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Speech Intelligibility Parameters for Evaluating the Perception of Background Noise in Open-Plan Office Users: A Case Study

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Abstract: This document presents a case study of acoustic analysis in an open-plan office. Since Mexico does not have a standard for evaluating acoustic conditions in offices, it is relevant to compare different acoustic evaluation methods used for open-plan offices. According to several studies, one of the main acoustic characteristics for open-plan office spaces is speech intelligibility. Therefore, the purpose of this document is to compare psychoacoustic parameters to evaluate speech intelligibility in open-plan offices. We analyzed physical factors as reverberation and speech clarity in different office points, as well as semantic factors based on subjective methods with standardized values of the quality of speech intelligibility. The study was carried out under real open-plan office conditions in a library in a university in northern Mexico. The study factors of interest were type of sound, sound source, and location of the listener, with Reverberation Time (RT), Speech Transmission Index (STI) and Loss of consonant articulation (%ALCons) as the measures of impact on intelligibility. This case study provides additional evidence of the relationship between intelligibility and the position of sound sources; also, it was noted that location of listeners influenced analyzed intelligibility parameters. On the other hand, this case study offers information concerning to use psychoacoustic parameters for subjective classification of quality of the speech intelligibility to evaluate how is background noise perceived in open-plan office users. However, it is noteworthy that this study represents a single office with its own interior and space design characteristics.

Keywords: Background Noise, Open-plan Office, Speech, Intelligibility, Acoustical Design.

1. Background

Open-plan office is a design style for workspaces that offer flexibility and adaptability to business needs (Seddigh et al., 2015), (Haapakangas et al., 2018). The distribution of the workspace of this design allows assigning workstations according to the requirements of the work processes. However, the characteristics of the open space generate unwanted sounds that affect users, causing discomfort, distraction, and the perception of unproductiveness (Oseland & Burton, 2012). Background noise is made up of sounds produced in offices, which cause annoyance to users of open offices; some sounds are those produced by office devices, telephone or chat bells, and conversations between co-workers or on the phone. Background noise has been related to negative effects on the performance of open office users, especially on how irrelevant sounds affect performance and productivity when perceived by users in open-plan offices.

Voices are sounds from background noise that impact performance, when listeners can hear clearly; some studies have associated background conversations as a distraction during task performance (Zaglauer et al., 2017). In addition, the location of the sound source, that is, how the speakers are distributed with respect to the listeners, influences the intelligibility (quality and clarity of speech) (Yadav & Cabrera, 2019). While other studies have indicated that background conversations impact semantic activities such as writing (Keus van de Poll et al., 2018). Many studies on the relationship between background conversations and writing have been conducted in laboratories to monitor conditions (Braat-Eggen et al., 2020). While some studies in real situations evaluate the perception of workers about productivity and performance, they do not focus on complex tasks, such as tasks with semantic interference (Yadav et al., 2017). For this case, it is important to consider what parameters can be used to correlate acoustic characteristics in open-plan offices under the conditions of background conversations and their impact on the performance of tasks.

Yadav et al. (2017) indicated that semantic interference should be studied with psychoacoustic parameters to evaluate relationship between the characteristics of the room related to the propagation and diffusion of sound with way in which sounds are perceived by listeners. One of the most important parameters is Intelligibility, which assesses relationship between physical and semantic factors of speech clarity using objective and subjective methods. Objective methods for evaluating intelligibility use signal-to-noise ratio when measuring physical characteristics of room such as reverberation and background sounds. While subjective methods use standardized values from human hearing tests, these values are result of calculations of predictive equations on correct interpretation of words heard (Sommerhoff & Rosas, 2007).

For practical uses, standards have been developed with objective methods to assess intelligibility in open offices, such is the case of the ISO 3382-3 Acoustics — Measurement of room acoustic parameters — Part 3: Open-plan offices standard (ISO STANDARDS, 2017). Based on ISO 3382-3 standard, Nocke (2014) suggested a scheme to classify the room acoustic quality, using the Reverberation Time (RT) that measures duration of echo time with respect to level of decay of sound with source; this scheme facilitates analysis of distance to distraction based on the Speech Transmission Index (STI) together with propagation pattern in room. On the other hand, one of the subjective methods is the Articulation of consonants (% ALCons) that evaluates understanding of oral messages based on correct perception obtained from RT and differences between sound pressure levels for direct field and reverberant field. In addition, % ALCons and STI are classified with rating scales on degree of intelligibility, these scales include ratings such as Excellent, Good, Fair, Poor, and Bad (Isbert, 2004).

