Proceedings of the 10th Annual World Conference of the
Society for Industrial and Systems Engineering,
2021 SISE Virtual Conference
September 23-24, 2021

Psychoacoustic Analysis of Reverberation in an Open-Plan Office to Identify Speech Volume Levels Based on ISO 3382-3

M. P. Serrano-Ruiz[1], J. A. Yarza-Acuña[2], and G. Ibarra-Mejía[1,3]

[1]Departamento de Ingeniería Industrial y Manufactura
Instituto de Ingeniería y Tecnología
Universidad Autónoma de Ciudad Juárez
Ciudad Juárez, Chihuahua, 32584, México

[2]Escuela de Sistemas
Unidad Torreón
Universidad Autónoma de Coahuila
Torreón, Coahuila, 27087, México

[3]Department of Public Health Sciences
University of Texas at El Paso
El Paso, Texas, 79968, USA.

Corresponding author's Email: maria.serrano@uacj.mx

Author Note: María P. Serrano Ruiz has a bachelor's and a master's degree in Industrial Engineering from the Instituto Tecnológico de la Laguna. She is a current Ph.D. student at the Universidad Autónoma de Ciudad Juarez. Her areas of interest are cognitive ergonomics, physiology, quality, and statistics. José Antonio Yarza-Acuña received a B.E. degree in mechatronics engineering, an M.Sc. degree in mechatronics and control, and a Ph. D. in mechatronics and control from the Instituto Tecnológico de la Laguna, Mexico, in 2007, 2009, and 2013, respectively. He is currently a researcher at the Escuela de Sistemas of Universidad Autónoma de Coahuila. His research interests are industrial engineering, mechatronics engineering, and automatic control. Dr. Gabriel Ibarra-Mejia has an MD and MS degree from Universidad Autonoma de Ciudad Juarez, an MS degree in Ergonomics from Lulea Tekniska Universitet in Sweden, and a Ph.D. in Environmental Science and Engineering from the University of Texas at El Paso. He is currently an Assistant Professor in the Department of Public Health Sciences at the University of Texas at El Paso.

Abstract: Background noise in an open office that affects the cognitive performance of its users. Open-plan office spaces have distinctive design styles, and used construction materials configure the acoustic room conditions; therefore, it is helpful to know how to evaluate the room's acoustic characteristics to avoid user performance effects. This study evaluates an open-plan office space without acoustic conditioning, essential to assess the acoustic reverberation characteristics. We present the psychoacoustic reverberation analysis to identify the speech volume levels required for the acoustic design of the open office. Voice volume levels were estimated using Nocke's scheme for office classification based on ISO 3382-3 for open office spaces. The study results indicate that voice volume levels were affected by the reverberant effects of this space without acoustic conditioning.

Keywords: Reverberation, Open-plan office, Background noise

1. Introduction

Open-plan design offices are widely used workspaces because of their versatility in adapting the space to the company's needs. The advantages offered by open-plan offices are that the distribution of the space is adjusted to the characteristics of the work processes. In addition, it reduces the costs of conditioning the workplace (Al Horr et al., 2017). However, in most cases, the open-plan offices interior design does not consider the acoustic design of the enclosure, so background noise is a factor associated with disruptive effects in its users, as they complain that background noise produces annoyance and discomfort, thus, affecting their productivity (Banbury & Berry, 2005).

The architectural acoustic design in open-plan office spaces can improve workplace comfort, which reduces the perception of discomfort and improves user productivity. In addition, the acoustic design of the enclosure can be adjusted to areas where intellectual and cognitive activities are performed (Passero & Zannin, 2012).

In open-plan offices, users are exposed to background noise generated by expected office sounds; but it is mainly background conversations that cause discomfort and distraction. The background noise generated by conversations has several factors that make it a disruptive event because these conversations trigger a sense of alertness. However, it much depends on the degree to which the speech is clear and understandable (Conway et al., 2001). Intelligibility is one of the main acoustic characteristics of a diaphanous office, which is related to the listener's perception of clear and understandable speech. Moreover, reverberation, or the time it takes for a sound wave to propagate in the room, is crucial. There are different subjective and objective methods to evaluate intelligibility. The subjective methods evaluate the quality and clarity of the speech to be heard, while the objective methods evaluate the acoustic characteristics of the enclosure. The subjective methods are based on lists of standardized words that evaluate the listener's subjective quality, while the objective methods use parameters to measure the room's reverberation, the clarity of the sound, and the signal-to-noise ratio of the room (Isbert, 2004). International standards have standardized objective methods for measuring intelligibility. Such is the case of ISO 3382-3:2012, Acoustics, Measurement of room acoustic parameters Part 3: Open plan offices. In addition, techniques have been generated to facilitate the evaluation of intelligibility. Such is the case of the office classification scheme proposed by Nocke, who presented the scheme to describe the acoustic quality of an open plan office (Nocke, 2014).

