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A modified technique to predict speech privacy and distraction distances in open-plan offices

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ABSTRACT

Open-plan offices have become widely adopted in various industries as a workplace environment. However, this office layout type suffers from speech privacy, which can be represented by the acoustic parameter known as the Speech Transmission Index (STI). ISO 3382-3:2012 provides guidelines for calculating the acoustic parameters of a room tailored explicitly for open-plan offices. However, the existing method in ISO 3382-3:2012 requires a parallel layout of workstations to determine the STI value, which is hardly found in modern office settings. This study presents a technique to predict the ideal values of rP and rD, based on the relationship between %Alcons and the Speech Transmission Index (STI) for a specific workstation, using linear regression and in-situ measurements. The analysis of acoustic conditions in an open-plan office reveals that modified techniques can predict the acoustic quality in a modern office layout. The D2, S values indicate good acoustic quality, but the Lp, A, S,4m values do not meet the required standard. Using %Alcons equations, the study shows how to predict distraction distances and categorize workstations as 'Distracted' or 'Not distracted'. The results indicate only a small percentage of workstations allow for private communication.

Introduction

The open-plan offices are large, open spaces where many occupants can simultaneously work at well-situated workstations (International Organization for Standardization 2012). Open-plan offices are one of the most popular workspace layouts as they provide increased net usable area, higher occupant density, ease of reconfiguration, and, most importantly, improved communication and interaction between employees (Acun and Yilmazer 2018; Aulia, Kusliansjah, and Budiyuwono 2021). However, these workstations generally lack full-height partitions that can separate an individual's acoustic environment from their co-workers, resulting in a shallow degree of speech privacy, as it refers to refers to the ability to prevent unintended individuals outside the workspace from overhearing private conversations (Jeon et al. 2022).

On the other hand, several studies have shown that cubicle spaces provide a more satisfactory noise level and speech privacy compared to open-plan offices (Sander et al. 2021; Kim and de Dear 2013). This condition is supported by other research based on surveys, simulations, and field assessments, which also indicate that the degree of enclosure of workspaces, such as partition height, is related to occupants' evaluation of the acoustic conditions, along with other parameters such as ceiling height and workstation size. Even small deteriorations in these parameters can harm occupants' health and well-being (Park et al. 2020; Yıldırım, Güneş, and Yilmaz 2019).

Moreover, ISO 3382-3:2012 outlines the procedure for predicting the acoustic performance of open-plan offices. The procedure is more suitable for improving the acoustics of open-plan offices using computer simulations, as demonstrated in studies conducted by Yadav et al. (2017); Christensen, Koutsouris, and Rindel (2013); Utami, Arifianto, and Nadiroh (2017). The findings of these studies provide better solutions for specific office typologies by reducing ceiling height, implementing symmetric layouts, and incorporating interior design solutions such as acoustic partitions, high-absorption materials, and sound masking (Park et al. 2020; Jukka Keränen, Hakala, and Hongisto 2020; Cabrera, Yadav, and Protheroe 2018). ISO 3382-3:2012 asserts that a single speaker in an open-plan office can lead to worker performance decrements. Therefore, regardless of whether there are one or multiple speakers in the office, the disruptive factor is the speech intelligibility determined by the Speech Transmission Index (STI) value (Rindel 2018; Jukka Keränen, Hakala, and Hongisto 2020; J. Keränen and Hongisto 2013).

The Speech Transmission Index (STI) is a parameter used to assess speech intelligibility in a given acoustic environment. Therefore, STI represents communication activities in the office that require clear communication within the range of a single workstation. STI is closely related to reverberation, reflecting the amount of reverberation and noise level that can reduce speech clarity (Davis, Patronis, and Brown 2013).

The existing method outlined in ISO 3382-3:2012 for determining STI in open-plan offices has a limitation. It requires a parallel layout of workstations, which is not commonly found in modern office settings. This condition poses a challenge because modern office layouts often have a more random arrangement of workstations due to factors such as furniture design and layout.