The architectural design uses psychoacoustic parameters to evaluate acoustic characteristics according to the needs to clearly hear voices in the room. However, if it were necessary to evaluate background conversations as a distraction through intelligibility, which psychoacoustic parameters are suitable for such studies, or if any of these parameters could be used? In this study, we compare different psychoacoustic parameters to evaluate the perception of background noise in open-plan office users.

2. Method

The current study involves evaluating different methods of room acoustic quality classification in open-plan office. The study was made at open-plan office of academic library on a University at North of Mexico which was used as a computer service area. The open-plan office has a space of 789 m^2 and the study was made in a section of office with 12 shared workstations with four cubicles by station. Moreover, the office section is ubicated among glass wall offices and an artificial garden with stone floor, where acoustic measurements were collected on 18 points around workstations on computer service area.

The acoustic measurements were made with an environmental noise study based on Mexican standard *NOM-011-STPS-2001 – Ruido* but later an acoustical study was made based on standard ISO 3382-3 - Acoustics — Measurement of room acoustic parameters — Part 3: Open-plan offices to determine parameters of Intelligibility. For environmental noise, the study used a sound level meter type 2 and for acoustics, the study used a microphone and two speakers omnidirectional and Dirac software. In environmental noise study in accordance with NOM-011-STPS-2001 and due to office characteristics

Acoustic Pressure Gradient Method was selected because the open-plan office has stable noise and fixed workstations. In this study a workspace grid was made with 3 m of distance, obtaining 47 positions to evaluate all sections. For the acoustical study, it was necessary to estimate RT of room using Sabine equation (1) with Mean absorbing power (2) in the room to determine with these data was calculate Minimal distance, Dmin (3) between measurement points.

$$RT = \frac{0.161\,V}{\bar{\alpha}S_t} \quad (1)$$

$$\bar{\alpha} = \frac{A_{tot}}{S_t} \quad (2)$$

$$Dmin = 2\sqrt{\frac{V}{cRT}} \quad (3)$$

Later, 18 measurement points were obtained with Dmin on the area of the 12 workstations. In each point we evaluated parameters of Intelligibility based on ISO 3382-3 standard, as RT, STI and %ALCons through Dirac software. Last, each acoustical measurement point was classified using a subjective rating scale on the level of intelligibility, both for the STI and the% ALCons (Table 1). To classify the results of RT, we used Nocke's schema (Nocke, 2014).

Table 1. Relationship among STI, %ALCons, and classification subjective rating scale about intelligibility grade (Isbert, 2004)

Speech Intelligibility	Speech transmission Index STI	Percentage Articulation Loss of Consonants (%ALCons)
Bad	0 – 0.30	27 – 46.5
Poor	0.30 – 0.45	12 – 24.2
Fair	0.45 – 0.60	5.3 – 11. 4
Good	0.60 – 0.75	1.6 – 4.8
Excellent	0.75 – 1	0 – 1. 4

The normative regulation in Mexico regarding noise measurement is focused on evaluation and control of environmental noise, mainly industrial noise. However, environmental background noise is a problem that also affects users of work centers, characterized by a stable noise, below the established permissible sound level limits (for Mexico the TWA level limits are 90 dB for 8 work hours). Hence, this study examines different acoustical parameters of Intelligibility based on classification and schema from other countries. The selected methods are procedures used to simplify collection and analysis of data.

3. Results

In the study, the following were evaluated: (1) the type of sound, (2) measurement point and (3) position of the sound source. The type of sound consisted of two conditions (a) Office Noise, which consists of the reproduction of an office sound recording, and (b) Silence, which represents the soundscape of the area that was used as a control variable. The measurement points were 18 among 12 stations in the evaluated space. Finally, the position of the sound source was used with two reference points, point A with positions outside the computer center in an open space, and point B with two positions located within the computer service area (see Figure 1).

