Spatial decay rate of speech in open plan offices: the use of $D_{2,S}$ and $L_{p,A,S,4m}$ as building requirements

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Summary

In 2012, new room acoustic parameters for open plan offices were introduced in the ISO 3382-3 standard. While concepts like the spatial decay rate and speech privacy have been used already in judging open plan office designs, now the standard provides an internationally agreed measurement procedure. Four single number ratings are proposed: the decay rate of speech, $D_{2,S}$, the A-weighted sound pressure level of speech at a distance of 4 m, $L_{p,A,S,4m}$, the distraction distance, r_D (above which the Speech Transmission Index, STI, falls below 0.50), and the average A-weighted background noise level, $L_{p,A,B}$. These new parameters are increasingly used in drawing up requirements for new buildings. The intention of the ISO 3382-3 is to evaluate all four single number ratings, because each parameter controls different acoustic quality aspects. In particular $D_{2,S}$ and $L_{p,A,S,4m}$ should always be used together. In this paper, measurement data of various rooms are discussed to find out whether requirements for $D_{2,S}$ and $L_{p,A,S,4m}$ would guarantee the desired reduction in speech level over distance. Results are compared to the classification system as suggested by Virjonen et al. and Nocke. It is found that the measured decay rate of speech can be relatively low ($D_{2,S} < 7$ dB) meeting class D, while the absolute speech level $L_{p,A,S}$ is below a class B rated trend line with $D_{2,S} > 10$ dB and $L_{p,A,S,4m} < 50$ dB. Such examples shows that the current suggested classification systems can fail. A different approach to judging offices is suggested using individual data points. Finally, a design chart is presented for values of $L_{p,A,S}$ considering the distraction distance and the background noise level.

PACS no.

1. Introduction

In 2012, new room acoustic parameters for open plan offices were introduced in the ISO 3382-3 [1] standard, based on research by Virjonen et al. [2]. While concepts like the spatial decay rate and speech privacy have been used already in judging open plan office designs, now the standard provides an internationally agreed measurement procedure. Four single number ratings are proposed: the decay rate of speech (level reduction when doubling the distance), $D_{2,S}$, the A-weighted sound pressure level of speech at a distance of 4 m, $L_{p,A,S,4m}$, the distraction distance, r_D (above which the Speech Transmission Index, STI, falls below 0.50), and the average A-weighted background noise level, $L_{p,A,B}$. These new parameters are increasingly used in drawing up requirements for new buildings. The intention of the ISO 3382-3 is to evaluate all four single number ratings, because each parameter might control different acoustic quality aspects. In particular, $D_{2,S}$ and $L_{p,A,S,4m}$ should always be used together, because they both concern the A-weighted speech level.

The privacy distance r_D has a clear perceptual meaning as it directly concerns the intelligibility of speech and hence the reduction of distraction. $D_{2,S}$ and $L_{p,A,S,4m}$ together describe the speech level as a function of distance $L_{p,A,S}(r)$. They directly relate to the actual physical environment of the office, like screens and absorbing materials [3]. However, the intelligibility of speech cannot be judged based on $D_{2,S}$ and $L_{p,A,S,4m}$ alone. The effect of background noise, $L_{p,A,B}$, and the effect of room acoustics (reverberation and reflection patterns) have to be taken into account.

Provided that they are sufficiently correlated to the human perception of acoustic quality of open plan offices, the parameters have the potential te be useful in judging and designing open plan offices. And, guidelines or requirements are yet to be established. Such requirements should allow designers to reach their goal through multiple solutions, and requirements should be both realistic and challenging. In this paper, the opportunities and limitations for using the suggested parameters $D_{2,S}$, $L_{p,A,S,4m}$, r_D and $L_{p,A,B}$ as design guidelines are investigated.

2. Suggestions for target values

2.1 Virjonen

Virjonen et al. performed measurements in 16 different open plan offices, 15 out of 16 offices having screens with a height above 1.2 m [2]. Based on their findings, they suggest to divide the acoustic quality of the offices into four different classes A to D, see table 1. The background noise level was not included in the table, but reference is made to Finnish guidelines that ask for a $L_{p,A,B}$ between 40 and 42 dB.

Table 1: Quality classes as suggested by Virjonen et al. Class A represents the highest speech privacy (Table V in [2]).

