculated and analysed. Based on this analysis, an optimum of i.e. low intelligibility over all WS can be found, which was not possible beforehand. Tab. I shows the STI between the first 16 sources and all 32 receivers. The full table is twice as large which was omitted for reasons of space.

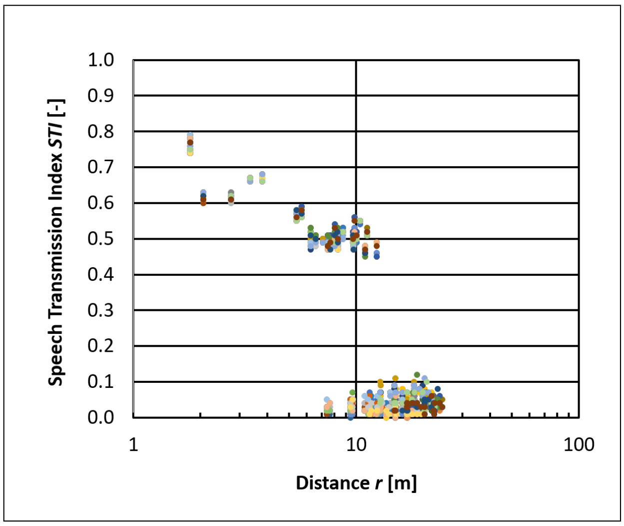

Figure 4. Plot of STI over distance for all source and receiver positions

As the distance between all sources and receivers is known, the results can be plotted over the distance from the source. This was done in Fig. 4. As the arrangement of furniture in the room is highly symmetrical and so are sources and receivers, there are groups of data. Those groups are analysed in the following, starting from the sources with highest STI.

5.1. Group 1: High intelligibility close to sources

There is a group of sources with STI values between 0.75 and 0.8, which is also the group closest to the receiver. Those are WS with desks side by side but

Table I. Source-Receiver Matrix of the first 16 sources and all 32 receivers in Fig. 3