The relationship between the direct field and the reverberant field evaluates the time decay curve. From this curve, different measures are obtained, such as the Early Decay Time (EDT) based on the decay of the impulse, for 0 to 10 dB, time of reverberation as the T20 decay time for -5 to -25 dB, the T30 decay time for -5 to -35 dB and the T60 decay time at 60 dB in space with the diffuse field. The RToptimal reverberation time (RTopt) is represented by T60, but if the room is small and EDT < T30, RTopt is the intersection of the estimated regression (Sommerhoff & Rosas, 2007).

An open-plan office's architectural and interior design features are an important part of the background noise generation, especially if these features are not adjusted to improve acoustically. The study's objective is to perform a psychoacoustic analysis of background noise reverberation in an open-plan office to identify the acoustic design needs and determine the voice volume levels in the room according to ISO 3382-3 for open-plan offices using the Nocke scheme for office classification. The reverberation characteristics of a room are the basis for evaluating the intelligibility of background noise and speech characteristics of an open-office space. Previous studies have used the r_D as a reference to make acoustic conditioning adjustments in open offices (Passero & Zannin, 2012). In this study, the selected open-office space had no acoustic conditioning. Therefore, we conducted a background noise reverberation analysis to determine the propagation lines using Nocke's scheme as a reference to establish the specifications for acoustic conditioning.

2. Methodology

The study evaluated the reverberation characteristics of background noise in an open-plan office and classified it according to the type of offices in the scheme proposed by Nocke (Nocke, 2014). The study was carried out in a 277m2 open-plan office space with the following characteristics: painted and plastered walls, concrete floor, and without acoustic conditioning. In addition, there are 15 glass-desk furniture with executive chairs, thirteen 32" screens, and three 25" monitors.

For the study, a bidirectional sound source and an omnidirectional microphone were used. In addition, three types of sound were emitted, Office Noise sound recording, Pink Noise recording and Soundscape of the office. The office's ambient noise was used as the control variable. We then classified each measure according to the analyzed reverberation and different types of sound. We used Dirac software for the acoustic analysis. Since Mexico does not have standards that evaluate acoustic characteristics of open offices, we followed the procedures include in the ISO 3382-3 standard for open offices. For the acoustic classification by type of office, we applied the Nocke classification scheme due to its practicality to represent the acoustics of open offices (Nocke, 2014).

We collected reverberation times for different sound decay levels data from six points close to the workstations around the office. The measurement points were selected by determining the minimum distance (Dm) between the position of the sound source and the placement of the measurement points, choosing those points with a distance to the sound source greater than Dm (ISO STANDARDS, 2017). The parameters for the office type classification were the RTopt for each sound type for each measurement point, based on the office type classification of the Nocke's scheme, see Table 1.

Table 1. Nocke's scheme for classification of open-plan offices

Office Class	Reverberation Time RT (s)		SPL $L_{NA,Bau}$ (dB)	Acoustic requirement by office class		
	125 Hz	250 Hz – 4 kHz		Step of propagation	Spatial decay rate $D_{2,S}$ [dB]	Level $L_{p,A,S,4m}$ [dB]
A	≤ 0.8	≤ 0.6	≤ 35	S1	≥ 8	≤ 47
B	≤ 0.9	≤ 0.7	≤ 40	S2	≥ 6	≤ 49
C	≤ 1.1	≤ 0.9	≤ 40	S3	≥ 4	≤ 51

Nocke's scheme for open offices proposes that the acoustic design be based on propagation lines. They recommend that the acoustic design for each type of office should be based on the propagation steps (Si) with respect to the spatial decay rate for speech (D2,s) and the sound pressure levels (SPL) in weighting A for distances of 4 m (Lp, A,s,4m) for the normalized SPL for the voice for each class of office. Nocke's scheme suggests that each proposed office class A should have at least 2/3 of the propagation lines to reach the S1 pitch. Class B should be at S2 and have at least 2/3 of the propagation lines to reach the S2 pitch, and the rest should be at S3. Class C should have 1/3 of the propagation lines to reach the S2 pitch, and the rest should be at S3.

3. Results

To determine the minimum distance between the location of the sound source and the placement of the measurement points, first, the 2000 Hz frequency was selected due to its greater contribution to speech intelligibility. For this frequency, the results showed that Dmin=1.98 m and six points were obtained that complied with this distance (see Figure 1).

Figure 1. Measurement points selected for study

Secondly, using Dirac software, the reverberation times were analyzed for the decay of -10, -20, and -30 dB, from which the TRopt was estimated. The results obtained showed that the Pink Noise allowed SPL stability, unlike the sound conditions generated by the soundscape and the Office Noise where SPL increases were presented in the different measurement points (see Figure 2).

