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Technical Note

An Experimental Study of Acoustic Comfort in Open Space Banks Based on Speech Intelligibility and Noise Annoyance Measures

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Tasks requiring intensive concentration are more vulnerable to noise than routine tasks. Due to the high mental workload of bank employees, this study aimed to evaluate acoustic comfort in open-space banks based on speech intelligibility and noise annoyance metrics. Acoustic metrics including preferred noise criterion (PNC), speech transmission index (STI), and signal to noise ratio (SNR) were measured in seventeen banks (located in Hamadan, a western province of Iran). For subjective noise annoyance assessments, 100-point noise annoyance scales were completed by bank employees during activities. Based on STI (0.56 ± 0.09) and SNR (20.5 ± 8.2 dB) values, it was found that speech intelligibilities in the workstations of banks were higher than the satisfactory level. However, PNC values in bank spaces were 48.2 ± 5.5 dB, which is higher than the recommended limit value for public spaces. In this regard, 95% of the employees are annoyed by background noise levels. The results show irrelevant speech is the main source of subjective noise annoyance among employees. Loss of concentration is the main consequence of background noise levels for employees. The results confirmed that acoustic properties of bank spaces provide enough speech intelligibility, while staff's noise annoyance is not acceptable. It can be concluded that due to proximity of workstations in open-space banks, access to very short distraction distance is necessary. Therefore, increasing speech privacy can be prioritised to speech intelligibility. It is recommended that current desk screens are redesigned in order to reduce irrelevant speech between nearby workstations. Staff's training about acoustic comfort can also manage irrelevant speech characteristics during work time.

Keywords: acoustic comfort; open-space banks; speech intelligibility; noise annoyance.

1. Introduction

Open-plan office is commonly designed to facilitate communication and interaction among employees and promote job satisfaction, work performance, and team work effectiveness (Smith-Jackson, Klein, 2009). In comparison with conventional offices, the main feature of these workspaces is the absence of full-height partitions for isolating workers from one another. However, due to removing internal walls, distraction by background noise and lack of speech privacy are identified as the key causes of dissatisfaction in open-plan offices (van de Poll *et al.*, 2014). These offices are commonly equipped with barriers such as panels to induce the condition of a private workstation. However, noise contributes to mental workload, poor performance, stress, and fatigue (Jahncke *et al.*, 2011). Mental performance can be disturbed by different types of noise, such as other peoples' voices, phone rings, ventilation systems, computer fans, keyboards, pieces of equipment, and outdoor noise. In many studies, office workers consistently identified speech as more intrusive than other types of noise sources (Jahncke *et al.*, 2011). It is stated that after an interruption by noise, about eight minutes is needed until the workers can reach the same level of concentration again (Kim, Dear, 2013). Moreover, unattended background speech has been shown to affect several cognitive tasks, such as short-term memory, mental arithmetic, reading comprehension, proofreading, and writing performance (Seddigh *et al.*, 2015; Jahncke *et al.*, 2013). A meaningful noise was found to be more annoying than a meaningless noise when performing simple mental tasks. This background provides enough reasons for experts to change policies and practices in designing these types of offices. Optimising the acoustic design of open-plan offices can be a difficult task, since some acoustic criteria must be considered (Keranen, Hongisto, 2013; Haapakangas *et al.*, 2014).

The International Organisation for Standardisation has published the ISO 3382-3 standard which specifies methods for measuring acoustic parameters in open-plan offices (ISO 3382-3, 2012). The acoustic quality of open-plan offices is generally characterised by speech intelligibility, which has been used by researchers in the past decades. Speech intelligibility is a sound quality descriptor that can be used to analyse the suitability of spaces where speech is crucial. Speech transmission index (STI) is the most common way to assess speech intelligibility. Houtgast and Steeneken developed a highly effective objective method, called the Modulation Transfer Function (MTF), which consists of the modulation of a frequency broad-band signal which reproduces the characteristics of human speech (Houtgast, Steeneken, 1973). The performance of a sound transmission as revealed by the MTF can be expressed in one single index (STI), which relates well to the performance as determined by intelligibility tests with speakers to listeners. Therefore, the STI value was used for estimating speech intelligibility, either from MTF calculations at the design stage of an auditorium or from MTF measurements in actual situations from the modulation reduction factor (Houtgast, Steeneken, 1985). STI describes the clarity of speech in a space taking account of the space's acoustic characteristics like reverberation time and the background noise level (Ebissou *et al.*, 2015; Passero, Zannin, 2012a). STI metric like reverberation time is considered one of the main acoustic characteristics of space which can be used to assess the effects of changes in acoustic properties of open-plan offices. Based on ISO 3382-3, its measurement was carried out without occupants, because this method focuses on the acoustic performance of the space in the presence of a single speaker (ISO 3382-3, 2012).

Distraction distance, defined as distance from speaker where the speech transmission index falls below 0.5, and privacy distance, defined as distance from speaker where the speech transmission index falls below 0.2, are derived from STI as useful criteria too. There is evidence that other types of metrics, such as rate of spatial decay of sound pressure levels and background noise levels, are needed for a more complete evaluation (ISO 3382-3, 2012). Reverberation times, which are indirect measurements of acoustical absorption in a space, are required to estimate speech intelligibility. Suitable reverberation times are required for clear communication of speech and acoustic performance of the open-plan offices. The reverberation time is defined in terms of the mid-frequency reverberation time, the arithmetic average of the reverberation times in the 500 Hz, 1 kHz, and 2 kHz octave bands (Desantana, Zannin, 2011; Galbrun, Kitapci, 2014).