This study presents a new methodology for assessing and improving the acoustic conditions in open-plan offices. It incorporates the principles and guidelines from ISO 3382-3:2012 but with more flexibility in the workstation layout. The study demonstrates a modified technique for evaluating acoustic conditions in real office settings by measuring speech privacy distance (r_P) and distraction distance (r_D) and considering the relationship between $\%Al_{cons}$ and STI.

Acoustic satisfactory in an open-plan office

Conducting small meetings around workstations is often considered in open-plan office settings. However, the challenge lies in providing clear communication among employees while maintaining good speech privacy to prevent unintentional speech propagation, which can lead to dissatisfaction among other employees (Kim and de Dear 2013; Sander et al. 2021; Haapakangas et al. 2018). Some employees, especially those far from the speaker, may perceive conversations as unwanted noise and experience distractions. Moreover, unwanted noise from conversations can be exacerbated by other sources of activity, such as footsteps, telephone conversations, opening and closing of drawers, as well as shared facilities like elevators and photocopiers (Sander et al. 2021). Therefore, the layout of workstations and the level of sound absorption provided by furniture, partitions, and equipment materials in open-plan offices play a crucial role.

The speech activity scenarios in an open-plan office are illustrated in figure 1. At workstation 1, a speaker requires good speech intelligibility for easy understanding of the communication content. However, high speech privacy is also necessary to prevent employees at workstation 2 from overhearing conversations originating from workstation 1. Consequently, employees at workstation 2 may be distracted by the discussions at workstation 1. These scenarios of speech activity involving the speaker, listener, and unintended listeners create a sound field, referred to as an "island."

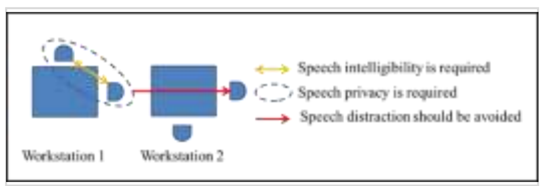

Figure 1. Scenarios of speech activities between the speaker, listener, and involuntary listeners in an open-plan office

Predicting the overall acoustic conditions of an open plan office

A standard measurement procedure to evaluate the acoustic conditions of open-plan offices is available in ISO 3382:3-2012. This standardized method was demonstrated using several open-plan offices in Jakarta, Indonesia, and the predicted conditions were evaluated using combined techniques performed by other (Utami et al. 2013; Utami 2014).

Standard ISO 3382:3-2012 measurement

There are several parameters used to evaluate the acoustic conditions in open-plan offices, such as the distraction distance (r_D), the spatial decay rate of A-weighted SPL of speech ($D_{2,S}$), the A-weighted SPL of speech at 4 m ($L_{p,A,S,4m}$), the average A-weighted background noise level ($L_{p,A,B}$) and the privacy distance (r_P). These parameters can be obtained by conducting room impulse response (RIR) and background noise measurements. For instance, the $D_{2,S}$ represents the spatial decay rate of the A-weighted sound pressure level of speech per doubling distance, which is obtained through linear regression analysis of the A-weighted sound pressure level to the distance between the receiver and the sound source. Therefore, the sound source and the receiver are positioned in a straight line to obtain accurate results. At least four measurement positions are required, with listener position number 1 representing the nearest workstation to the sound source.

A single source represents the position of a distracting talker while the rest of the workers are assumed to be silent listeners. Therefore, in the in-situ measurement, a single source is used with an omnidirectional sound source positioned 1.2 m above the floor and at least 2.0 m away from any surfaces or walls that can reflect sound. The receivers are placed at a distance of 0.5 m from any obstacles. Pink noise is generated from the sound source to obtain the A-weighted speech level values at measurement position *n*, referred to as variable $L_{p,A,S,n}$. However, these spatial decay values alone do not accurately depict speech privacy as they do not account for the masking effect of background noise, particularly in scenarios where additional speakers may be present in the room, leading to masking effect of background noise (Hongisto et al. 2021; Hongisto and Keränen 2021; J. Keränen and Hongisto 2013).

