27th INTERNATIONAL CONGRESS ON SOUND AND VIBRATION
12 – 16 July 2020, Prague

ICSV27
PRAGUE

Annual Congress of the International Institute of Acoustics and Vibration (IIAV)

ANALYSIS OF OPEN PLAN ACOUSTIC PARAMETERS BASED ON SWISS AND INTERNATIONAL DATABASES OF IN SITU MEASUREMENTS

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The parameters described in ISO 3382-3 were chosen to describe the acoustic conditions specifically found in open plan offices (OPO), such as distraction due to irrelevant speech and lack of speech privacy. This paper presents and analyses a set of measurements performed in 22 OPO in Switzerland, supplementing the limited existing empirical data in this field. The results are compared with 4 other databases found in literature and with the requirements found in various standards (ISO, FIN, D, F). Based on 108 OPO from the joint databases, the correlations and relations between ISO parameters and room variables (room dimensions, screen and absorption characteristics) are also studied. It is first found that ISO parameters are quite independent from each other. The most relevant characteristics are found to be the screen height, the ceiling absorption and background noise (especially for distraction distance). Simple empirical equations to calculate acoustic parameters are then derived from the large database, which allows improvement of existing models. Finally, concrete solutions are suggested for practical purposes.
Room Acoustics, Open Plan Office, ISO 3382-3, Distraction Distance, Planning Values

1. Introduction

Open plan offices (OPO) are intended to facilitate communications and encourage collaboration between workers as well as blur workplace hierarchies. Other benefits also exist on the economic level, with higher occupant densities and ease of reconfiguration. However one of the drawbacks for the workers in such working environments are the inconvenient acoustic conditions, resulting in high distraction by irrelevant speech, lower productivity and low privacy [1], [2], [3]. Architectural solutions to these problems include the use of absorbing materials, partitions between workspaces and high background sound. Careful use of these solutions is necessary, as they can have negative effects (ex. adding sound absorption can lead to higher speech distraction).

The ISO 3382-3 [4] acoustic parameters (distraction distance r_D, spatial decay rate of speech per distance doubling $D_{2,s}$, A-weighted SPL of speech at distance of 4m$L_{p,A,s,4m}$, background noise level $L_{p,A,B}$) were specifically chosen to describe the peculiar acoustic conditions of OPO. Only through the consideration of all 4 parameters is it possible to obtain sufficient acoustic conditions [5]. The aim of this paper is to investigate the inter-correlation and the effects of architectural design (absorption, screens, sound masking, room variables) on the ISO 3382-3 acoustic parameters. This is done by investigating OPO databases containing measured acoustic parameters and corresponding room variable

2. Previous works

Keränen et al. developed [6] and later revised [7] a regression model to predict acoustic parameters from room variables based on a Finnish database containing 16 OPO [8] (plus 10 offices to check the model). They also investigated the correlations between the acoustic parameters and room variables, giving insight on the complex interactions between them.

Haapakangas et al. [5] investigated the relation between acoustic parameters and perceived noise disturbance in a study based on measurements and questionnaires in 21 Finnish offices. The distraction distance r_D was found to be the parameter most correlated with noise disturbance. Although it is noted in the paper that r_D should not be the only defining parameter for designing an OPO. For example high reverberation and high background noise allow for low r_D, but lead to uncomfortable acoustic conditions.

Selzer et al. [9] investigated the performances of 13 OPO according to the German standard [10] classification scheme. It was shown that the proposed classes are extremely difficult to achieve. Only 4 of 13 reached the acoustic room classes B or C while the nine remaining did not reach the conditions for class C. The author also points out the pitfalls associated with the measurements in accordance with ISO 3382-3, where the choice of measurement paths can lead to a change in acoustic class.