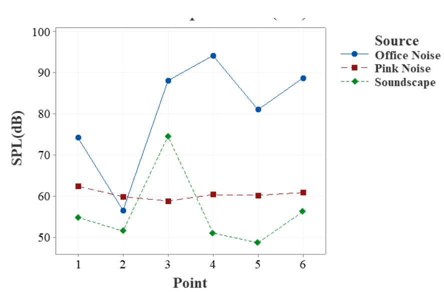

Figure 2. Line plot for SPL (dB) by measurement points

Regarding the office classification using Nocke's scheme, results indicated that the soundscape conditions vary between class A and class C, unlike the external sound emitted, which is generally classified as class C. The acoustic conditions presented in this enclosure demonstrate the lack of acoustic conditioning, probably due to the type of construction and furniture materials, which are not sound-absorbing (see Table 2). In this study, results indicate that according to Nocke's scheme, this diaphanous office conforms to class C, so for its acoustic design, it must have 1/3 of the propagation lines in step S2, that is, the distance D2,s must be far from the sound source in terms of a decrease of at least 4 dB, and for the normalization of the voice, consequently, the expected volume of the sound source the Lp, A,s,4m must be less than 51 dB (Nocke, 2014).

Table 2. Nocke's scheme for classification of open-plan offices

Sound	Soundscape						Pink noise						Office Noise					
Point	EDT [s]	T20 [s]	T30 [s]	RTopt (s)	SPL (dB)	Office class	EDT [s]	T20 [s]	T30 [s]	RTopt (s)	SPL (dB)	Office class	EDT [s]	T20 [s]	T30 [s]	RTopt (s)	SPL (dB)	Office class
1	0.009	0.223	1.523	0.223	35	A	15.545	2.755	2.741	3.077	62	C	3.503	0.271	0.258	0.271	74	C
2	0	0.065	0.051	0.065	32	A	8.456	3.124	2.956	10.995	60	C	2.322	1.161	1.05	1.161	57	C
3	7.633	4.405	3.66	6.011	55	C	8.139	0.103	0.081	0.137	59	C	6.829	4.119	4.119	4.119	88	C
4	9.756	2.326	2.266	2.942	51	C	12.405	3.63	3.525	4.016	60	C	2.223	2.032	2.372	2.372	94	C
5	0	0.04	0.037	0.04	29	A	10.112	4.501	4.357	5.646	60	C	14.139	1.216	1.063	1.063	81	C
6	8.651	0.602	0.527	0.794	56	C	2.303	0.063	0.057	0.061	61	C	1.119	0.139	0.135	0.139	89	C

4. Concluding Remarks

Reverberation is an acoustic characteristic of the enclosure that allows estimating the voice volume levels that, together with the speech transmission parameters, will determine the distraction distance (rD) and the privacy distance (rP) that serve as an approximation for the acoustic horizons in enclosures (Keränen & Hongisto, 2013). This study presents how to perform a reverberation analysis in an open office. The results show variation in the types of sounds emitted. Therefore, it is recommended to analyze and determine the effects of background noises on the acoustic characteristics of an open-office.

4. References

Al Horr, Y., Arif, M., Kaushik, A., Mazroei, A., Elsarrag, E., & Mishra, S. (2017). Occupant productivity and indoor environment quality: A case of GSAS. *International Journal of Sustainable Built Environment*, *6*(2), 476–490. https://doi.org/10.1016/j.ijsbe.2017.11.001

Banbury, S. P., & Berry, D. C. (2005). Office noise and employee concentration: Identifying causes of disruption and potential improvements. *Ergonomics*, *48*(1), 25–37. https://doi.org/10.1080/00140130412331311390

Conway, A. R. A., Cowan, N., & Bunting, M. F. (2001). The cocktail party phenomenon revisited: The importance of working memory capacity. *Psychonomic Bulletin & Review*, *8*(2), 331–335. https://doi.org/10.3758/BF03196169

Isbert, A. C. (2004). *Diseño acústico de espacios arquitectónicos*. Universitat Politècnica de Catalunya. Iniciativa Digital Politècnica.

ISO STANDARDS. (2017). *ISO 3382-3:2012*. ISO. https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/04/65/46520.html

Keränen, J., & Hongisto, V. (2013). Prediction of the spatial decay of speech in open-plan offices. *Applied Acoustics*, *74*(12), 1315–1325. https://doi.org/10.1016/j.apacoust.2013.05.011

Nocke, C. (2014, November 16). *Open plan offices—Classification scheme based on ISO 3382-3 parameters | Request PDF*. https://www.researchgate.net/publication/290017737_Open_plan_offices_-_Classification_scheme_based_on_ISO_3382-3_parameters

Passero, C. R. M., & Zannin, P. H. T. (2012). Acoustic evaluation and adjustment of an open-plan office through architectural design and noise control. *Applied Ergonomics*, *43*(6), 1066–1071. https://doi.org/10.1016/j.apergo.2012.03.007

Sommerhoff, J., & Rosas, C. (2007). Evaluación de la inteligibilidad del habla en español. *Estudios Filológicos*, *42*, 215–225. https://doi.org/10.4067/S0071-17132007000100014