Equation (1) calculates $D_{2,S}$ by using variables of the the A-weighted speech level values at measurement position *n* ($L_{p,A,S,,n}$), the measurement position distance to the source (r_n), the reference distance (r_0), 1 m.

$$D_{2,S} = -\log(2)\frac{N\sum_{n=1}^{N}\left[L_{p,A,S,n}\log\left(\frac{r_n}{r_0}\right)\right]-\sum_{n=1}^{N}L_{p,A,S,n}\sum_{n=1}^{N}\log\left(\frac{r_n}{r_0}\right)}{N\sum_{n=1}^{N}\left[\log\left(\frac{r_n}{r_0}\right)\right]^2-\left[\sum_{n=1}^{N}\log\left(\frac{r_n}{r_0}\right)\right]^2} \quad (1)$$

The $D_{2,S}$ indicates the effectiveness of materials and partitions (heights) within the room for sound absorption. Once the values of $D_{2,S,}$ and $L_{p,A,S,4m}$ are obtained, the acoustical condition of open-plan office can be predicted using the distraction distance (r_D). Table 1 provide the values for $D_{2,S}$, and $L_{p,A,S,4m}$ that describe the acoustic condition of an open-plan office based on ISO 3382-3:2012 (International Organization for Standardization 2012).

Regression model of $D_{2,S,}$ and $L_{p,A,S,4m}$ by Keränen and Hongisto

In some references, $D_{2,S}$ can also be affected by other factors, and their influence can be predicted using a regression model, as shown in Equation (2) (J. Keränen and Hongisto 2013).

$$D_{2,S} = 8\frac{h}{H} + 0.16\frac{L}{H} + 4\alpha_c + 1.7\alpha_f \quad (2)$$

Meanwhile, the regression model for $L_{p,A,S,4m}$ is given in Equation (3) (J. Keränen and Hongisto 2013).

$$L_{A,S,4m} = 3h - 0.1W - 4.6\alpha_c - 0.84\alpha_f \ \dots (3)$$

Equations (2) and (3) are regarded as the most straightforward methods to calculate $D_{2,S,}$ and $L_{p,A,S,4m}$ as they rely solely on the room's characteristics. This approach offers the benefit of requiring fewer measurement points and eliminates the need for the source and receivers to be positioned in a straight alignment. These two parameters can be determined by knowing the geometry of the partition, room dimensions, and absorption characteristics.

The followings are the definition of mentioned variables: (1) Room length L, in meter; (2) Room width W, in meter; (3) Room height H, in meter; (4) Mean screen height h, in meter, (sound-absorbing screen); (5) Mean ceiling absorption coefficient d a_c; (6) Apparent furnishing absorption coefficient a_f.

Predicting the speech privacy distance (r_P) and distraction distance (r_D)

ISO 3382-3:2012 utilizes the privacy distance (r_P) and distraction distance (r_D) to predict workstations' speech privacy and distraction levels in open-plan offices. The r_D is considered a reliable measure that accurately reflects the acoustic conditions experienced by workers. While open-plan offices are generally associated with poor acoustic conditions, individual workstations within these offices may still offer better privacy and reduced distractions during work activities.

The estimation of r_P and r_D relies on the Sound Transmission Index (STI) values obtained from measurements taken at various positions. These values are derived using the same measurement procedure employed for $D_{2,\ S,}$ $L_{p,\ A,S,4m}$, and the average A-weighted background noise level ($L_{p,A,B}$). The previous section did not provide a detailed explanation of $L_{p,A,B}$ regarding the specifications and adjustments made to address acoustic conditions during the measurement process when establishing the regression model for $D_{2,S,}$ and $L_{p,A,S,4m}$.