In a paper proposed by Yadav et al. [11], the ISO 3382-3 measurement repeatability and reliability is investigated. These measurements are carried out in 27 offices and show that the repeatability of measurements can be considered reasonable, especially for r_D. These good results are possibly due to the fact that the sine-sweep method was used as excitation signal and the recording was done simultaneously at all receiver positions with multiple microphones.

3. Swiss Open plan office database

In the past decades, EcoAcoustique SA has performed ISO 3382-3 measurements in 22 OPO in Switzerland (cf. Table 1). This database also contains very detailed information about the room's physical parameters (room dimensions, ceiling absorption, partition information, number of workplaces, cf. Table 2). It is to be noted that the measurements were often carried out due to complaints and thus this database represents generally poor acoustic conditions (even though some rooms in which complaints were made showed good conditions based on the objective parameters). A GABO questionnaire (which is found in annexe C of the French standard NF S 31-199 [12]) was carried out along with the measurements in room M(1). The questionnaire showed that in this office the sound sources from most disturbing to least were 1. Intelligible conversations, 2. Unintelligible conversations, 3. machinery noise, 4. phone ring and 5. Passage of people.

4. Statistical study of joint database

For a more statistically robust investigation of correlations among acoustic parameters and room variables, the Swiss OPO database was supplemented with the 4 other OPO databases ([7]/[8],[9],[11], cf. section 2) containing various combinations of ISO 3382-3 measurements and room variables. Table 3 compares the average values of the acoustic parameters and room variables from each of the databases. Interestingly, the OPO in Australia (measurements by Yadav et al.) generally have the best r_D conditions, but the worst $L_{p,A,S,4m}$ and $D_{2,s}$ conditions. This conflicting result is due to higher background noise in these OPO than in the other countries. The worst results for r_D are found in Germany, but there is no information on neither the background noise nor partitions in the database. The best results for $L_{p,A,S,4m}$ are found in Switzerland and those for $D_{2,s}$ are found in Finland. The average reverberation times and ceiling absorptions in the databases are quite similar to each other, which shows that classical acoustic treatments are generally applied.

Table 1 : Measured ISO 3382-3 parameters in the 22 OPO in Switzerland.

Building (office)	r_D	$L_{p,A,S,4m}$	$D_{2,s}$	$L_{A,B}$	T_r
A(1)	11.8	50.4	5.0	32	0.33
B(1)	11.7	56.5	4.9	38	0.50
C(1)	15.9	50.0	5.7	34	0.50
D(1)	10.6	51.0	6.0	38	0.50
E(1)	8.4	44.1	7.6	30	0.35
F(1)	21.2	48.4	4.2	27	0.52
F(2)	15.1	49.4	4.1	28	0.45
G(1)	10.5	42.6	5.3	34	0.50
G(2)	13.0	45.7	6.3	34	0.50
H(1)	9.3	49.2	8.0	27	0.61
I(1)	5.2	41.2	6.3	33	0.50
I(2)	9.7	49.1	5.8	41	0.50
J(1)	7.3	48.4	6.7	39	0.55
J(2)	16.0	52.0	7.0	26	0.55
K(1)	6.8	46.0	4.2	34	0.63
L(1)	11.5	47.0	7.5	33	0.39
l(2)	10.1	46.9	8.6	33	0.39
L(3)	10.1	47.4	8.4	37	0.39
M(1)	9.6	49.6	5.5	36	0.63
N(1)	12.0	48.6	11.8	26	0.25
N(2)	15.0	49.7	7.0	31	0.30
N(3)	6.5	39.7	5.7	31	0.30

Table 2 : Room variables of the 22 OPO in Switzerland.