One of the simple acoustical criteria, expressed in dB, is the signal to noise ratio (SNR), which provides an indication of the intelligibility of speech at a given receiver's location. The signal to noise ratio represents the arithmetical difference between the signal level in decibels and the noise level in decibels. To ensure excellent intelligibility, this ratio is recommended to be at least 10–15 dB for people with good hearing and 20–30 dB for hearing impaired. On the other hand, the signal to noise ratio for good privacy in speaker's location is recommended to be −5 dB or lower for people with normal hearing. It should be noted that for the last criterion, signal is irrelevant speech surrounding the workstation of speaker (ISO 3382-3, 2012). In situ acoustic measurements in open-plan offices provide important information for planning acoustically adequate spaces along with very suitable speech clarity and intelligibility. Some important factors affecting the acoustical performance of open-plan spaces are sound absorption, height of screens, background noise, degree of workstation enclosure, distance between workstations, and room dimensions (Passero, Zannin, 2012a). In designing open-plan offices, absorbing ceiling materials and screens between adjacent workstations are used in order to provide desirable speech intelligibility between workstations, while conversation of nearby people and other noise pollution sources are not disturbing (Haapakangas *et al.*, 2014).

The mentioned criteria for evaluation of speech intelligibility focus on architectural characteristics of space. However, the alternative criteria for evaluation of the acoustic comfort of employees are objective metrics like preferred noise curve (PNC) and subjective metrics like noise annoyance scale (NAS) which were determined during activities in the presence of an occupant.

In a financial institution, the activities require concentration and cognitive resources since most of the responsibilities are not considered to be routine work. Since the workstations in an open-space bank, as a special openplan office, are near each other, surrounding intelligible speech is often distracting and may affect work performance. Acoustic problems of open-plan offices have been widely documented in the literature. Despite the high mental workload of bank employees, the amount of available information on bank acoustics is less than that of other open-plan offices. Most studies until now have been conducted in typical open-plan offices (Ebissou *et al.*, 2015; Passero, Zannin, 2012a; Desantana, Zannin, 2011). This study aimed to evaluate acoustic conditions of typical banks and determine the level of noise annoyance among their employees. The new data about speech intelligibility and acoustic comfort in typical banks can help acoustics experts analyse the architectural design in a way that background noise is reduced.

2. Material and methods

2.1. Source of data

This study was conducted in governmental banks located in Hamadan, a western province of Iran. Seventeen open-space banks with similar structures and layouts were selected to evaluate their acoustic quality with regard to speech intelligibility. The characteristics of materials used for internal surfaces and furniture of the banks were recorded carefully, and their sound absorption coefficient values were specified in the light of valid resources. In this regard, the sound absorption coefficients for the materials were extracted from the national acoustics database (Road, Housing & Urban Development Research Center, part 18). It should be noted that this database has been provided based on ISO 354:2003 specifications of methods for measuring the sound absorption coefficient of acoustical materials used as wall or ceiling treatments, or the equivalent sound absorption area of objects, such as furniture, persons or space absorbers, in a reverberation room. Noise reduction coefficient (NRC), which is defined as the average of noise absorption coefficients in the 250 Hz, 500 Hz, 1000 Hz and 2000 Hz octave bands was also calculated for banks' buildings based on ISO standard (ISO 12354-6, 2003).

2.2. Measurement of acoustic measures

2.2.1. Preferred noise criterion

Preferred noise criterion curve is a noise measurement system for continuous or ambient noise in indoor environments proposed by Beranek (1971). PNC curves are often used to judge the acceptability of ventilation and other background broad band noise sources. In each case, standardised curves are used in conjunction with measured noise levels in a room to yield a single-number rating for background noise. The PNC rating values result from plotting the measured octave band sound pressure level spectrum on each chart and noting the lowest standard curve that is not exceeded by the measured values. This single value is then compared with the recommended limits for different spaces. The recommended PNC value for public spaces such as open-plan offices is approximately 35–40 dB (Rossing, 2007). It should be noted that PNC values were determined in the studied banks during activities in the presence of an occupant.

2.2.2. Noise annoyance scale

For subjective noise annoyance assessments among employees, a 100-point noise annoyance scale was used (Pawlaczyk-Łuszczyńska *et al.*, 2005; Kaczmarska, Łuczak, 2007; Pierrette *et al.*, 2015) (see Fig. 1). Employee's annoyance related to the different noise sources during the activities was also evaluated based on NAS questionnaire. The questionnaire was completed by 175 employees of the studied banks.

2.2.3. Reverberation time

Measuring the reverberation time was performed based on ISO 3382-2 in the studied banks (ISO 3382-2, 2008) Measurements were made in the absence of bank employees and customers. Reverberation time is not identical in different locations in a room, so it is usually measured at several locations. The reverberation time was measured based on interrupted noise method for two positions of the sound source and for each of them in two positions of the microphone at the centre and at one corner of each bank. The results were then averaged. For each location of the source-microphones, measurement of the reverberation time was repeated thrice. The distances between microphone locations should be at least half the wavelength of the lowest frequency range, about two meters from the sound source. The distance from the nearest microphone position with reflective surfaces should preferably include at least one quarter of the wavelength, which is typically about one meter. VA-Lab REV module which is developed by BSWA Technology Co. Ltd was employed for measuring RT. It supports the interrupted noise method which includes omnidirectional sound source with sound power of 115 dB pink noise, and the 1/2″ prepolarised free-field microphones. To measure the reverberation time, the omnidirectional source was used in the absence of bank clerks and clients (Aliabadi *et al.*, 2014a). Source and micro-

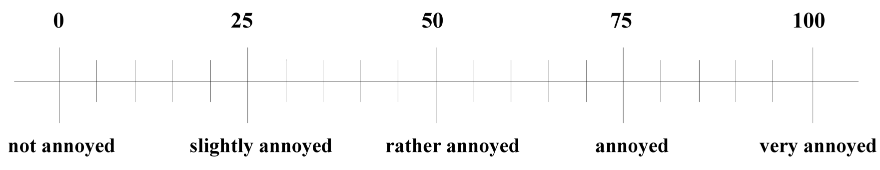

Fig. 1. A 100-point noise annoyance scale (NAS).

phone combinations and positions for measuring reverberation time in each bank are shown in Fig. 2. Reverberation time was determined for the octave bands normally used in room acoustics, which extends from 125 Hz to 8000 Hz. The resulting values were analysed for each point individually. Afterwards, the spatial means were considered in order to obtain a general evaluation of the bank space. Hence, the mean values of mid-frequency reverberation time at representative frequency ranges of the one octave-band frequencies from 500 to 2000 Hz were considered (Aliabadi *et al.*, 2014b; Desantana, Zannin, 2011; Galbrun, Kitapci, 2014).