Prediction of r_P and r_D based on ISO 3382-3:2012

In ISO 3328-3:2012, the concept of privacy distance (r_P) is introduced, which refers to the distance from a sound source where the Speech Transmission Index (STI) falls below 0.2 (International Organization for Standardization 2012). Similarly, the distraction distance (r_D) is defined as the distance at which the STI drops below 0.5. Beyond this distance, the level of distraction experienced by a listener at a specific position can be minimized. By employing linear regression analysis of STI values based on microphone distances from the sound source, it is possible to determine both r_P and r_D. These distances can then be used to estimate speech privacy and distraction levels across various workstations, ranging from the nearest to the farthest workstation from the sound source.

Prediction of r_P and r_D using $\%Al_{cons}$ and STI

Prior research has commonly employed open-plan offices without a specific arrangement of workstations, leading to the inability to predict r_P and r_D through the linear regression line between STI and microphone distances (Peutz 1971). In this paper, we propose an alternative approach by utilizing the relationship between $\%Al_{cons}$ and STI. The STI parameter mentioned here corresponds to the one previously discussed. Peutz (1971) discovered a linear correlation between the room's acoustic condition, the liveliness factor, and the articulation loss of consonants, as depicted in Equation (4). It is worth considering that the STI parameter in this context is identical to the one mentioned earlier.

$$\%Al_{cons} = 200\frac{r^2 T_{60}{}^2}{V} + a \ldots (4)$$

Where r is the distance between source and receiver, T_{60} is the reverberation time, V is room volume, and a is a correction factor, varies from 1.5% to 12.5% for a "good" listener to 12.5% for a "bad" listener. A slightly different way of defining the correction factor (a) above is given by Equation 5 (Bistafa and Bradley 2000).

$$\%Al_{cons} = 200\frac{r^2 T_{60}{}^2}{VQM}(n+1) \ldots (5)$$

In room acoustics research, Equation (5) is utilized to evaluate the performance of a sound system within a room, serving as a substitute for an ideal speaker. When analyzing a single observed speaker or source, the value of n in the Equation is set to 1. Two variables required in Equation (5) that have not been previously defined are QM and $\%Al_{cons}$. QM represents the product of the sound source's directivity (Q) and the room absorption factor (M) (Haapakangas et al. 2014). QM is treated as a single variable and can be determined by solving Equation (5) using a known $\%Al_{cons}$. Equation (6) in the subsequent section presents an illustration of this calculation. Bistafa and Bradley (2000) introduced a relationship between the $\%Al_{cons}$ algorithm and the STI, as specified in Equation (3) (Bistafa and Bradley 2000).

$$\%Al_{cons} = 170.5405e^{-5.419*STI} \ldots (6)$$

Method

Mechanism of r_P and r_D prediction using the relation between $\%Al_{cons}$ and STI

This study demonstrates the application of Equation (5) and Equation (6) in estimating r_P and r_D. In Equation (5), the $\%Al_{cons}$ algorithm is employed, incorporating the distance variable (r) between the speaker (source) and the listener (receiver). This distance variable plays a vital role in predicting the speech privacy and distraction level within an open-plan office, as defined by the privacy distance (r_P) and distraction distance (r_D) outlined in ISO 3382:3. To determine these distances; it is necessary to have access to the STI values at each measurement position, which allows for the derivation of a linear regression depicting the relationship between STI and the distances. Therefore, the proposed approach relies on Equation (5) and adheres to the ISO 3382:3 threshold of STI ≤ 0.2 for a private condition and STI < 0.5 for the distraction distance ($_{rD}$).

Experiment setups based on ISO 3382-3:2012

Two experimental settings of different receivers' alignments are assigned in an open plan office in Jakarta, Indonesia, as shown in figure 2 and labeled as 'Experiment Setup-1' and 'Experiment Setup-2'.