Building (office)	L	W	H	h	αc	αf *	n° workplaces
A(1)	11.3	9.8	2.5	-	0.6	0.4	14
B(1)	15.0	4.0	2.8	-	0.1	0.3	8
C(1)	24.0	5.6	2.6	-	0.6	0.2	18
D(1)	13.4	8.0	2.7	1.2	0.3	0.2	14
E(1)	16.7	11.3	2.5	1.8	0.8	0.4	24
F(1)	23.0	6.0	2.7	1.2	0.8	0.1	16
F(2)	16.0	16.0	2.7	1.2	0.8	0.1	20
G(1)	15.2	6.4	2.5	1.6	0.7	0.4	26
G(2)	34.0	6.4	2.5	1.1	0.7	0.4	41
H(1)	24.0	6.5	3.0	1.8	0.2	0.5	10
I(1)	15.0	14.0	3.5	1.2	0.8	0.5	54
I(2)	10.0	13.0	3.5	-	0.8	0.3	30
J(1)	16.0	7.0	6.0	-	0.6	0.3	12
J(2)	31.5	7.7	3.0	-	0.6	0.4	16
K(1)	21.7	14.2	4.0	1.2	0.8	0.4	10
L(1)	26.0	6.5	2.4	1.5	0.6	0.5	20
l(2)	26.0	6.5	2.4	1.8	0.6	0.5	20
L(3)	26.0	6.5	2.4	1.5	0.6	0.5	20
M(1)	25.0	10.5	3.4	1.2	0.6	0.3	40
N(1)	19.0	9.0	2.5	2.0	0.6	0.6	13
N(2)	12.5	9.0	2.5	-	0.6	0.6	10
N(3)	12.5	9.0	2.5	2.5	0.6	0.6	10

* *αf : Apparent furnishing absorption (cf. [7])*

4.1 ISO 3382-3 classification

Design goals and guidelines are necessary for the acoustic designer to be able to implement realistic (yet challenging) solutions [13]. Annexe A of the ISO 3382-3 standard proposes acoustic quality classes for each of the acoustic parameters. The acoustic classes of the 108 OPO in the joint database are shown in table 4. With this classification scheme it is shown to be extremely difficult to obtain "good" conditions, especially for r_D (as mentioned in the standard itself). Thus this classification scheme is shown to be too strict.

Table 3 : Average values and standard deviation of measured acoustic parameters and room variables in each database.

Average (SD)	Ecoacoustique (CH)	Virjonen/ Keränen (FIN)	Haapakangas (FIN)	Selzer (DE)	Yadav (AUS)	**Total**
N° offices in database	22	25	21	13	27	**108**
r_D [m]	11.2 (3.7)	10.5 (3.4)	10.6 (3.8)	12.1 (3.9)	9.9 (2.2)	**10.7 (3.4)**
$L_{p,A,S,4m}$ [dB]	47.9 (3.7)	49.7 (2.8)	48.0 (2.5)	49.7 (3.1)	51.5 (2.4)	**49.4 (3.2)**
$D_{2,s}$ [dB]	6.4 (1.8)	8 (2.5)	7.4 (2.2)	5.8 (1.4)	5.1 (1.1)	**6.6 (2.2)**
$L_{p,A,B}$ [dB]	32.8 (4.3)	35.9 (4.0)	36.3 (4.6)	-	42.9 (4.1)	**37.2 (5.6)**
T_r [s]	0.46 (0.11)	0.54 *	-	0.45 (0.12)	0.50 (0.18)	**0.48 (0.15)**
Room surface [m²]	165 (62)	407 (368)	-	298 (126)	223 (178)	**215 (111)**
Partition height [m]	1.5 (0.4)	1.5 (0.3)	-	-	1.2 (0.6)	**1.4 (0.3)**
Ceiling absorption [-]	0.6 (0.2)	0.6 (0.2)	-	-	0.7 ×	**0.6 (0.2)**
N° workplaces	20 (12)	-	42 (33)	27 (11)	-	**22.6 (11.9)**

* The values for Tr given in the Virjonen/Keränen database are Early Decay Time (EDT)

× The ceiling absorption in the Yadav database has been estimated from descriptions in the paper (but are not used in this paper).