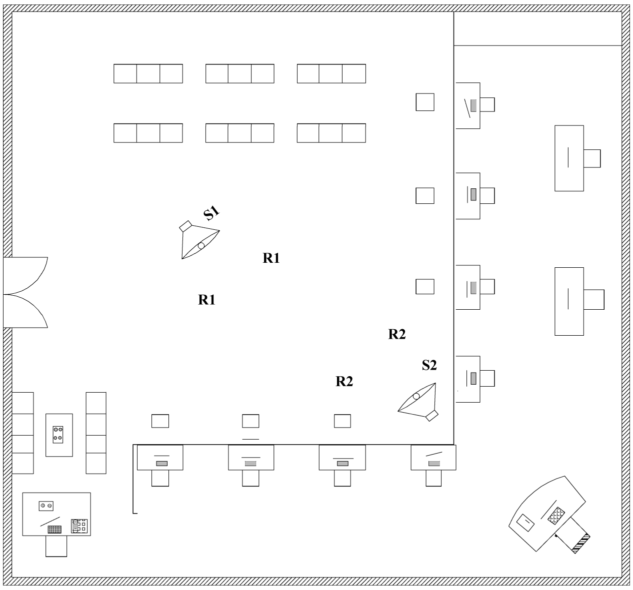

Fig. 2. Source and microphone positions for measurement of reverberation time.

2.2.4. Speech transmission index

Measurements in accordance with ISO 3382-3 were made in banks, without the presence of employees, except the persons that carried out the measurements. As mentioned, STI is criterion for assessment of the quality of speech transfer from speaker to listener and therefore, it is an index for evaluating architectural design of offices. Measurements in accordance with this part of ISO 3382 have to be carried out when people are absent. Thus, the noise from people talking in the room is not included in the measured background noise level. It is recognised that noise from people talking in the open-plan office can sometimes cause a positive masking effect. In such cases, the actual distraction distance (r_D) and privacy distance (r_P) are shorter than the measured r_D and r_P, respectively.

As the main parameters which can be included, all such outdoor and indoor noise sources (i.e., ventilation systems, traffic noise, office equipment), the background noise levels were measured at each station in one octave bands. The noise sources were operated on the same power as during typical working hours. Measurements were conducted along a line which crossed workstations. Ten points were in the line as the measurement positions. The loudspeaker and microphones were positioned 0.5 m from tables and at least 2.0 m from walls and other reflecting surfaces. The loudspeaker and the microphone were placed at the height of 1.2 m above the floor (ISO 3382-3, 2012). The sound source was located in a position where the customers usually give requests to the employees in the first workstation. Figure 3 shows positions of the microphones and noise source (loudspeaker) for measurement of spatial decay of STI. According to the standard method, because people in an open-plan office continuously speak in any directions, an omnidirectional sound source producing pink noise was used. Figure 4 illustrates the layout of workstations in typ-

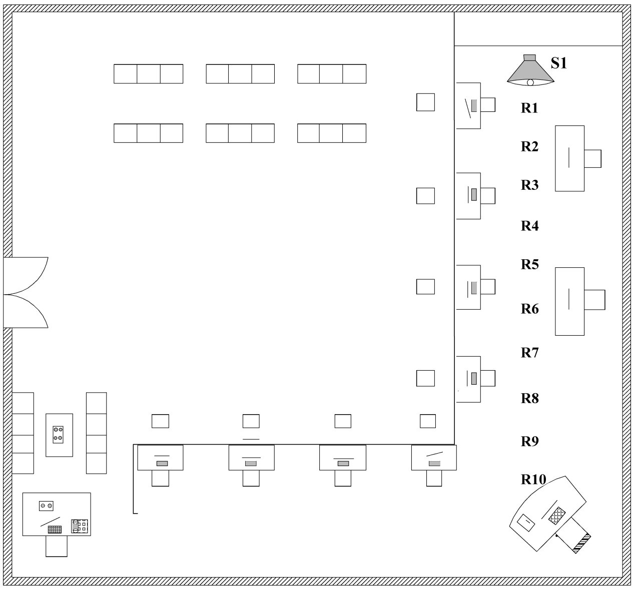

Fig. 3. Typical positions of microphones and noise source for measurement of spatial decay of STI.

Fig. 4. Layout of workstations in typical studied open-space banks.

ical studied open-space banks. Table 1 shows sound power level (SWL) and sound pressure level (SPL) of normal effort speech at distance of 1 m from the source. The microphones were positioned in the seating area, near the stations at a distance at least 0.5 m from chairs, and a relative height of 1.2 m from the floor, reproducing the condition of a seated audience (ISO 3382-3, 2012).

Table 1. Sound power level (SWL) and sound pressure level (SPL) of normal effort speech.

Octave band frequency [Hz]	SWL of speech [dB]	SPL of speech at distance of 1 m from source [dB]
125	60.9	49.9
250	65.3	54.3
500	69.0	58.0
1000	63.0	52.0
2000	55.5	44.8
4000	49.8	38.8
8000	44.5	33.5

Sound pressure levels of pink and background noise levels were measured in octave bands in the frequency range which extends from 125 Hz to 8000 Hz in every position. The integration time was at least 30 seconds. Intelligibility of the speech is mainly affected by the reverberation time and the background noise of the room. STI is based on the determination of modulation transfer function obtained for 14 frequencies at one-third octave intervals from 0.63 Hz to 12.5 Hz combined for seven octave bands with central frequency between 125 Hz and 8 kHz. The modulation reduction factor for each frequency is calculated mathematically as a product of background noise and reverberation time on the signal that simulates speech (Houtgast, Steeneken, 1973; Desantana, Zannin, 2011; Galbrun, Kitapci, 2014).