For the Reverberation analysis, ANOVA was performed with a general linear model, with four factors: Type of Sound (Office Noise, Silence), Measurement point (18 points), Position of the sound source A (P1A, P1B, P1C) and Position of the sound source B (P2A, P2B), Figure 1. The response variables were taken from the Dirac Reverberation analysis, from which two indicators were selected: Reverberation Time and Early Decay Time (EDT), for Reverberation Time Two indices RT and T30 were selected; RT explains the duration of reverberation time for 60 dB because it is the most commonly used measurement, but in the case for spaces with sound pressure level (SPL) in less than 60 dB, for an office it is recommended to use T30 (Reverberation Time to 30 dB) (Nti audio, 2021).

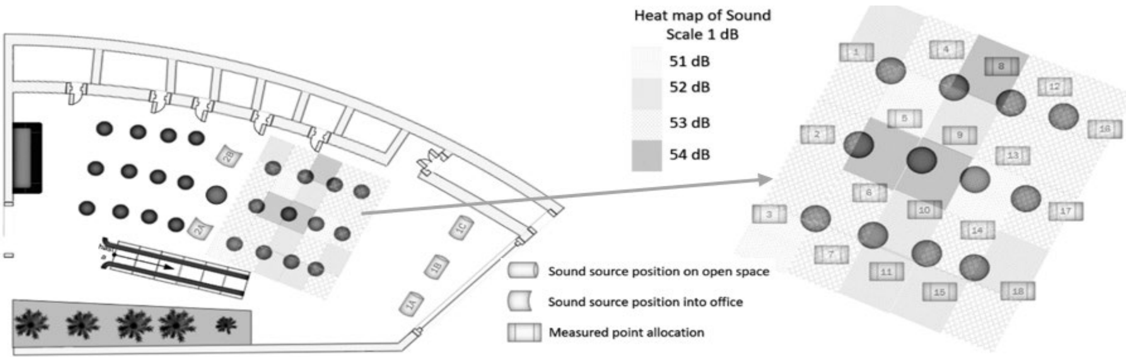

Figure 1. Schema of study area in computer service area

The EDT is an index that expresses the duration time of sound reflection in a room used to evaluate direct sound. The response variables analyzed were selected with the ISO-3382-3 standard. RT indicated that it was affected by the Measurement Point (p = 0.0) and the Sound Source, position A (p = 0.012) and position B (p = 0.029). The EDT indicated a similar behavior to the RT, Measurement Point (p = 0.0) and Sound Source, position A (p = 0.012) and position B (p = 0.030). However, T30 showed a completely different behavior because no factor affected it (see Figure 2).

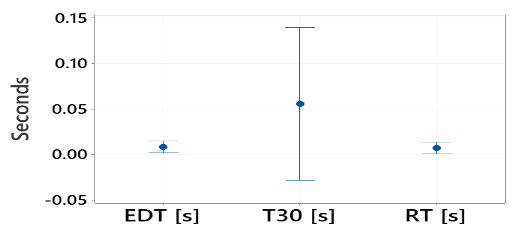

Figure 2. Interval Plot for 95% IC

Speech intelligibility was evaluated under two approaches: physical and semantic. For physical approach, the same analysis was performed for Reverberation using the same ANOVA factors with the general linear model. In this case, variables of interest were selected with ISO-3382-3 standard, the STI which is an index that evaluates on a scale of 0-1 clarity of speech in room calculated by propagation of sound waves, and the % ALCons that assesses comprehension of oral message through standardized values obtained from relationship between RT and different levels of SPL(Isbert, 2004). Meanwhile, for the semantic approach, Subjective Classification of Quality of Speech Intelligibility was used, which offers five categories: Excellent, Good, Fair, Poor and Bad, this classification is used for STI and% ALCons (Isbert, 2004). An Open Office Classification scheme was also used that classifies three types of offices according to a combination of RT and SPL conditions for each office class (Nocke, 2014).