Table 4 : Distribution of acoustic classes for 108 OPO in joint database

% in acoustic class	Good	Satisfactory	Poor
r_D	**4 %**	45 %	51 %
$L_{p,A,S,4m}$	34 %	24 %	42 %
$D_{2,s}$	36 %	41 %	23 %

4.2 Correlations between acoustic parameters

Objective parameters describing the acoustic conditions in OPO are useful for design and classification purposes. Ideally these parameters should be independent from one another (non-redundant). Table 5 shows the coefficients of determination R^2 between the acoustic parameters. The distraction distance r_D is shown to be independent from $L_{p,A,S,4m}$ and $D_{2,s}$. There is a small correlation between $L_{p,A,S,4m}$ and $D_{2,s}$ (as expected, due to the fact that they are calculated from the same spatial attenuation curve). Each is nevertheless necessary as $L_{p,A,S,4m}$ is useful in describing the near-field and $D_{2,s}$ the far-field (as is r_D). It is also seen that there is a good correlation between r_D and background noise $L_{A,B}$ ($R^2 = 0.24$). More surprising is the correlation between $L_{A,B}$ and $L_{p,A,S,4m}$ or $D_{2,s}$.

Table 5 : coefficients of determination (R^2) between acoustic parameters.

Coefficients of determination (# OPO)	r_D [m]	$L_{p,A,S,4m}$ [dB]	$D_{2,s}$ [dB]
$L_{p,A,S,4m}$ [dB] (108)	0.02		
$D_{2,s}$ [dB] (108)	0.01	0.11	
$L_{p,A,B}$ [dB] (95)	**0.24**	0.15	0.15
T_r [s] (62)	0.01	0.02	**0.22**

Table 6 : coefficients of determination R^2 between acoustic parameters and room variables

Coefficients of determination (# OPO)	r_D [m]	$L_{p,A,S,4m}$ [dB]	$D_{2,s}$ [dB]	T_r [s]
L [m]	0.00	0.05	0.13	0.12
W [m]	0.03	0.01	0.00	0.04
H [m]	0.03	0.02	0.02	**0.27**
Partition height [m] (77)	**0.15**	0.12	**0.19**	0.01
Ceiling absorption [-] (47)	0.03	**0.17**	0.08	0.08
Density [persons/m²] (35)	0.03	0.13	0.00	0.00

4.3 Correlations between acoustic parameters and room variables

Table 6 shows the correlations between the measured acoustic parameters and the room variables. Partition height is the room variable that correlates the most with all three acoustic parameters and can thus be considered a very important design criteria.

4.4 Distraction distance (r_D) correlations

The distraction distance r_D is shown as a function of background noise $L_{A,B}$ in Fig. 1. The trend curve (black curve, calculated from 95 OPO data points) presents a correlation of R^2 = 0.24 and a slope of -0.28. This shows that on average 4 dB of extra background noise is required for a 1 m drop in r_D. For satisfactory r_D values (10 m according to the ISO 3382-3 (2006) annexe A) 38 dB background noise is required on average.

Figure 2 shows the relation between r_D and partition height. The trend curve slope (-3.6) shows that by adding 0.5m of height to the partitions, on average the r_D is reduced by 1.5 m. Thus, to achieve satisfactory conditions partitions with at least 1.5 m height are necessary.