Class	DL_2 [dB]	$L_{p,S,4m}$ [dB]	r_D [m]
A	>11	<48	<5
B	9 to 11	48 to 51	5 to 8
C	7 to 9	51 to 54	8 to 11
D	<7	>54	>11

Virjonen et al. suggest that an open plan office for individual work should meet class A. For teamwork, a class C office is recommended, however, between separate teams, again class A is recommended.

It is clear that both $D_{2,S}$ and $L_{p,A,S,4m}$ requirements should be met within a class. To investigate the relationship between the values for the existing offices and the suggested classification system, in figure 1, the boundaries between each class are projected on the measured data from Virjonen et al. [2]. The class edges are not equally spread over the data. This suggests, that at least $D_{2,S}$ = 7 and $L_{p,A,S,4m}$ = 54 should be reached to substantially improve speech privacy conditions in an open plan office.

It is unclear whether r_D should be used as an additional or separate requirement.

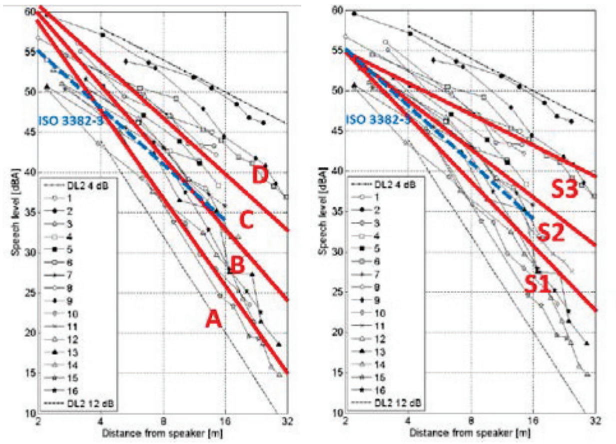

Figure 1: speech level as a function of distance $L_{p,A,S}(d)$ measured by Virjonen et al. (Figure 3 in [2]). Left: classification by Virjonen et al. [2]. Right: classification by Nocke [4]. Blue: ISO 3382-3 target.

Table 2: Single number ratings for mesaurement data [2,3]. '*class (no r_D)*': classification Virjonen et al. without juding r_D [2]. '*step*': classification Nocke [4].

Office	*1: $D_{2,S}$*	*2: $L_{p,A,S,4m}$*	*3: r_D*	*class (no r_D)*	*step*
1	4	53.8	14.2	D	-
2	4.2	57.2	18.5	D	-
3	4.6	52.5	9.5	D	-
4	5.7	49.4	5.6	D	3
5	6	50.9	15.4	D	3
6	6.2	52.6	5.4	D	-
7	6.3	47.5	13.8	D	2
8	6.4	52.4	10.3	D	-
9	6.7	54.4	15.3	D	-
10	9	43.4	5.5	C	1
11	9.2	48.3	9.9	B	2
12	9.4	49.4	9.3	B	3
13	11.4	46.5	9.5	A	1
14	11.5	47.1	6.2	A	2
15	11.7	49	8.1	B	2
16	12.4	49.9	10	B	3
A	4.9	47.4	16.2	D	3
B	6	49.1	15.3	D	3
C	6.4	44	11.4	D	2
D	6.4	50.4	11.9	D	3
E	7.8	47.9	8.8	C	2
F	8.2	51.5	11.1	C	3
G	9.3	50.3	14	B	3
H	9.4	50.3	6	B	3
I	9	53.9	9.7	C	-
J	11.6	49.3	9.3	B	3

The single number ratings of the study by Virjonen et al. [2] (office 1 to 16), and a follow-up study of the same research group [3] (office A-J) are presented in table 2. In the 4th column of the table, the class is indicated when judging the single number ratings $D_{2,S}$ and $L_{p,A,S,4m}$ only. Figure 2 shows the percentage of offices in a certain category, with and without judging r_D.

As Virjonen et al. point out "The idea of ABCD classification is to promote the design of higher acoustic quality instead of the present culture where certain minimum requirements, i.e. class D, is considered to be sufficient." Based on results for $D_{2,S}$ and $L_{p,A,S,4m}$, a class A was possible in office 13 with 1.6 m high sound absorbing screens and office 14 with 2.2 m high reflective cellular screens. However, the distraction distance $r_D < 5$ m was not reached, not even in these offices. It is striking that none of the offices measured in their research, of which many have a substantial amount of screens, cannot meet all class A requirements.