According to the analysis, STI was affected by Type of Sound (p = 0.0) and Measurement Point (p = 0.002); also, %ALCons followed same behavior, Sound Type (p = 0.00) and Measurement Point (p = 0.026). The test Bonferroni indicated a significant difference for mean values of STI, values STI for Office Noise ($\bar{x}$=0.56) were bigger than values STI of Silence condition ($\bar{x}$=0.71), see Figure 3a. Meanwhile, test Bonferroni for mean percentages of %ALCons showed that Office Noise ($\bar{x}$=4.85) were mean percentage lesser than mean percentage of Silence condition ($\bar{x}$=11.08) (see Figure 3b).

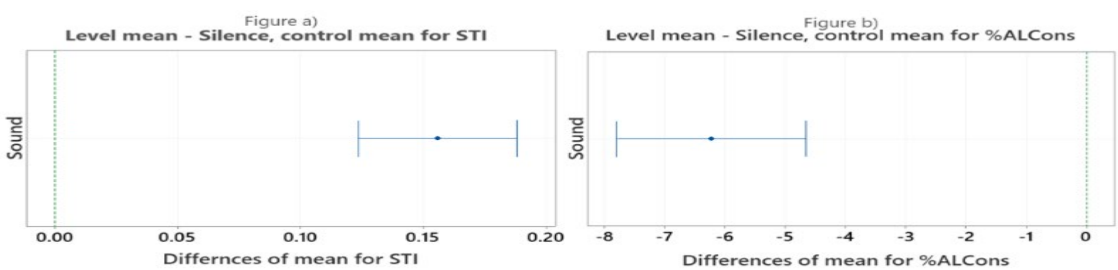

Figure 3. Dunnet test for differences of mean with control: a) test for STI and b) test for %ALCons

The location of Measurement Point (MP) is the factor that was influenced by all parameters, but in general it did not show variation between them; only 5 points out of 18 showed significant differences on measured values. For Reverberation, only point 14 presented an average RT different from the other points, Figure 4a and 4b. While, for intelligibility, four points marked significant differences with others: MP5, MP7, MP12 and MP13, Figure 4a and 4c; of these points, MP12 and MP13 coincide with significant differences for mean percentages obtained from% ALCons and mean STI values in those locations**,** Figure 4a and 4d.

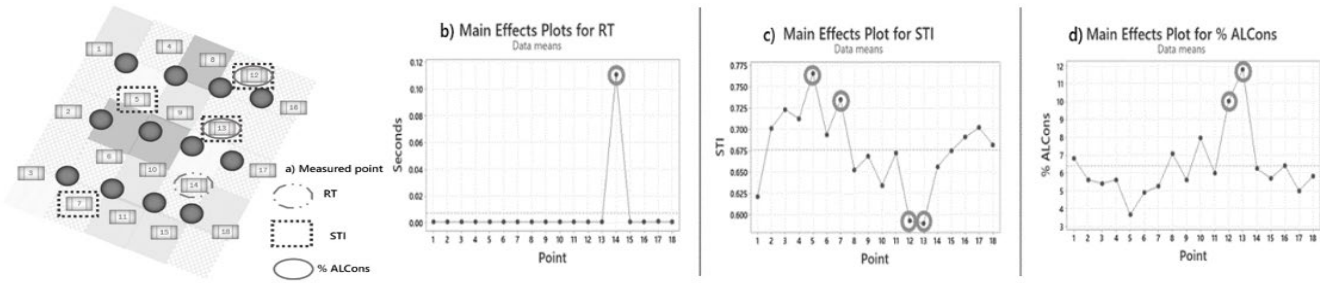

Figure 4. Measured Point Analysis: a) Schema of studied Open-Plan Office, b) Main Effects Plot for RT, c) Main Effects Plot for STI and d) Main Effects Plot for %ALCons

For semantic factors, analysis of Quality of Intelligibility of speech was performed for STI and %ALCons. The results indicated that the Office noise condition for both parameters are classified among Excellent and Good categories. By contrast, the Silence condition noted that %ALCons had better classification that STI, because %ALCons was concentrated on Fair category while STI was classified among Fair and Poor categories, see Figure 5. Nevertheless, the Nocke (2014) office type scheme was not possible to realize because the conditions of the study area did not meet the required values of RT and sound levels of the background noise. In the case of the data obtained from the Reverberation time, its average value RT = 0.007 seconds (at a frequency of 2000 Hz) and the SPL levels were around 51 dB and 54 dB, but for the acoustic classification of the room, the time of Reverberation should be set to RT for 250-4000 Hz with sounds below 40 dB (Nocke, 2014).