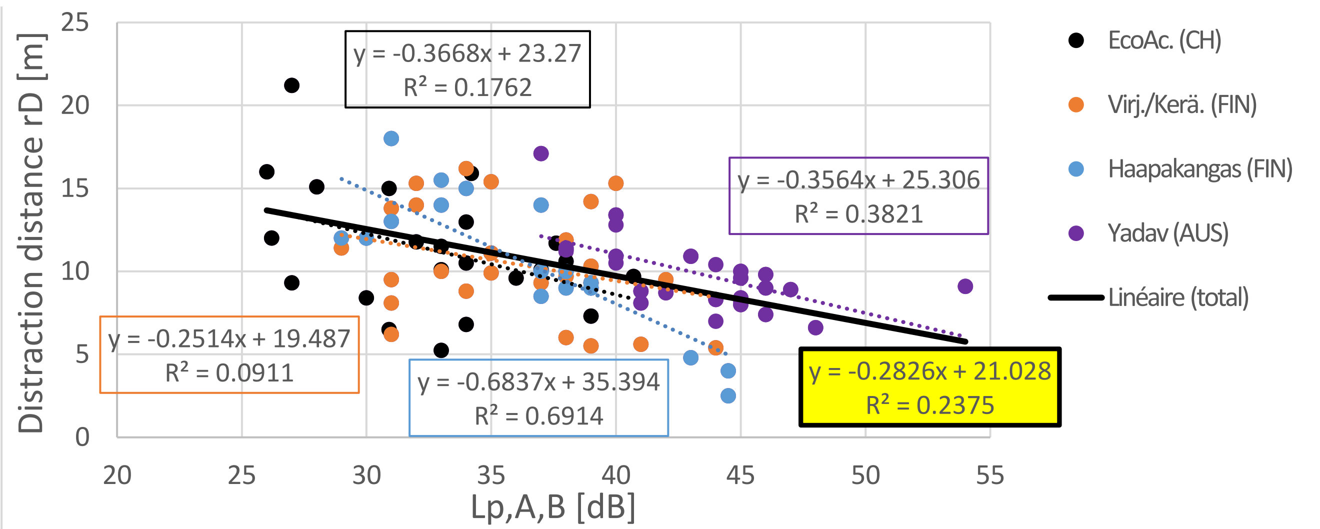

Figure 1: Relation between distraction distance (r_D) and background noise level ($L_{A,B}$) (95 OPO)

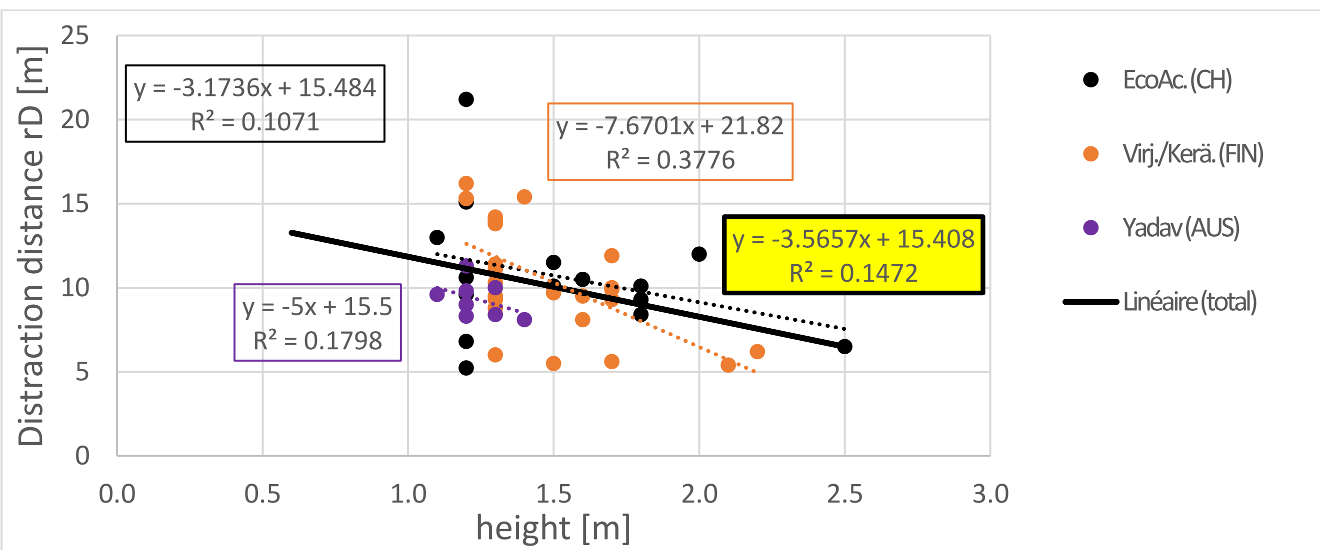

Figure 2 : Relation between distraction distance (r_D) and partition height (53 OPO)