The STI is calculated from the modulation reduction factor $m(f_m)$, with f_m ranging from 0.63 to 12.5 Hz in 1/3 octave intervals, and each $m(f_m)$ is calculated for octave bands from 125 Hz to 8 kHz. To obtain the STI, the apparent signal-to-noise ratio, LSNapp (dB), should be calculated first. LSNapp is then averaged over all modulation frequencies for each octave band frequency (125 Hz to 8 kHz) to give seven average LSNapp values. These average LSNapp values are then summed to give a single weighted average apparent signal-to-noise ratio. The STI can be calculated from the average LSNapp. The value of the STI can vary between 0 and 1. Value of 1 represents the perfect speech transmission channel between the speaker and the listener and value of 0 represents the worst possible case, where not a single syllable from the speach is understandable. Degree of speech intelligibility based on STI values between a speaker and a listener according to ISO 60268 is shown in Table 2 (ISO 60268-16, 2011; ISO 9921-1, 2003). It should be noted again, the measurements of the RT and SNR were repeated thrice for each position.

Table 2. Degree of speech intelligibility based on STI and SNR [dB] values.

Speech intelligibility	STI	SNR
Excellent	0.75–1.00	> 20
Good	0.60–0.75	15–20
Satisfactory	0.45–0.60	10–15
Poor	0.30–0.45	3–10
Very poor	0.00–0.30	< 3

2.2.5. Distraction and privacy distances

The background noise level averaged over the measurement positions of the measurement line is used for the determination of STI. This is used because spatial variation of the background noise level can cause strong variations in STI and the determination of distraction and privacy distances may not always be unambiguous. The distraction and privacy distances were determined using a linear regression line from the STI values as a function of the distance on a linear axis in station distances. After drawing the custom regression line, r_{D} and r_{P} were determined. Distraction distance is the distance from the speaker where the speech transmission index falls below 0.5. Above the distraction distance, concentration and privacy start to improve rapidly. Privacy distance is the distance from the speaker where the speech transmission index falls below 0.2. Above the privacy distance, concentration and privacy are experienced to be very much the same as between separate office rooms (ISO 3382-3, 2012).

3. Results

The results of the subjective annoyance among bank employees related to background noise levels are presented in Fig. 5. The results indicate that 95% of the employees are annoyed by background noise levels. Figure 6 illustrates the means of employees' annoyance scores related to different noise sources in banks' environments. It should be noted that a 100-point annoyance score is unitless. The result shows that irrelevant speech is the main source of subjective annoyance among bank employees

The results of subjective feelings of fatigue among employees related to background noise levels are presented in Fig. 7. Loss of concentration and effort for high speech are the main consequences of background noise levels for bank employees.

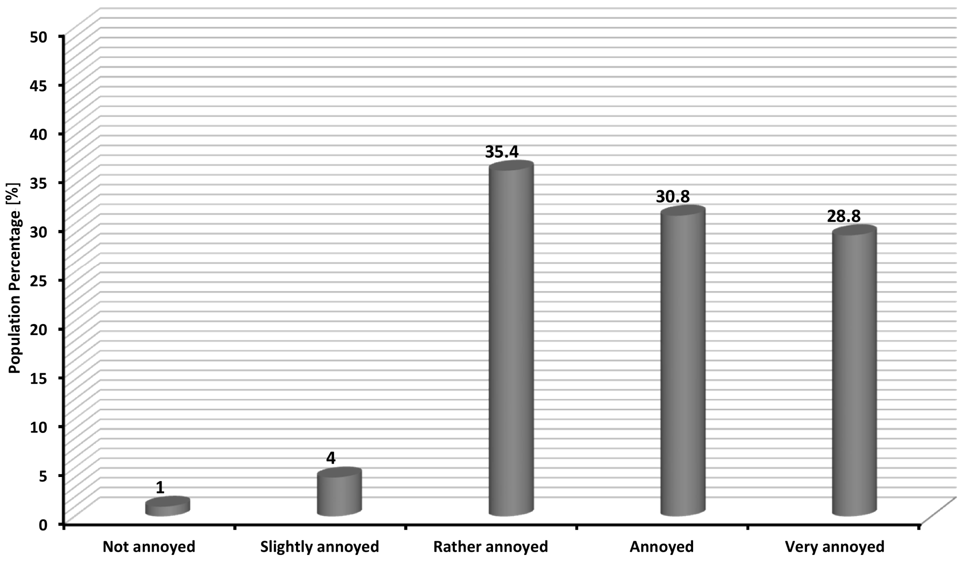

Fig. 5. Subjective noise annoyance among employees related to background noise levels.

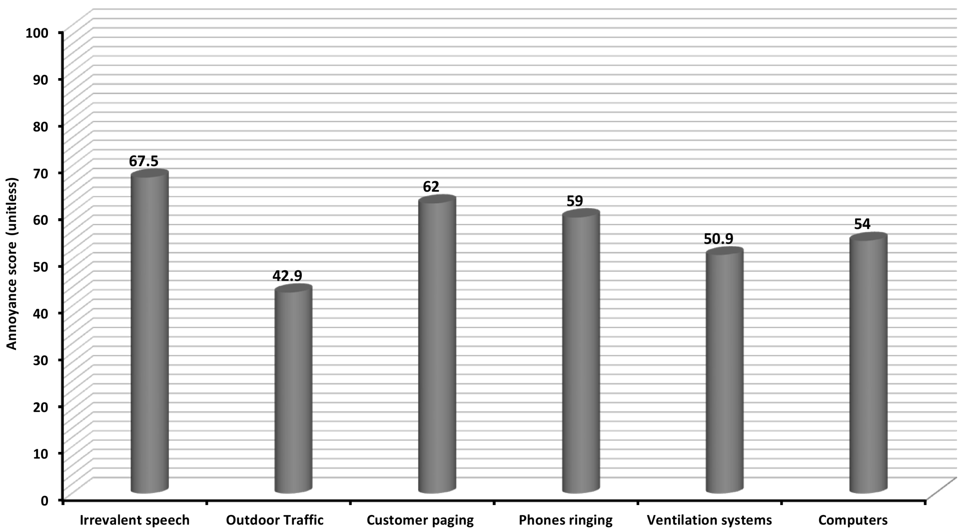

Fig. 6. The means of employees' annoyance scores related to noise sources in banks' environments.