2.2 ISO 3382-3

The recommended classification system was not included in the final version of the ISO 3382-3 standard. Instead, it is stated that "an example of target values could be $D_{2,S} \geq 7$ dB, $L_{p,A,S,4m} \leq 48$ dB and $r_D \leq 5$ m". The resulting target 'line' for $D_{2,S}$ and $L_{p,A,S,4m}$ is shown in figure 1 as a blue curve. When judging the single number ratings $D_{2,S}$ and $L_{p,A,S,4m}$ only, 23% of the offices measured by Virjonen et al. would fulfill the target. However, again, when also taking into account the desired privacy distance, none of the offices fulfill.

2.3 Nocke (German code VDI 2569)

Nocke [4] presented other target values for ISO 3382-3 parameters, to be included in the German standard VDI 2569. Table 3 gives an overview of target values for room acoustics (table 3a) and sound propagation (table 3b) related parameters. To achieve a certain quality class, table 3c shows which room acoustic and sound propagation requirements should be met.

The distraction distance, r_D, based on STI measurements, is not included in the classification system. According to Nocke, the STI measurement is too unreliable because the background noise can vary and, as a result, measurement conditions may not reflect actual working conditions. This might indeed be the case when using a modulated noise signal for the STI measurement. However, when performing STI measurements, the background noise can be measured separately. An example of such a measurement using impulse responses is shown by Wenmaekers et al. [5]. Besides, it is striking that Nocke suggests upper limits for the background noise level instead of minimum masking levels. In the 5th column of the table 2, the classification score by Nocke is indicated for the measured offices.

Table 3: Quality classes as suggested by Nocke [4] for the German guideline VDI 2569.

a: room acoustics class

Room Acoustic Class	Reverberation time T_{max}[s] 125 Hz	250 Hz – 4000 Hz	Level $L_{NA,Bau}$ [dB]
A	≤ 0.8	≤ 0.6	≤ 35
B	≤ 0.9	≤ 0.7	≤ 40
C	≤ 1.1	≤ 0.9	≤ 40

b: sound propagation class

Step of propagation	Spatial decay rate $D_{2,S}$ [dB]	Level $L_{p,A,S,4m}$ [dB]
S1	≥ 8	≤ 47
S2	≥ 6	≤ 49
S3	≥ 4	≤ 51

c: quality classification

Class	Requirement on step of propagation	Requirement room acoustics
A	2/3 of propagation lines in S1 rest in S2	room acoustic class A
B	2/3 of propagation lines in S2 rest in S3	room acoustic class B
C	1/3 of propagation lines in S2 rest in S3	room acoustic class C

2.4 Overview

Figure 2 shows the classification scores for each suggested set of targets. Because the Nocke classification is less strict in terms of $D_{2,S}$, but requires a lower $L_{p,A,S,4m}$, a similar amount of offices measured reach class A/B or Step 1/2 if ignoring the r_D target. The ISO target divides the data into the better (class A/B or Step 1/2) and worse (class C/D or Step 3/no) offices.

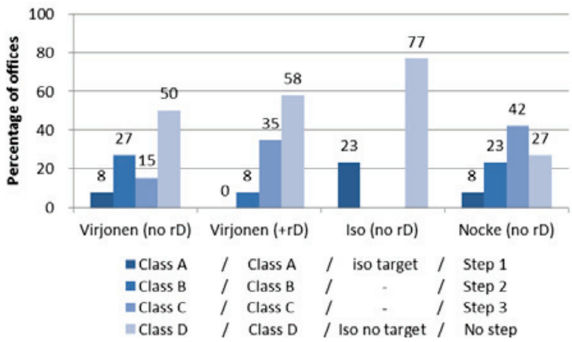

Figure 2: various classification scores for 26 measured offices, based on data from [2,3]

3. Judging speech level reduction

3.1. Problems with classification

The single number ratings are determined for the data points at source to receiver distance between 2 and 16 meters using the least squares method. However, in figure 1, it is shown that the individual measurement points of many offices fall into two different classes. However, following ISO 3382-3, offices should not be judged based on their individual data points, but on their single number ratings. This can be problematic.