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	-	0.77	0.62	0.62	0.57	0.57	0.50	0.49	0.51	0.56	0.48	0.51	0.50	0.52	0.46	0.49
2	0.77	-	0.63	0.61	0.58	0.57	0.51	0.51	0.51	0.53	0.49	0.49	0.52	0.51	0.48	0.48
3	0.61	0.61	-	0.75	0.66	0.67	0.58	0.58	0.49	0.52	0.49	0.50	0.51	0.55	0.50	0.51
4	0.62	0.6	0.74	-	0.67	0.66	0.59	0.57	0.50	0.50	0.47	0.49	0.50	0.52	0.51	0.50
5	0.58	0.58	0.66	0.68	-	0.75	0.61	0.61	0.51	0.53	0.50	0.55	0.49	0.49	0.48	0.50
6	0.59	0.58	0.66	0.66	0.74	-	0.61	0.6	0.52	0.52	0.49	0.53	0.48	0.49	0.49	0.48
7	0.50	0.50	0.57	0.57	0.62	0.62	-	0.78	0.47	0.49	0.50	0.52	0.47	0.50	0.49	0.52
8	0.51	0.51	0.58	0.57	0.62	0.61	0.78	-	0.47	0.48	0.51	0.50	0.48	0.48	0.50	0.51
9	0.54	0.53	0.50	0.51	0.52	0.53	0.47	0.48	-	0.78	0.63	0.62	0.57	0.56	0.49	0.49
10	0.56	0.52	0.51	0.50	0.52	0.50	0.46	0.46	0.79	-	0.62	0.62	0.57	0.56	0.48	0.47
11	0.51	0.51	0.49	0.50	0.52	0.50	0.51	0.52	0.62	0.61	-	0.74	0.66	0.67	0.58	0.57
12	0.52	0.50	0.50	0.48	0.54	0.52	0.51	0.50	0.61	0.61	0.74	-	0.68	0.67	0.57	0.56
13	0.51	0.53	0.52	0.50	0.49	0.49	0.50	0.50	0.58	0.57	0.66	0.67	-	0.75	0.62	0.61
14	0.52	0.51	0.55	0.52	0.50	0.48	0.51	0.49	0.57	0.56	0.67	0.67	0.76	-	0.6	0.61
15	0.47	0.48	0.51	0.53	0.48	0.51	0.53	0.52	0.49	0.48	0.57	0.57	0.62	0.62	-	0.77
16	0.45	0.46	0.51	0.50	0.49	0.49	0.53	0.50	0.48	0.47	0.56	0.55	0.61	0.62	0.78	-
17	0.02	0.07	0.04	0.06	0.04	0.07	0.01	0.02	0.04	0.01	0.07	0.05	0.04	0.01	0.04	0.02
18	0.04	0.07	0.03	0.07	0.04	0.05	0.01	0.01	0.05	0.01	0.07	0.05	0.03	0.02	0.04	0.02
19	0.05	0.04	0.03	0.08	0.07	0.03	0	0.01	0.04	0.02	0.07	0.04	0.01	0.01	0.05	0
20	0.05	0.04	0.03	0.08	0.05	0.06	0.01	0.02	0.04	0.01	0.06	0.04	0.02	0.02	0.03	0.01
21	0.03	0.03	0.09	0.08	0.04	0.04	0.01	0.02	0.02	0.02	0.09	0.07	0.03	0.01	0.04	0.02
22	0.03	0.04	0.05	0.08	0.05	0.05	0.01	0.03	0.03	0.03	0.08	0.05	0.03	0.02	0.04	0.02
23	0.06	0.02	0.04	0.08	0.02	0.01	0.01	0.01	0.04	0.05	0.04	0.02	0.03	0.01	0.04	0.01
24	0.05	0.05	0.03	0.06	0.02	0.02	0	0.01	0.04	0.03	0.05	0.02	0.04	0.02	0.03	0.01
25	0.04	0.05	0.08	0.07	0.02	0.05	0.02	0.04	0.02	0.03	0.07	0.07	0.04	0.02	0.03	0.02
26	0.03	0.05	0.07	0.07	0.01	0.03	0.02	0.03	0.03	0.02	0.07	0.05	0.03	0.03	0.03	0.02
27	0.02	0.06	0.05	0.08	0.02	0.04	0.02	0.04	0.04	0.02	0.08	0.03	0.02	0.01	0.02	0.03
28	0.02	0.04	0.03	0.06	0.01	0.03	0.02	0.04	0.04	0.02	0.06	0.03	0.01	0.03	0.02	0.01
29	0.03	0.06	0.05	0.07	0.05	0.05	0.03	0.03	0.04	0.03	0.07	0.03	0.02	0.02	0.03	0.02
30	0.02	0.04	0.04	0.06	0.02	0.04	0.02	0.03	0.02	0.03	0.07	0.03	0.02	0.02	0.02	0.02
31	0.03	0.04	0.02	0.06	0.02	0.04	0.02	0.02	0.06	0.04	0.05	0.02	0.03	0	0.01	0.03
32	0.03	0.02	0.03	0.07	0.02	0.03	0.01	0.05	0.01	0.05	0.07	0.01	0.04	0	0.01	0.01

without screen (i.e. WS 1–WS 2). The next group with STI around 0.68 are transmission paths to the next workstation without screen (i.e. WS 3–WS 5). There are two groups of sources with STI around 0.63 at two different distances, which are the transmission paths across the screen (i.e. WS 1–WS 3 and WS 1–WS 4, respectively). Those sources within the distance of 4 m are all highly intelligible.
A brief count in Tab.I shows that for this floor layout, there are typically 3–5 sources, which are close to the receiver and highly intelligible.

5.2. Group 2: Intelligibility at larger distance

The majority of intelligible sources in this example is located 5 m–11 m from an arbitrary receiver WS. All sources are intelligible ($STI \approx 0.5$) and as such potentially distracting.

