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Technical Note

Study of the Acoustic Suitability of an Open Plan Office Based on STI and DL_2 Simulations

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Many business offices around the world are organized as open plan offices. Therefore, studies about the acoustic comfort of the people who work in them have become increasingly important. The focus of this work is the acoustic evaluation of an open plan office combining several architectural characteristics and levels of ambient noise. This evaluation was performed through a computational model calibrated from a real office. The rate of spatial decay of sound pressure levels per distance doubling (DL_2) and the speech transmission index (STI) were simulated for the acoustic evaluation of the office, allowing for the determination of the radius of distraction (rD). These parameters were simulated for 6 situations using different floor and ceiling covering materials and inserting or withdrawing screens between workstations. In addition, STI and rD were simulated under two conditions of ambient noise. The results indicated that the DL_2 and rD are adequate acoustic parameters for the acoustic evaluation and improvement of an open plan office. The DL_2 was strongly influenced by the presence or absence of screens between workstations and by the ceiling covering material. The rD was more sensitive to changes in ambient noise.

Keywords: open plan offices, acoustic evaluation, acoustic improvement.

1. Introduction

The open plan office design, or "bürolandschaft", was created by the Schnelle brothers in Germany in about 1955 (Duffy, 1980). This type of office was based on some fundaments which relate the principles of design to those of organization.

In the 1970s and early 1980s, occupants of open plan offices reported the lack of privacy and the distraction caused by the noise produced by coworkers (Pejtersen *et al.*, 2006). Even when objective measurements demonstrated that the background noise of conversations in the room was not excessively high (approximately 50 dB), this noise distracted the workers (Van Der Voordt, 2004).

Hongisto *et al.* (2007) stated that it is not the sound level of speech but its intelligibility that determines its distraction effect. Speech is the sound source that causes the highest distraction, since it occurs unpredictably, its intensity is variable and it has the highest possibility of information content among the sounds that occur in the office. In a study performed by Kjellberg *et al.* (1996), the degree of distraction of workers proved to be more closely related to sound events, noise control capacity and noise predictability than to the actual noise levels.

According to Egan (1988), speech privacy is influenced by three factors: source, environment and receiver. With regard to workspaces, the acoustic environment of open plan offices can be incremented technically by three main factors: 1) the room's absorption, which reduce reverberation and early reflections; 2) barriers, which control direct sound; and 3) artificial masking of the sound, which provides a uniform sound environment and reduces the distraction caused by adjacent workstations (Hongisto *et al.*, 2004).

Speech privacy and the distraction caused by the speech of coworkers can be described by the speech intelligibility between workstations. Asselineau (2007) argues that speech intelligibility should be good locally in order to promote conversation among members of the same group. However, as the distance from the speaker increases, speech intelligibility should become poorer.

Speech inteligibility can be attained through objective and subjective methods (Brachmanski, 2007;

2008). According to Bradley (2007), while measurements of the articulation index (AI) are used to indicate speech privacy in North American offices, values of the speech transmission index (STI) are normally used in European offices. The standard IEC 60268-16 (2003) defines the STI as the "physical amount that represents speech transmission quality in relation to intelligibility" (International Electrotechnical Commission, 2003). According to Harris (1994), the STI is similar to the articulation index (AI), but its application is more general since it considers the effects of reverberation time and noise for the determination of speech intelligibility. Acoustical quality of several working spaces (classrooms, open offices, etc.) can be evaluated through STI and reverberation time (Zannin, Marcon, 2007; Zannin, Zwirtes, 2009; Passero, Zannin, 2010; Augustynska *et al.*, 2010, Zannin *et al.*, 2011)

In a study of Hongisto *et al.* (2007), two main descriptors were determined from measured data for the evaluation of offices: 1) the radius of distraction, rD; and 2) the rate of spatial decay of sound, DL_2.

The radius of distraction, rD (m) can be determined basing on measurements of the STI. The radius of distraction has been defined as the distance from the speaker at which the STI is lower than 0.5 (Hongisto *et al.*, 2007). These authors made preliminary recommendations for the rD based on several studies. Thus, for an office to be considered acoustically excellent, the rD should be lower than 5 m. Offices with an rD higher than 11 m are considered acoustically poor, according to the studies by Hongisto *et al.* (2007).