In figure 3, the speech level as a function of distance is presented for a selection of two different offices measured by the authors:

- Office 1a: absorbing ceiling, no screens ($D_{2,S}$ = 4.2 dB, $L_{p,A,S,4m}$=52.2 dB)
- Office 1b: office 1a with screens and side wall absorption added ($D_{2,S}$ = 5.6 dB, $L_{p,A,S,4m}$=43.6 dB)
- Office 2: absorbing ceiling with cupboards ($D_{2,S}$ = 5.5 dB, $L_{p,A,S,4m}$=51.9 dB)

Besides, the limits for the A-D classification system as suggested by Virjonen et al. are shown in the graph.

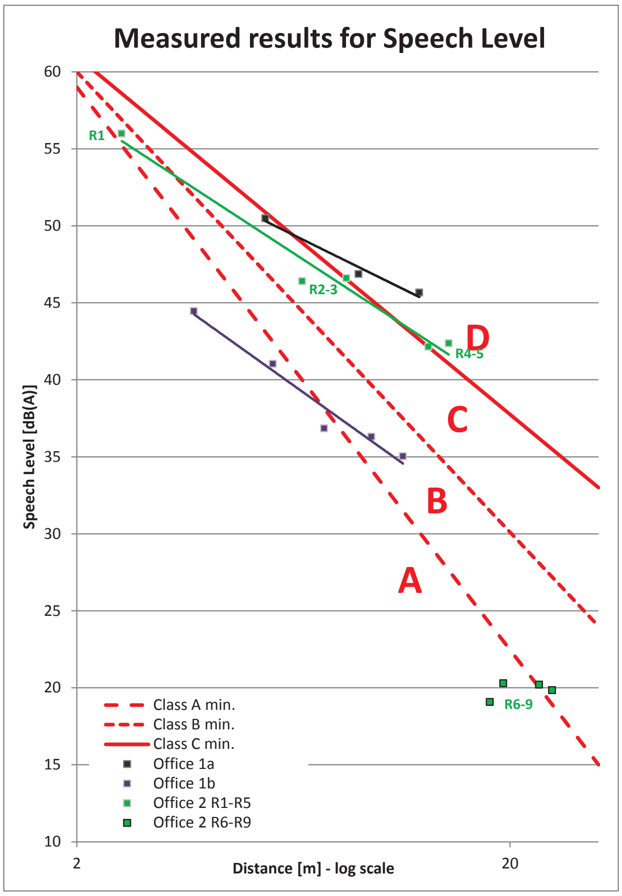

Figure 3: speech level as a function of distance

When comparing the individual data points and their trend lines to the A-D class limits, we can conclude that the measured decay rate, $D_{2,S}$, is always less than any of the limits. For office 1, adding a vast amount of screens and absorption reduced the speech level at all distances by at least 10 dB, and a reduction of 8.6 dB in $L_{p,A,S,4m}$. However, the decay rate is only reduced by 1.4 dB, which means that this office remains class D. The individual points fall into class A and B, which would clearly be a better judgment for this office.

For office 2, the data points up to 16 meters fall into class B, C and D, while the $D_{2,S}$ would suggest class D. Besides, the data points beyond 16 meters, that are located behind a partition wall in the office (see figure 4), are near or below the class A limit.