5. Prediction models

In the Keränen et al. paper [7], simple prediction models were presented for $D_{2,s}$ and $L_{p,A,S,4m}$. as well as a more complex prediction model for r_D. The prediction accuracy of the model is tested on the EcoAcoustique database. The average and standard deviation for the $D_{2,s}$ model is -0.9 ± 2.5 dB. The average and standard deviation for the $L_{p,A,S,4m}$ model is 2.4 ± 2.2 dB. The Keränen model could unfortunately not be tested on the other databases due to the fact that the model required a (very relevant) variable for "apparent furnishing" (α_f). This value attempts to incorporate all the sound absorption of the room (excluding the ceiling), but is subject to much judgment on the part of the information collector. A different perception of this value may be one of the reasons the EcoAcoustic database did not perform as well as the Virjonen/Keränen database with the model. Building on the method developed in the Keränen et al. paper, new prediction models were developed using the joint database. The goal of these models is to help acoustic designers prove the necessity for the special acoustic treatment of OPO backed with numerical evidence at the planning stage.

5.1 Distraction distance prediction

5.1.1 Wenmaekers model

Equation (1) is a simple model for r_D prediction presented in [13]. Using the database (95 OPO) an optimised value for the $SNR_{D,optimal}$ is found to be 5.1 dB (improvement of 3.7 dB proposed in [13]). The results are found in Fig. 3 (left). The model tends to underestimate r_D (especially for the Yadav data points). The average and standard deviation for the model is -1.5 ± 3.1 m.

$$r_D = 10^{\left(\frac{L_{A,B}-L_{A,S,4m}+SNR_D}{-3.3D_{2,s}}+log(4)\right)} \quad (1)$$