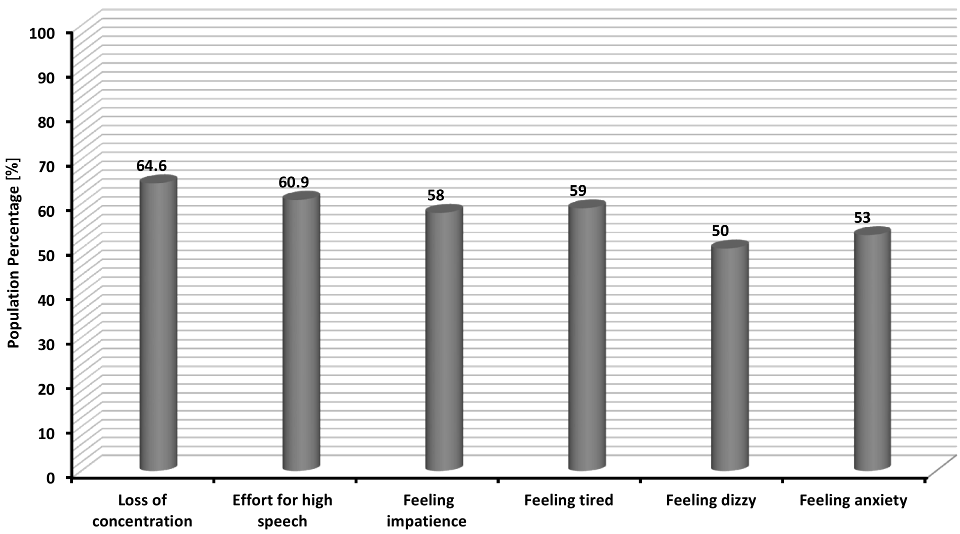

Fig. 7. Subjective feelings of fatigue among employees related to background noise levels.

The descriptive statistics of objective acoustic measures based on the ISO 3382-3:2012 are shown in Table 3. The main architectural characteristics of the offices under study included space volume (mean = 1 223.1 m^3, SD = 930.4 m^3) and space area (mean = 340.2 m^2, SD = 185 m^2). Table 3 summarises the acoustic conditions in open-space banks based on speech intelligibility and noise annoyance measures. Based on STI and SNR values (between a speaker and a listener), speech intelligibilities in the workstations of banks are somewhat higher than the satisfactory level. The standard deviations of the acoustic measures like STI reported in Table 3 can be related to some features like different cubature, NRC, etc. As shown in Fig. 8, there was a significant linear correlation between STI values and distance from the speaker ($p < 0.01$). The linear trend observed between STI values and distance from the speaker in all the banks was used for estimation of the distraction distance (r_D) and privacy distance (r_P). Based on ISO 3382-3, in an open-space office, STI (between a speaker and a listener) must be high, while distraction distance and speech privacy, as indicators of STI for irrevalent speech, must be as low as possible. Moreover, SNR (between a speaker and a listener) must be as high as possible according to Table 2. PNC values in bank spaces were 48.2 ± 5.5 dB, which is higher than the recommended limit value for public spaces such as open-plan offices (35–40 dB). The results of objective acoustic measures based on volume of banks' space were also presented in Table 4. These results show that the RT values of spaces have more impact on STI values as compared to the SNR values. The measurements also showed a maximum

Table 3. Descriptive statistics of of acoustic measures in the studied open-space banks.

Acoustic descriptors	Mean ± SD	Min	Max
Reverberation time[a], RT_{60} [s]	1.24 ± 0.56	0.45	2.45
STI (between a speaker and a listener)	0.56 ± 0.09	0.41	0.74
SNR (between a speaker and a listener) [dB]	20.52 ± 8.20	9.70	35.20
Distraction distance, r_D [m]	5.06 ± 3.13	4.20	8.50
Privacy distances, r_P [m]	23.81 ± 8.18	8.93	26.74
Preferred noise criterion, PNC [dB]	48.2 ± 5.5	40.2	56.3

[a] Mean value at the octave-band frequencies of 500–2000 Hz.

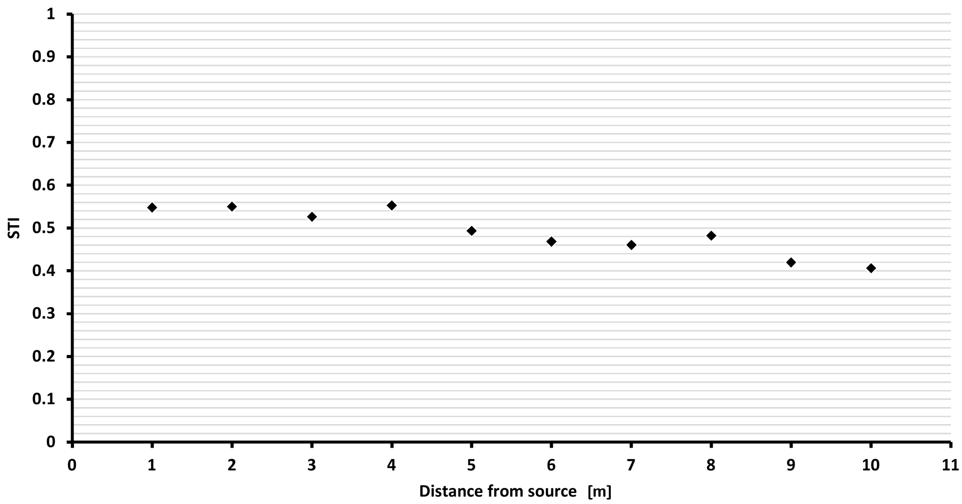

Fig. 8. Spatial decay of STI values based on distance from source in the studied banks.

Table 4. Results of objective acoustic measures based on volume of banks spaces.

Space volume	STI	RT [s]	SNR [dB]
	Mean ± SD	Mean ± SD	Mean ± SD
$V \leq 1000$ m^3	0.58 ± 0.09	1.15 ± 0.56	18.52 ± 8.30
$V > 1000$ m^3	0.52 ± 0.07	1.34 ± 0.54	21.52 ± 5.20

change about ± 0.01 in the STI values for each position when measurements were repeated several times, which can prove the reliability of the STI measurements.