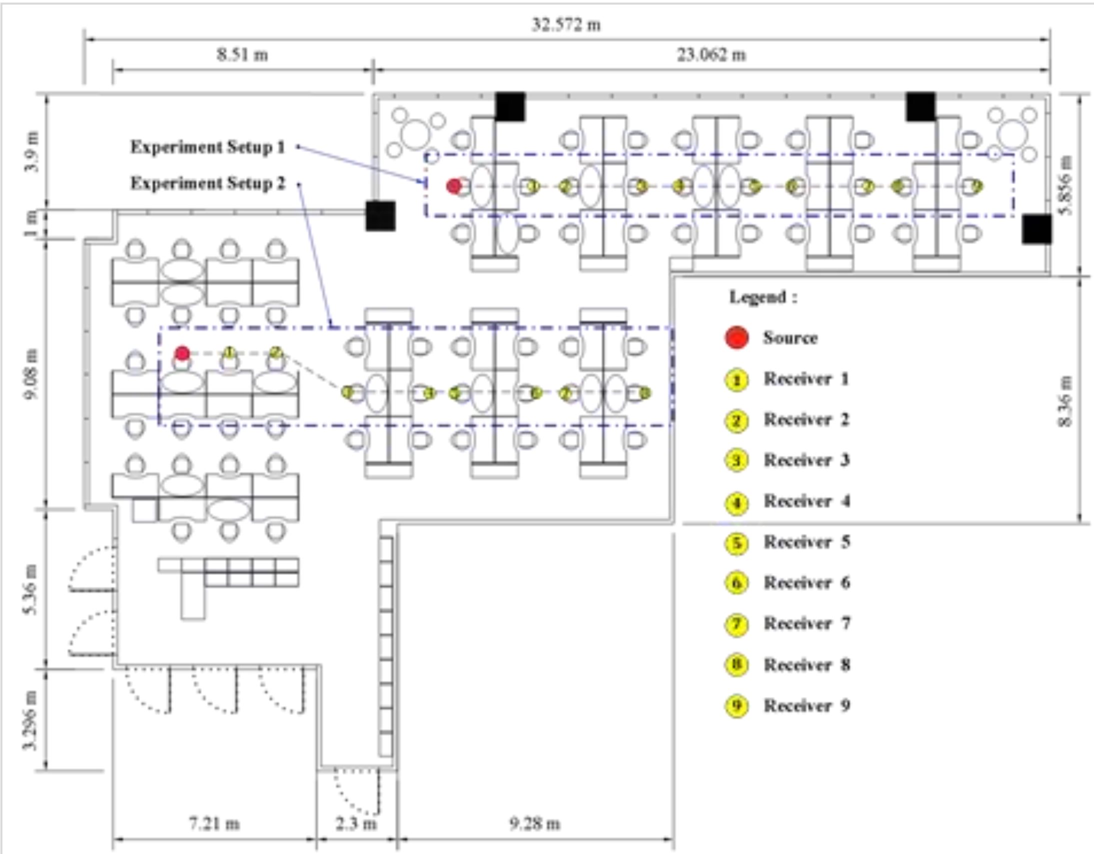

Figure 2. Interior layout and the two experiment settings of an open plan office; experiment setting 1 and experiment setting 2
Source: (Utami 2014)

Experiment Setup-1 involved a configuration where the source and receivers were aligned in an aligned manner. On the other hand, experiment Setup-2 deviated from perfect alignment, potentially resulting in less accurate approximations of the acoustic conditions when utilizing the regression model for $D_{2,S}$ and $L_{p,A,S,4m}$ as described in Equations (2) and (3). To ensure versatility in speaker direction, a dodecahedron loudspeaker was utilized, allowing for speech projection in any orientation. The speech level was carefully adjusted to simulate conversational levels slightly below the standardized normal speech typically observed in open-plan offices. According to a previous study by Haapakangas et al. (2014), the A-weighted mean level in a free field at a distance of 1 m was measured to be 53.0 dB. For comparison, standardized normal effort speech is typically around 57.4 dB. The speech parameters were derived from room impulse response (RIR) measurements conducted at each position within the experiment.