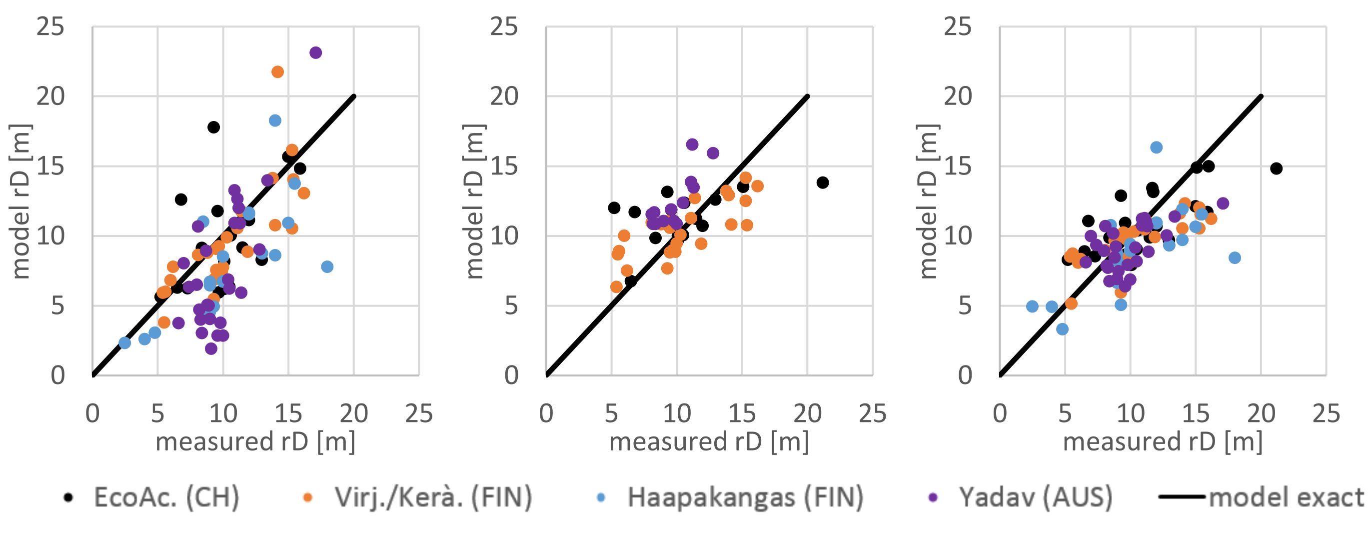

Figure 3 : Accuracy of the revised Wenmaekers rD model (left), the rD1 regression model (middle) and the rD2 regression model (right)

5.1.2 Multiple regression models

$$r_{D1} = 31 - 0.3\, L_{A,B} - 3.7\, \alpha_c - 5.1\, h \quad (2)$$

$$r_{D2} = 8.8 - 0.4\, \left(L_{A,B} - L_{p,A,S,4m}\right) - 0.6\, D_{2,s} \quad (3)$$

Two further models were developed using multiple regression software in Matlab. The r_{D1} regression model (Eq. (2)) calculates r_D with background noise ($L_{A,B}$), ceiling absorption (α_c) and partition height (h). The r_{D2} regression model (Eq. (3)) calculates r_D from the measured acoustic parameters $L_{P,A,S,4m}$ and $D_{2,s}$ as well as from the background noise $L_{A,B.}$ The average and standard deviation for the r_{D1} model is - 0.8 ± 2.6 m (53 OPO, cf. Fig. 3 (middle)) and that for the r_{D2} model is -0.9 ± 2.4 m (95 OPO, cf. Fig. 3 (right)).

6. Design recommendations

Based on database results shown above and from our experience as acoustic consultants, the following practical measures are highly recommended to be implemented in the design phase: effective ceiling absorption ($\alpha c > 0.8$, acoustic baffles perpendicular to the propagation are particularly effective), soft materials on the floor (to reduce the impact sounds and high frequency T_r), sufficient space per workstation (> 10m2/person), enough absorbing materials in the room (curtains, absorbing partitions, furniture).

A sufficient amount of acoustically isolated rooms (phone booth, meeting rooms, 1-3/15 workstations according to the French standard [12]). These rooms are also very effective partitions between workspaces. Workstations should be protected from the passage ways of other workers.

Background noise and partition heights should be sufficiently high. Partitions are especially important between non-collaborating groups.

General practice has also shown the importance of good behaviours to be respected by workers in OPO. A charter of good (acoustic) behaviour is proposed in annexe B of NF S 31-199 [12], which if respected can improve the acoustic conditions of an OPO considerably in itself.

7. Conclusions

This paper presents the results and analysis of a database compromising of 108 open plan office measurements and room variables, including a novel database of 22 Swiss OPO.

It is shown that the distraction distance r_D is mostly correlated with background noise level and partition height. Trend curves show that on average adding 0.5m of height to the partitions reduces r_D by 1.5 m and that 4 dB of extra $L_{A,B}$ is required for a 1 m drop in r_D. The trend curves also show that $L_{A,B}$ > 38 dB and partition height > 1.5 m are required for satisfactory r_D conditions (< 10m).

The A-weighted speech level at 4m $L_{p,S,A,4m}$ is correlated with ceiling absorption coefficients while the spatial decay $D_{2,s}$ is correlated with reverberation time and partition height. Indeed, according to the trend curves developed in this study, decreasing the reverberation time by 0.1 s will increase the spatial decay ($D_{2,s}$) on average by 0.5 dB. To obtain satisfactory acoustic conditions for $D_{2,s}$ (> 5 m) a $T_r < 0.6$ s is required

Finally three new empirical models are developed from the database for the calculation of r_D and design recommendations are given.

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