Figures 9 and 10 illustrate the impact of acoustic parameters like reverberation time and signal to noise ratio on STI values in the banks. The figures empirically describe the variations' pattern of acoustic metrics based on STI values in different bank spaces. Based on the STI calculation, in each room, the main acoustic measures affecting STI are RT and SNR. Therefore, RT and SNR which are also influenced by other factors like the cubature and NRC of rooms can be considered as the main indicators of rooms. In other words, the effect of cubature and NRC of rooms on STI calculation can be covered by

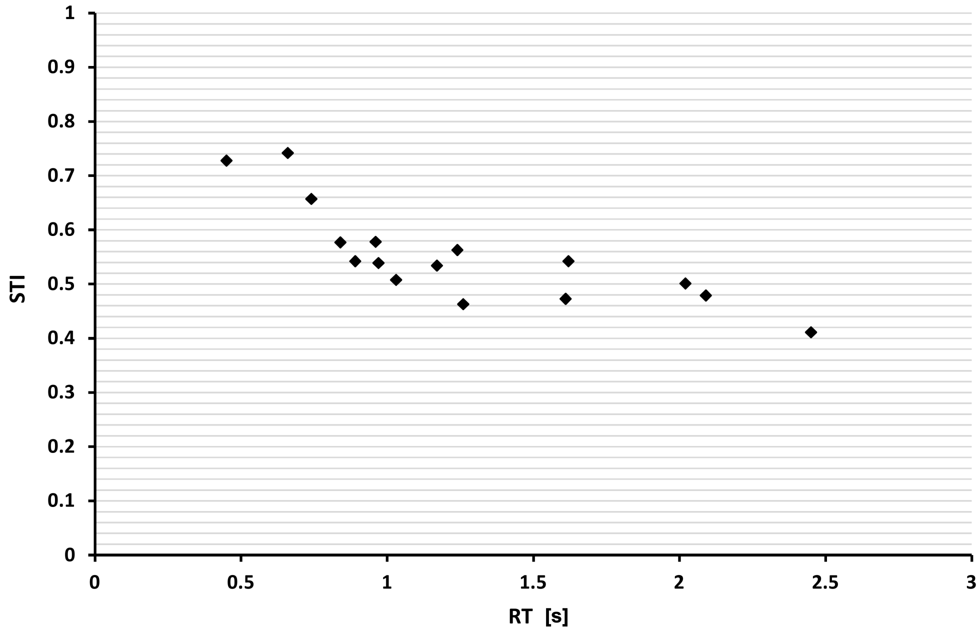

Fig. 9. Scatter plots of STI values compared with the RT values of banks.

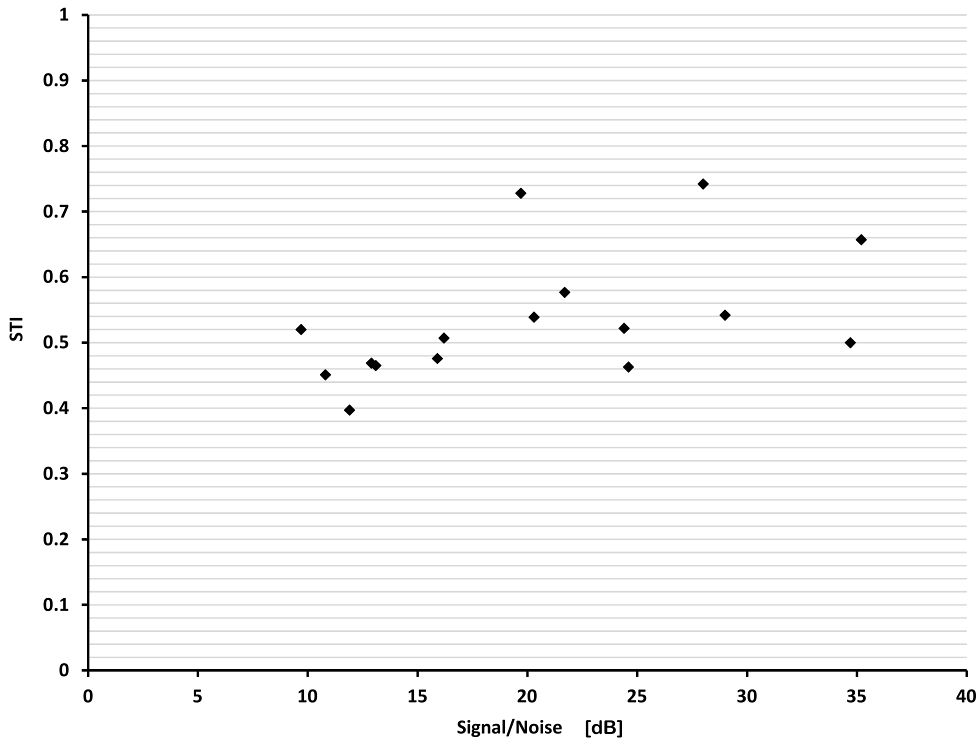

Fig. 10. Scatter plots of STI values compared with the signal to noise ratios of banks.

RT value. The effect of background indoor and outdoor noise sources of rooms on STI calculation can be also covered by SNR value.

Figures 11 and 12 show the impact of NRC and cubature on RT values in the studied banks. An arithmetic average value of mild-frequency reverberation times at the octave-band frequencies of 500–2000 Hz were considered to be RT value for each bank space. Variations of RT values as a function of banks volume generally showed that the studied banks with the largest volumes had the highest RT values Reverberation time theoretically depends on noise reduction coefficient (NRC) and volume of the indoor environments. The empirical equations like Sabine, Eyring and Arau-Puchades' formulas have been developed for estimating reverberation time based on acoustic characteristics of space (Desantana, Zannin, 2011). These results empirically confirmed that room volume is one of the most crucial variables affecting sound fields in banks. The figures could present the detail descriptions about reverberation times in real types of open-plan offices. The relations pattern observed in the scatter plots can be used for analysing the current empirical RT prediction model based on the main architectural acoustics parameters like space volume and absorption coefficient of surface materials.