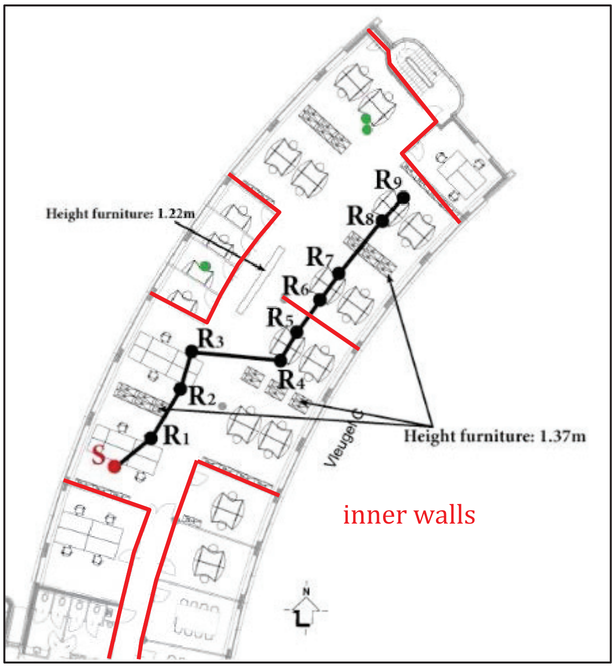

Figure 4: Floor plan of office 2

3.2. Other ways of judging speech level

We can conclude that the speech level as a function of distance can vary outside the limits of the suggested classes. It seems that a class system based on $D_{2,S}$ together with $L_{p,A,S,4m}$ is too rigid for judging open plan offices. To allow for more freedom in judging open plan offices, we suggest to project the individual data points in a graph together with a set of class limits (to be determined). For example, as shown in figure 2, one could judge office 2 as follows: R1-R3 = class C, R4-R5 = class D and R6-R9 = class A.

4. Distraction distance

The primary goal in an open plan office is to reduce speech intelligibility below acceptable limits. Judging speech level only is not sufficient to predict the speech intelligibility in an open plan office because room acoustics and noise are not taken into account. In that context, the distraction distance, based on the STI, is a more complete parameter to use as a requirement for the acoustics in an office. However, the distraction distance is difficult to use as a design parameter, because the interaction of the different factors speech level, reverberation and background noise is difficult to see through.

Keränen and Hongisto [3] have presented a model that predicts the speech level as a function of distance $L_{p,A,S}(r)$ based on architectural parameters like room size, screen height and absorption, ceiling absorption and room absorption. The speech level $L_{p,A,S}(r)$, background noise level $L_{p,A,B}$, and the early decay time, EDT, are used in the STI model to predict the distraction distance r_D. Surprisingly, the EDT is estimated based on Sabine's equation, even though it is known to be inaccurate for large, flat spaces with unequal absorption distribution [6].

The STI calculation is a quite a laborious process, see equations 1 to 4 in [3]. So, a method to avoid such calculation would be valuable to be able to understand the effect of architectural parameters and to predict r_D. In this section, we will investigate how accurate we might predict r_D based on measured values of $D_{2,S}$, $L_{p,A,S,4m}$, $L_{p,A,B}$ only.

4.1 Simplified prediction of r_D

The first step is to determine the average modulation transfer function for the effect of reverberation for the single number rating EDT and the 14 modulation frequencies F_i 0.63 to 12.5:

$$m_{avg,rev} = \frac{1}{14}\sum_{i=1}^{14} \frac{1}{\sqrt{1+[2\pi F_i EDT/13.8]^2}} \qquad (1)$$

As we discard the weighting factors because we can only use single number ratings, m_{avg} directly yields the STI for the effect of reverberation only.

Then, we determine at what Signal to Noise Ratio ($L_{p,A,S}$ - $L_{p,A,B}$) the STI would be 0.5 while taking into account the effect of reverberation denoted SNR_D (with a maximum of 15 dB):

$$SNR_D = -10\lg\left[\frac{m_{avg,rev}}{0.5} - 1\right] \qquad (2)$$

The last step is to calculate the distraction distance which is the distance where $L_{p,A,S}$ - $L_{p,A,B}$ = SNR_D:

$$r_D = 10^{0.3\left(\frac{L_{A,S,4m} - L_{p,A,B} - SNR_D}{-D_{2,s}}\right)+0.6} \qquad (3)$$

The results for the calculated SNR and error between calculated and measured distraction distance are given in table 3.

Table 3: calculated SNR and r_D error

Office	*EDT*	*$L_{p,A,B}$*	*SNR_D STI=0.5*	*r_D error SNRcalc*	*r_D error SNR=3.7*
1	0.36	39	1.9	-23	-13
2	0.63	45	3.8	3	2
3	0.47	42	2.6	-3	-2
4	0.71	41	4.5	-1	-1
5	0.31	35	1.5	-5	-1
6	1.37	44	15.5	4	-1
7	0.55	31	3.2	-3	-2
8	0.64	39	3.9	-1	-1
9	0.77	40	5.0	5	3
10	0.66	39	4.1	1	1
11	0.53	35	3.1	1	2
12	0.54	37	3.1	1	2
13	0.6	31	3.6	1	1
14	0.75	31	4.8	-2	-2
15	0.64	31	3.9	-1	-1
16	0.69	33	4.3	2	2
A	0.61	34	3.7	1	1
B	0.68	32	4.2	-2	-3
C	0.37	29	1.9	-5	-2
D	0.56	38	3.3	1	2
E	0.42	34	2.3	-2	-1
F	0.39	35	2.1	-2	-1
G	0.33	32	1.7	0	2
H	0.5	38	2.9	-2	-1
I	0.46	38	2.6	-1	0
J	0.37	39	1.9	3	3