According to the ISO 14257 standard (2001), the rate of spatial decay of sound pressure levels per distance doubling (DL_2) is the decline, in decibels per double the distance, of the spatial sound distribution curve for a given range of distances (International Organization for Standardization, 2001). According to Ondet and Suer (1995), the DL_2 is independent of the power of the source. This parameter is highly dependent on the reverberation of the room: a value of 0 dB corresponds to the case of a highly reverberating room; while a value of 6 dB corresponds to a room treated ideally, corresponding to the open field.

For Chigot (2007), the DL_2, which was originally applied in industrial settings, has proved to be a consistent and realistic descriptor of the acoustic conditions of open plan offices. According to this author, the DL_2 has been included in acoustic quality standards for buildings. The French standard NF S31-080 published in 2006 proposes the use of the DL_2 to evaluate large offices (volume higher than 300 m^3). This standard precludes the use of the DL_2 for offices with distances of less than 6 m between walls, which should be evaluated based on the reverberation time. This standard specifies DL_2 values according to the performance requirements of the workers: standard performance, $DL_2 > 2$ dB(A); efficient performance, $DL_2 > 3$ dB(A); and high performance, $DL_2 > 4$ dB(A) (Chigot, 2007).

Pursuant to acoustic measurements of five open plan offices, Nilsson *et al.* (2008) concluded that the DL_2 is an applicable parameter for the assessment of these environments. For Hongisto *et al.* (2007), in most case the DL_2 and rD suffice to describe the acoustic conditions of an open plan office.

Therefore, the objective of this paper is to present and discuss the variation in the acoustic parameters DL_2 and STI (based on which the rD is determined), according to changes in the architectural and ambient noise parameters, by means of a calibrated computational model of a real open plan office.

2. Material and methods

The acoustic parameters STI and DL_2 were obtained from a calibrated computational model of a real office. The computational model was calibrated by a comparison between the RT data measured *in situ* and the data produced by the computational simulation of the office in real conditions. According to Golas and Suder–Debska (2009), an important question, when computational simulations are employed, is whether the computational model does reflect the current state of the studied room. After the model was calibrated, changes were made in the architectural characteristics and ambient noise in order to verify the behavior of the acoustic parameters STI and DL_2 in response to the changes.

2.1. Object of study

The object of study here was an open plan office in a large multinational company (Figs. 1, 2):

Fig. 1. Internal view of the office under study.

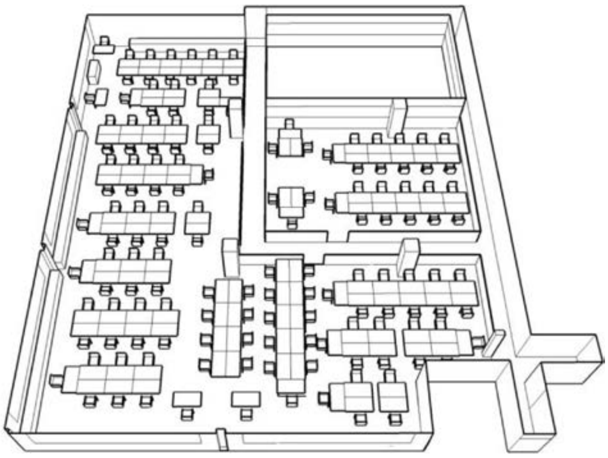

Fig. 2. 3D modeling of the office under study.

The main architectural features of this office are described in Table 1.

Table 1. Main architectural characteristics of the office under study.

Real characteristics	
Area [m^2]	613.03
Volume [m^3]	1716.48
No. of workstations	147
Area/workstation (m^2 workstation)	4.17
Ceiling height [m]	2.80
Ceiling material$^{(1)}$	0.49
Flooring material$^{(1)}$	85%$^{(2)}$: 0.18
	15%$^{(2)}$: 0.01

(1) Mean α between the octave bands from 125 to 4000 Hz.

(2) Percentage of total floor area covered with material with $\alpha = 0.18$ or $\alpha = 0.01$.

As can be seen in Fig. 1, the office in question did not have dividing panels between the workstations. The ceiling was finished in mineral wool board and the floor was covered with carpeting in the desk area (85% of the total area) and by ceramic tiles in the corridors (15% of the total area). The desks were made of particle board covered with high pressure laminate.

2.2. Computer simulations

The computer simulation was performed using the ODEON Version 9.0 software package. This software uses the hybrid method, which calculates the early reflections using a combination of the image source method and ray tracing, while the late reflections are calculated by a special ray tracing process that generates diffuse secondary sources. This simulation requires a three-dimensional model of the room.