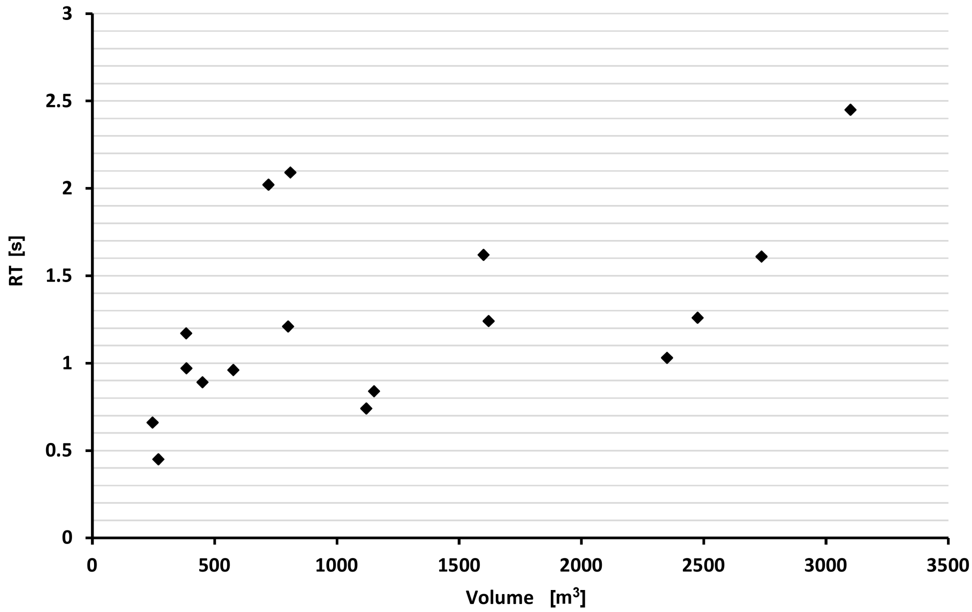

Fig. 11. Scatter plots of RT values compared with the volume of banks.

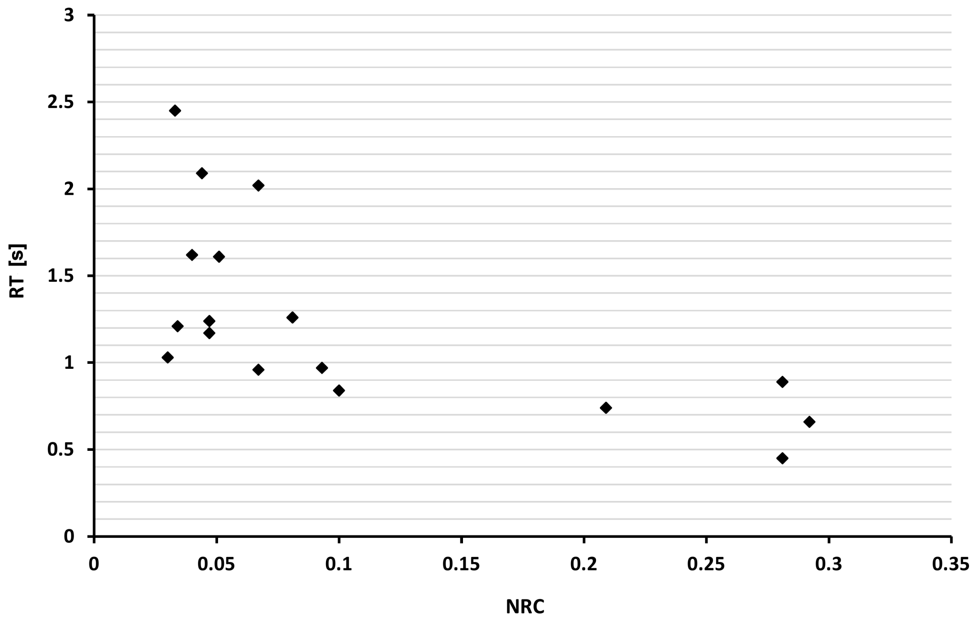

Fig. 12. Scatter plots of RT values compared with the NRC values of banks.

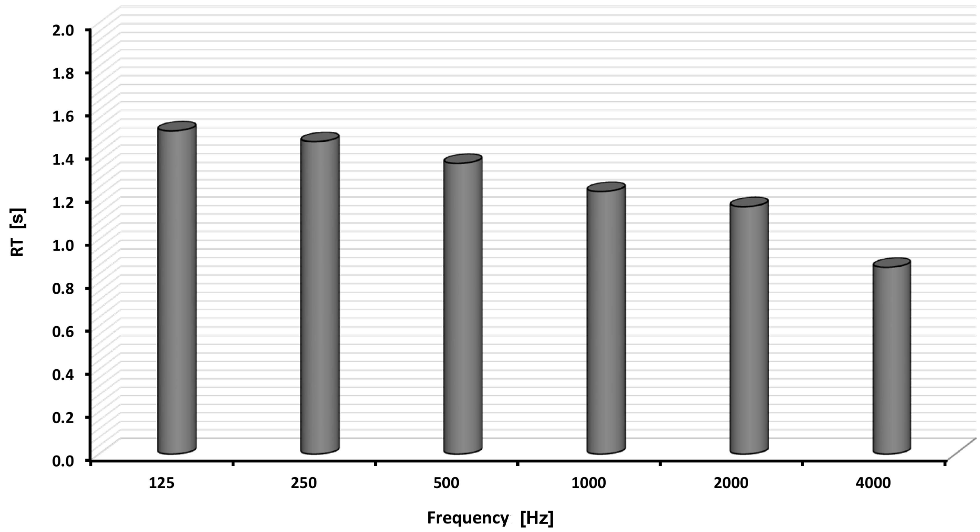

Fig. 13. Mean values of RT spectrum in one octave band frequency for whole banks.

Figure 13 presents the run of reverberation times as a function of frequency for all studied open-space banks. The results show that in the open-space banks mean values of RT in the low frequencies were somewhat higher than the medium and high frequencies.