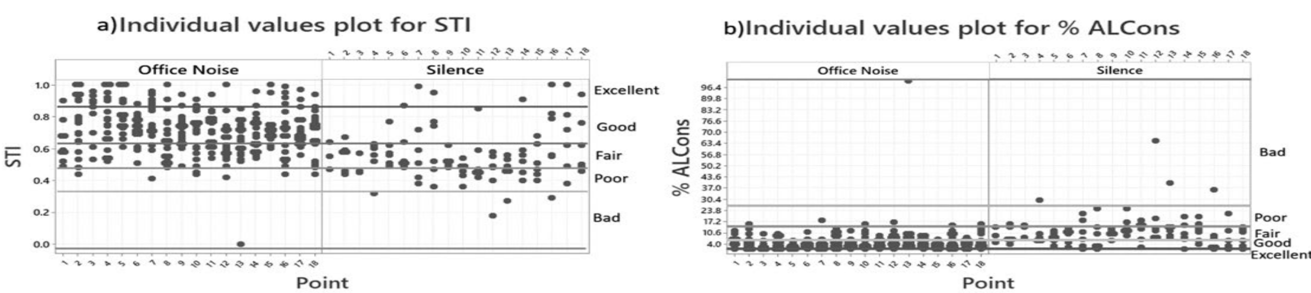

Figure 5. Individual values plot with Classification of Speech Intelligibility Quality by Measured: a) plot for STI and b) plot for %ALCons

4. Concluding Remarks

The objective of this work was to compare different psychoacoustic parameters for evaluating the perceived background noise of open-plan office users, for which three selected acoustic parameters i.e. Reverberation, Speech transmission and Loss of articulation of consonants. The evaluated indices were selected from the ISO 3382-3 standard, of which the STI is the most widely used index. Several studies discuss the cognitive performance of open office users (Brocolini et al., 2016), (Lou & Ou, 2019). Braat-Eggen et al. (2020) and suggest the use of RT to design workstations to improve writing performance. However, Reverberation is a parameter used in acoustic design to evaluate room acoustic conditions regarding absorption and isolation of sound for open offices (Isbert, 2004).

The results indicate that the three parameters were affected by the location of measurement points, while Reverberation was affected by the position of the sound source. Intelligibility parameters were impacted by the type of Sound. The results showed differences in how parameters represent the room's acoustic properties, which may explain why Reverberation is used in acoustic design, and Intelligibility for office interior design. The acoustic parameters of Intelligibility are influenced by various characteristics such as the size of the office, the materials of construction, the position of the sound source, and the type of sound and the design of the office style. Under these conditions, different approaches have been proposed. Sedding et al. (2015) indicated that the size of the office impacts on the cognitive performance of users. In addition, they suggested that the reverberation of the room is a factor in the design of the office that influences an office condition that can be improved to reduce the perception of distraction. On the other hand, Keus van de Poll et al. (2018) indicated that the position of the sound source and the type of sound (background noise generated by multi-speakers) has a disruptive effect on specific activities such as writing.

In this case study, it was observed that the studied area does not meet characteristics to be adjusted to Nocke's (2014) scheme, because this area is an open field with reverberant elements that cause sound behaviors depending on location of sound points. For these circumstances it is suggested to carry out an analysis with Nocke's (2014) office classification scheme in offices with sound conditions lower than SPL = 40 dB or spaces where the reverberant zones do not vary at different points around open offices. This work compares how the psychoacoustic parameters evaluated sound characteristics in the room, especially intelligibility, highlighting objective methods with parameters such as RT and STI. But also compares subjective methods with% ALCons, which is a parameter that can be used to evaluate behavior with a semantic approach. Many studies have focused on objective methods to evaluate acoustic characteristics of room; however, this study also focused on the use of subjective classifications to evaluate the quality of intelligibility in open offices, which is relevant to associate with perception and specific activities, such as writing in open office users.

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