From the calculated SNR_D values, we can conclude that the effect of reverberation on speech intelligibility at STI = 0.5 varies between 1.5 and 5 dB in 'apparent SNR' with an average of 3.7 dB (with one exception of 15.5 dB in the reverberant office 6).

To avoid the laborious STI calculation, and possibly avoiding EDT measurements or predictions, we tested the r_D prediction model in equation 3 using the average SNR_D = 3.7 dB.

Results are found in table 3, in the 6th column. Surprisingly, the error in r_D prediction using an average SNR, instead of the real SNR, seems smaller for most cases (R^2=0.75). The average absolute error is 1.7 m, which might be acceptable.

5. Towards a design chart

We can now define r_D in a simplified and straightforward way:

The distraction distance is the distance where the Speech Level equals Background Noise + 3.7 dB.

Using this definition, we developed an example of a design chart, see figure 5. We give examples for finding an appropriate design for an office.

Example 1:
required: $r_D \leq 5$ m, noise level $L_{p,A,B} = 40$ dB
goal: design an office with screens and absorption matching decay class A, distance between teamed workstations > 5 m.

Example 2:
required: $r_D \leq 8$ m, noise level $L_{p,A,B} = 35$ dB
goal: design an office with screens and absorption matching decay class B or higher, distance between teamed workstations > 8 m.

Example 3:
required: $r_D \leq 8$ m, few or no screens desired
goal: design a class D office with a masking level $L_{p,A,B} > 40$ dB and distance between teamed workstations > 8 m.

Example 4:
required: $r_D \leq 5$ m, low noise level $L_{p,A,B} < 35$ dB
goal: likely not possible

These examples show the potential of the design chart. However, a proper classification system for $D_{2,S}$ and $L_{p,A,S,4m}$ is still to be developed. Possibly, as discussed in section 3.2, judging individual data points for $L_{p,A,S}$ might be inevitable instead of using the single number ratings (only).

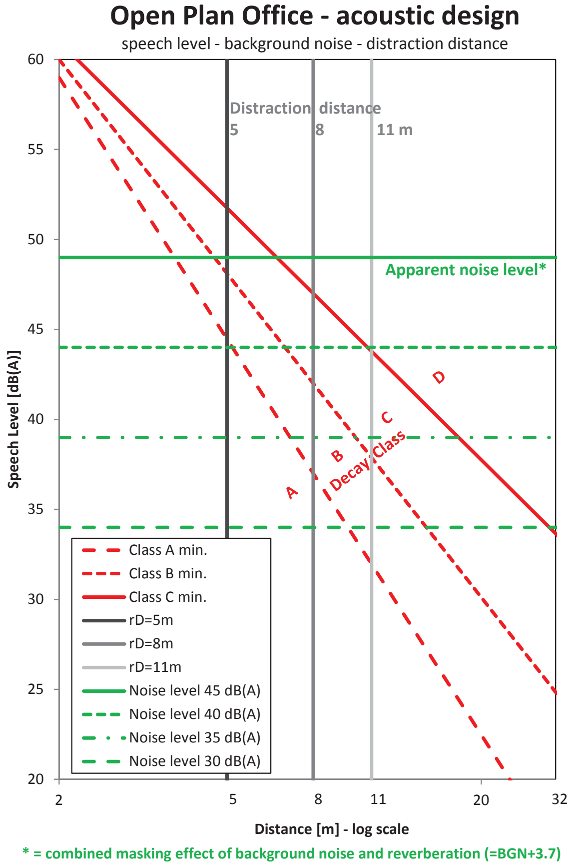

Figure 5: Design chart example using Virjonen classes.

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