4. Discussion

The current study intended to provide new data about speech intelligibility and acoustic comfort in open-space banks, which can be considered for analysing acoustic conditions and architectural design of this type of space. The results confirmed that speech intelligibility between speakers and listeners in the workstations of the studied banks are somewhat higher than the satisfactory level. However, PNC values in bank spaces were higher than the recommended limit values for public spaces such as open-plan offices. Moreover, about 95% of the employees felt noise annoyance during daily activities in their workstations. It can be stated that acoustic properties of banks' spaces provide enough speech intelligibility, while the subjective noise annoyance and distraction of the staff are not acceptable. Gholami *et al.* (2014) also showed that, in open-space banks, subjective fatigue of employees increased in different classes of noise exposure ($p < 0.01$). A study about annoyance caused by low frequency noise during mental work in offices shows that over 50% of the subjects reported problems with concentration in the work environment (Kaczmarska, Łuczak, 2007). Pierrette *et al.* (2015) also showed that most of the employees interviewed consider that the noise in their workspace is high or very high (56%) and that it is annoying or very annoying (58%) (Pierrette *et al.*, 2015). Our results are in line with the previous studies (Seddigh *et al.*, 2015; Ebissou *et al.*, 2015; Passero, Zannin, 2012b) and report that concentration of employees is affected negatively when exposed to irrevalent speech during activities.

However, in addition to the previous research findings, we find that due to proximity of workstations in the studied open-space banks, access to very short distraction distance is necessary. In this regard, for providing comprehensive acoustic comfort, increasing speech privacy can be prioritised to speech intelligibility. Jahncke *et al.* (2013) stated that the STI of irrelevant speech is very important. They demonstrated that attempts to increase speech privacy will yield increases in cognitive performance (Jahncke *et al.*, 2013).

The proximity of workstations in the studied open-space banks can be solved using suitable acoustic screen in order to reduce the background noise level (irrelevant speech) between nearby workstations. Currently, some existing sound-barrier screens between the desks do not have good acoustic designs and dimensions. For providing acceptable speech privacy, the height of screen panels separating workstations must be high enough to remove the direct path of speech from one workstation to another and also reduce the sound level of diffracted over the panel. It is proposed that floor-mounted desk screens are designed between workstations. It can minimise distraction at work place and allow employees to communicate freely at the same time. The height of 50 cm above desk top ensures acoustic comfort and separates the workstation visually. The need of visibility between workstations can be also solved through using glass desk partitions (ISO 17624, 2004; Bradley, 2003).

The results demonstrate that bank spaces with the highest RT value were those with the lowest NRC values. Moreover, the detailed results confirm that reverberation time values have more effects on STI values as compared to SNR values (see Table 4). The lack of suitable sound-absorbing surfaces such as acoustic tiles in ceiling and walls produces more reverberant spaces. Open-space banks areas are covered with relatively hard materials such as marble, glass, laminates, and wooden flooring. They can provide an acceptable interior aesthetics, but these surfaces also increase reverberation times.

In the current study, two simple and relatively complex indicators for speech intelligibility (i.e., SNR and STI) were investigated. These criteria generally focus on the architectural design of open-space offices. As mentioned, speech transmission index (STI) is the most objective method for evaluating the speech intelligibility in open-plan offices. Duquesnoy and Plomp (1980) also confirmed that the speech reception thresholds of subjects are changed as a function of reverberation time and can be expressed as a single number, namely the required speech transmission index.

Different methods have been proposed for determination of STI, including computer simulation and the calculation method based on MTF function. Some studies have been conducted for evaluation of the accuracy of these approaches. Li and Lam (2005) developed a theoretical model based on an image-source method using computer simulation for the prediction of reverberation time and speech transmission index in rectangular long enclosures which have good agreement with the experimental data. Desantana and Zannin (2011) also show that calculated STI values by MTF function and predicted values by computer simulation are consistent.

On the other hand, Galbrun and Kitapci (2014) state that STI calculations based on RT and LSN tend to underestimate the STI, with average differences between measured and predicted STI values lower than 0.06. Recently, Nowoświat and Olechowska (2016) investigated the empirical feasibility of fast estimation of speech transmission index using the reverberation time. The results confirmed that the fast estimation results are very close to those obtained in the computer simulation using ODEON software (Nowoświat, Olechowska, 2016). Based on the literature, it can be concluded that, determination of STI based on MTF function can be considered a reliable and simple method which is available to all designers, architects and acoustics professionals for analysing acoustic conditions and architectural design of open-plan spaces.

Nowoświat and Olechowska (2016) presented the function of STI in the domain of reverberation time for lecture halls. Their results showed that the determination coefficient for that approximation between STI and RT is 0.98 and, therefore, STI can be quickly estimated in the lecture hall by knowing only the time of room reverberation (Nowoświat, Olechowska, 2016). Bistafa and Bradley (2000) also plotted STI values versus reverberation time for unamplified speech in classrooms. However, in the current study, as it is shown in Fig. 9, the poor relation between STI and RT values can be due to different background noise levels of banks' spaces and, consequently, different SNR values.

The results of the current study show a change of about ± 0.01 in the STI values for each speaker to listener position when the measurements are repeated thrice. According to the previous research, these differences are not noticeable and therefore negligible, since 0.03 is defined as just noticeable difference in STI value (Bradley *et al.*, 1999).

The criteria like preferred noise curve and noise annoyance scale could also help us conduct more complementary investigations about acoustic comfort of employees during activities in bank spaces. The current study has empirical nature and, therefore, the detail empirical data in a clear form can be applied by architectural and acoustics professionals in designing of this type of office. The results confirmed that a combination of objective and even subjective acoustic indicators is necessary for a sufficient characterisation of the acoustical conditions in open-plan offices.

5. Conclusions

The results confirmed that acoustic properties of bank spaces provide enough speech intelligibility, while staff's noise annoyance is not acceptable. It can be concluded that, due to proximity of workstations in the studied open-space banks, access to very short distraction distance is necessary. In this regard, increasing speech privacy can be prioritised to speech intelligibility. It is recommended that the current desk screens are redesigned in order to reduce irrelevant speech as much as possible between nearby workstations. Staff's training about acoustic comfort can also manage irrelevant speech characteristics during work time. Data about speech intelligibility and acoustic comfort were gathered in open-space banks, as a special open-plan office. These data can be used by the acoustics experts to implement effective architectural designs in this typical workspace.

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Conflicts of interest

The authors have no conflict of interests to declare.

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