5.3. Group 3: Unintelligible sources

The location of the meeting rooms in the floor layout leads to an effective division into two acoustical subgroups which do not interfere with each other. In Tab. I all WS within the first subgroup (WS 1–WS 16) show $STI < 0.2$ for the remaining WS, see Tab. I, lines 17–32. This means that WS 1–WS 16 are not disturbed by conversations in WS 17–WS 32. From the acoustical perspective this means that a maximum of 16 sources can be present at the same time in each of the subgroups.

6. Discussion

In the example given, there is no measurement path which is compliant to ISO 3382-3: No four measurement points can be found which are placed 2 m or more from the next wall, located 2 m < r < 16 m from the source. So the choice it to the acoustician, which rules of the standard to uphold or violate. In the existing version, the standard can be applied in full only to larger offices with suitable layout.
With the new source-receiver matrix, there are no restrictions on source or receiver positions, as all existing user positions are included. As such, the procedure is much more versatile than any procedure based on paths. The source-receiver matrix holds all information on the relevant positions in the room. There are many new opportunities to analyse the matrix and to draw conclusions from it.

In Sections 5.1 – 5.3 Groups 1 – 3 were introduced. It is unlikely, that highly intelligible sources of Group 1 can be rendered completely unintelligible. However, certain floor layouts might allow to reduce the number of highly intelligible sources. To render sources of Group 2 unobtrusive, increasing acoustical measures such as absorption or screen hight may be an option. However, there are many sources in Group 2. With the theoretical considerations in Fig. 2, any source receiver path that can be reduced to $STI < 0.35$

would drop out of the number of workstations contributing to the interference. So the perceived time without distraction in receiving WS would increase. This procedure is possibly simpler to communicate to laymen then certain changes in acoustical parameters. Finally, the existence of Group 3, which does not interfere with many WS at all is very simple to show with the source-receiver matrix and is not explicitly shown by the parameters of ISO 3382-3. This may help to organise floor designs in areas for different tasks to be carried out i.e. in an activity based organisational approach.
Speech intelligibility is easier to communicate to acoustical laymen such as most architects than i.e. decibel values. As speech intelligibility appears to play the most important role both for annoyance [6] and cognitive performance [2] in the open-plan office, the STI can be used to explain the impact of certain design changes in projects, see i.e. Fig. 1.

6.1. Limitations

The proposed approach is not meant to replace the approach of ISO 3382-3. For measurement of suitable spaces, the procedure is well established and validated. The source-receiver matrix is proposed to foster simulative approaches for open-plan offices. Using it should lead to more insight on which sources are potentially disturbing and can be eliminated. As such it has the same limitations as all room acoustical simulation approaches: The model needs to resemble the building project and the algorithms used need to fit the purpose.

6.2. Further research and progress needed

As the solution relies on simulation of many different source-receiver positions, it would be helpful to include certain simulation routines in all common room acoustical software solutions. In comparison to the calculation of grids the source-receiver matrix comprises more sources and fewer receivers. As such, it will be computationally less expensive than grids. However, a sensible user interface to set the combined sources and receivers would be helpful.
Furthermore, a number of new tools for the analysis of source-receiver matrices is required. Firstly, the density of highly intelligible workplaces could be plotted in a color map. Secondly, the transmission paths for a single receiver could be colour-coded to analyse details.
More research is required to understand the distribution of conversations (space and time) taking place in open-plan offices to further develop the model.

Finally, the source-receiver matrix holds all information on parameters found by measurement according to ISO 3382-3. So $D_{2,S}$, $L_{p,A,S,4m}$ and r_D can be derived from the matrix of room impulse responses calculated. Certainly, the rules of ISO 3382-3 need to be applied to a suitable geometry. From it, the typical spread of $D_{2,S}$, $L_{p,A,S,4m}$ and r_D can be statistically predicted for a building given. Like this, the source-receiver matrix could be translated back into ISO 3382-3 target values.

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