To ensure the reliability of the simulation, it was very important to use suitable calculation parameters. Most of the calculation parameters were defined by the Odeon 9.0 software itself, leaving the choice of the essential parameters such as the surface materials (α), surface scattering coefficients (δ), definitions of the source and receiver (location and characteristics), among others.

The scattering simulation method is a calculation procedure that must be defined by the user of the program. Odeon 9.0 offers three options: 1) Lambert, 2) without scattering, and 3) total scattering. If the scattering method chosen is the Lambert method, all the directions of the early reflections will be calculated using the scattering coefficients indicated for the surfaces on the list of materials. If the method is defined as without scattering, scattering is not considered, so all the reflections will be calculated as specular. Lastly, if the total scattering method is selected, 100% of the scattering will be applied to all the surfaces, but this method is not recommended (Christensen, 2003). For Rindel (2000), the attribution of surface scattering coefficients in computer simulations has proved to be essential in obtaining reliable results. Thus, Lambert's scattering method was chosen for all the simulations in this study.

2.2.1. Simulations with interventions

For the STI simulations with architectural and ambient noise modifications, the source was located in one position, the workstation of a speaker, and the receivers in a 0.50 m × 0.50 m grid. After the simulation, the radius of distraction (rD) was calculated from the grid. This parameter was chosen because, unlike the STI, it generates a single value which is independent of the position of the receiver in the room. However, in addition to the discussion about the rD, the grid of the STI was also analyzed, since it provides important data about the behavior of sound inside the room.

The Odeon 9.0 software calculates the DL_2 for each frequency band from 63 Hz to 8 kHz, and the DL_2,Co, which is the A-weighted rate of spatial decay for the frequency bands 125 Hz to 4 kHz. The data generated in this study were analyzed using only the DL_2, Co because it presents the results of noise reduction per distance by means of a since number. In this simulation, the source and receivers were positioned at a height of 1.20 m, which is equivalent to the average height of a sitting person. The ISO 14257 standard (2001) determines that there should be a minimum distance of 1.5 m between the receivers and vertical objects or surfaces. On the other hand, for the source, this distance should be 3.00 m. These parameters of the standard were observed in the simulations. The variation of distance between the source and receivers may follow a constant or logarithmic increment. In addition, the standard recommends that the receivers be located in the middle region, i.e., at a distance of 5 to 16 m from the source. Therefore, 12 receiver points were used, Fig. 3, a distances of 5 to 16 m from the source, with a constant distance increment of 1 m.

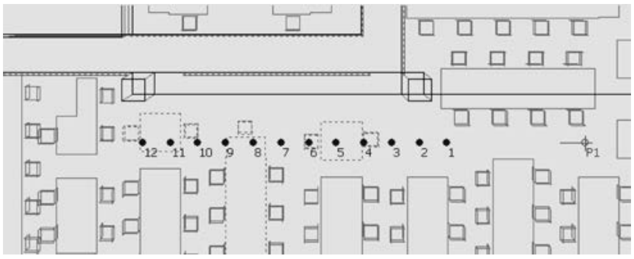

Fig. 3. Simulation of the DL_2 using Odeon 9.0 software. P1 represents the sound source and points 1 to 12 indicate the receivers.

The source utilized in the simulation of the DL_2 was of the omnidirectional pointwise type (International Organization for Standardization, 2001). The STI was simulated using a source with directivity resembling that of the human mouth (International Electrotechnical Commission, 2003). The frequency spectrum and the sound power are predetermined by the manufacturer, according to the specifications of the ISO 14257 (2001) and IEC 60268-16 (2003) standards.

The architectural modifications employed in the simulations of the office involved the materials covering ceiling and floor surfaces and the presence or absence of office partitions. Modifications in ambient noise were also made, albeit only for the STI simulations. Six simulations of the DL_2 and twelve simulations of the STI were made since in each physical condition of the environment the STI was simulated at two levels of ambient noise. These noise levels are equivalent to the average sound pressure levels found in real offices. Table 2, below, describes the modifications made to the office in the six simulated situations. In Table 2, α represents the mean value of the absorption coefficient between the one-third octave bands from 125 to 4000 Hz.

Table 2. Characteristics of the physical changes and sound pressure level used in the simulations.

Characteristics	Situations					
	A	B	C	D	E	F
Ceiling material (α)	0.81	0.81	0.02	0.81	0.81	0.02
Flooring material (α)	0.18	0.01	0.01	0.18	0.01	0.01
High of the partitions between workstations (m)	–	–	–	1.30	1.30	1.30
Material of the partitions between workstations (α)	–	–	–	0.10	0.10	0.10
Sound pressure level dB(A)	64.1	64.1	64.1	64.1	64.1	64.1
	55.4	55.4	55.4	55.4	55.4	55.4

In the six physical situations of the environment, the STI was simulated with two levels of background noise, 64.1 dB(A) and 55.4 dB(A). These combinations of materials, situations of partitions and sound pressure level are commonly found in real offices.

3. Results and discussion

The combination of the constructive elements of ceiling and floor materials and presence/absence of partitions resulted in six simulated situations, which are referred to as A, B, C, D, E, and F. For each of these situations two sound pressure levels (SPL) were inserted, 64.1 and 55.4 dB(A), for the STI simulation, from which the rD was obtained, resulting in twelve values of rD. Table 2 describes the simulated situations, while Table 3 lists the values obtained for the rD and DL_2. In Table 3, the first line of rD values indicates the results obtained in the simulations with 64.1 dB(A) of SPL and the second line presents the values obtained in the simulations with 55.4 dB(A) of SPL.

Table 3. Simulated rD and DL_2, Co values of the open plan office.

Acoustic parameter	Situations					
	A	B	C	D	E	F
rD (m)	1.00	1.00	1.00	1.00	1.00	1.00
	2.50	2.50	2.50	2.50	2.00	2.00
DL_2, Co	3.11	3.18	2.29	4.40	4.33	2.83

The values of rD listed in Table 3 indicate that when the ambient noise is high, 64.1 dB(A), the ceiling and floor covering material do not interfere in the speech intelligibility. Moreover, at these noise levels, the insertion of partitions caused no interfere of the rD value. When the ambient noise was reduced to 55.4 dB(A), there was a significant increase in speech intelligibility, increasing the values of rD. At this noise level in the simulations without partitions, i.e. situations A, B and C, the floor and ceiling covering material did not interfere in the values of rD, which remained unchanged at 2.50 m in the three situations. Inserting partitions in situation D caused the rD to remain the same as in the situations without partitions. However, there was a significant difference with regard to the workstations with higher intelligibility in situations A and D, as can be seen in Figs. 4 and 5. In Fig. 4, situation A, note that the workstations most affected by the speaker's speech are in front of him, while in Fig. 5, situation D, the highest intelligibility in the workstations is behind and to the sides of the speaker.

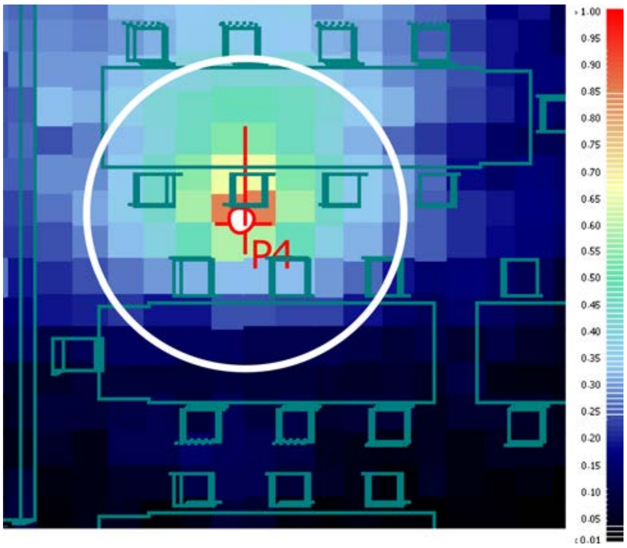

Fig. 4. Simulated STI, situation A, with weak noise. P4 represents the sound source, and the white circle around it represents the radius of distraction. The longer line in P4 indicates the direction of the sound source.

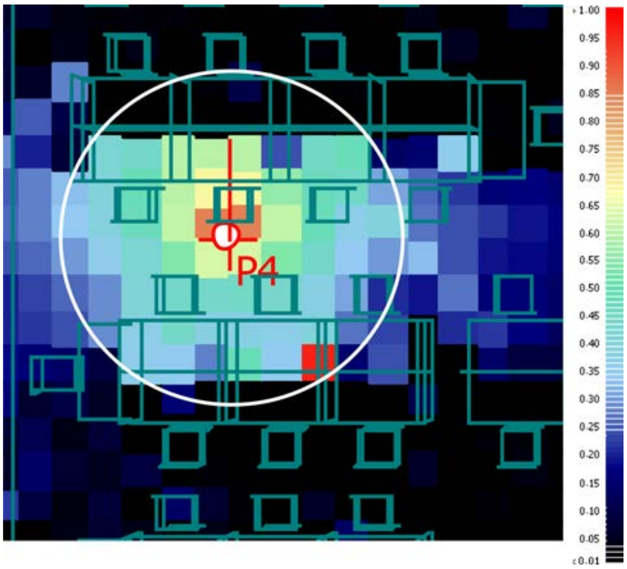

Fig. 5. Simulated STI, situation D, with weak noise. P4 represents the sound source and the white circle around it represents the radius of distraction. The longer line in P4 indicates the direction of the sound source.

In situations E and F, with a background noise of 55.4 dB(A), there was a reduction of the rD in relation to the values found for the room in the situations without partitions and in situation D. This reduction can be explained by the decrease in intelligibility due to the reduction in sound absorption when compared with situation D, and dulling of the speaker's voice by the partitions when compared with situations A, B and C.

According to Hongisto *et al.* (2007), for an office to be considered acoustically excellent, the values of rD should be lower than 5 m. Therefore, according to this classification, the office can be classified as acoustically excellent in all the simulated situations.

With regards to the DL_2, as Table 3 indicates, this parameter is strongly influenced by the floor and ceiling finishing materials and the insertion/removal of partitions between workstations. The highest DL_2 was found in situation D, i.e., with acoustic materials covering both floor and ceiling, as well as the presence of partitions between workstations. The lowest DL_2 was found in the opposite situation, C, with reflective material covering the floor and ceiling and without partitions between workstations. Based on these data, it can be stated that to achieve a high sound reduction with distance, the office environment should have considerable sound absorption and partitions between workstations.

If the simulated values of DL_2 were compared to the values specified by the French standard, NF S31-080 (Ondet, Suer, 1995), the office in situations D and E would be suitable for activities requiring high performance from the workers. The office in situations D and E is characterized by the presence of partitions between workstations and considerable acoustic absorption in the ceiling and floor (situation D) or only the floor (situation E). When the partitions are removed from the model in situations A and B while maintaining the same ceiling and floor materials as in situations D and E, the office can be considered suitable for activities requiring efficient performance, according to the French standard. On the other hand, in situations C and F, which are characterized by the absence of acoustic material on both ceiling and floor, the office is considered adequate only for activities requiring standard performance, regardless of whether it has partitions (situation F) or not (situation C).

4. Conclusions

Based on the simulated data, the rD and DL_2 proved to be suitable parameters for the acoustic evaluation of open plan offices in the various simulated situations of acoustic conditioning and ambient noise. Moreover, the calibrated computational model proved to be an excellent tool for studying the acoustic conditioning of an open plan office. This finding was also reported in studies carried out by Zannin *el al.* (2009).

The advantage of the rD over the STI lies in the fact that it characterizes the speech intelligibility in an office by means of a single number. However, the rD does not allow one to observe the workstations most affected by a speaker's speech, as can be seen from the STI maps in Figs. 4 and 5. Therefore, the spatial organization of work groups in an open plan office requires an analysis of STI maps, ensuring not only that the space is organized to provide reasonable intelligibility among group members but also speech privacy between work groups.

An analysis of the values of rD indicates that this parameter is strongly dependent on the environment's sound pressure level. When the noise in the room is high, at a value close to 65 dB(A), the rD values are low. At this SPL, the change in floor and ceiling finishing materials and the insertion/removal of partitions did not affect the values of rD, since the radius of distraction is very small. Reducing the value of the SPL to approximately 55 dB(A) led to a significant increase in speech intelligibility and therefore an increased rD.

The DL_2 parameter was strongly influenced by the presence/absence of partitions. In the situations with partitions, the simulated DL_2 values were higher than those simulated in the other situations. Moreover, the DL_2 decreased considerably when the acoustic material on the ceiling and floor was removed, both in the situation with partitions (situation F) and in that without partitions (situation C). These results are similar to those obtained from acoustic measurements in earlier studies conducted by Virjonen *et al.* (2009).

As for the data recorded in the literature for comparison with the values found in this work, the values stipulated for the DL_2 by the French standard appear to be compatible with those reported here for the six simulated situations. However, in terms of the rD, the classification proposed by Hongisto *et al.* (2007) seems inadequate for classifying the simulated situations of this office since, according to those authors, all the simulated situations of this office would classify it as acoustically excellent based on the values of rD obtained (rD $<$ 5 m). This difference may be attributed to the method employed to obtain this parameter, since the earlier studies (Hongisto *et al.*, 2007; Virjonen *et al.*, 2009) were based on measurements while the present study was based on acoustic simulations.

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