Result and discussion

The overall acoustic condition

In this study, the prediction of the overall acoustic condition was examined using two different methods: the J. Keränen and Hongisto (2013), and the ISO 3382:3 methods. The results obtained from these two methods were compared and presented in table 1.

The table consists of several rows, with the first two rows specifically indicating the categories of good and poor acoustic conditions. The comparison allows for a comprehensive evaluation of each method's performance in assessing the acoustic conditions based on the given criteria.

By utilizing ISO 3382-3:2012 measurements, both Set-up 1 and Set-up 2 demonstrated substandard acoustic conditions, as the $D_{2,S}$ values fell below 5 dB, while the $L_{p,A,S,4m}$ exceeded 50 dB. Conversely, implementing the modified technique (Hongisto and Keränen 2015) revealed improved $D_{2,S}$ values, indicating a satisfactory acoustic quality ($\geq$ 7 dB). However, the $L_{p,A,S,4m}$ measurements still failed to meet the criteria for desirable acoustic quality. Nevertheless, it remains plausible that some workstations could exhibit favorable acoustic conditions when employing the modified technique.

Table 1. Predicted acoustic conditions of experiment Setup-1 and Setup-2 using ISO 3382-3:2012 and Keränen and V. Hongisto method

Acoustic conditions	Parameters		
	$D_{2,s}$	$L_{p,A,S,4m}$	r_D
Good	$\geq$ 7 dB	$\leq$ 48 dB	$\leq$ 5 m
Poor	< 5 dB	> 50 dB	> 10 m
Results obtained from experiment setups in figure 2			
Setup-1 (ISO 3382:3)	1.65 dB	70.5 dB	43.8 m
Setup-2 (ISO 3382:3)	1.40 dB	68.6 dB	49.7 m
Setup-1 (J. Keränen and Hongisto 2013)	7.17 dB	65.5 dB	-
Setup-2 (J. Keränen and Hongisto 2013)	7.03 dB	68.1 dB	-

The r_P and r_D calculation steps using $\%Al_{cons}$ and STI

As the modified technique holds the potential to meet all the criteria for good acoustic quality, we can proceed to calculate the distances required for speech privacy and distraction distance for individual workstation.

The room impulse response (RIR) data collected from the experiment conducted in Setup-1, as shown in figure 2, was utilized to determine the r_P and r_D values. The STI value at receiver 1 was found to be 0.835, with a corresponding source-receiver distance (r) of 2.59 meters and a T30 value of 0.331. By substituting the T30 value into Equation (6), the $\%Al_{cons}$ was calculated to be 1.85. These variables were then used in Equation (5) to solve for the unknown QM, resulting in a QM value of 0.143 as shown in Equation (7).

$$\%Al_{cons} = \frac{200 \times (2{,}59)^2 \times (0.33)^2(1+1)}{768{,}75 \times QM} = 1.85$$

$$QM = 0.143 \ldots (7)$$

Once the QM value has been determined, the same methodology and equations are employed to calculate the $\%Al_{cons}$ for the optimal speech privacy distance, using a measured STI value of 0.2. Similarly, an STI value of 0.5 is utilized to estimate the distraction distance (r_D), with a resulting $\%Al_{cons}$ value of 57.7%.

Moreover, by applying Equation (5) using the known ideal $\%Al_{cons}$, the distance between the receiver and source (r) is computed and designated as the predicted privacy distance (r_P). Table 2 presents the predicted r_P and r_D distances for all receivers, ranging from position number 1 to number 9, in experiment Setup-1.

Table 2. The predicted r_P and r_D in experiment setup-1 using the modified technique

P_x	Distance (m)	T_{30} (s)	STI	$\%Al_{cons}$	QM	r_p	r_D (m)
1	2.59	0.331	0.835	1.85	0.143	14.5	6.42
2	3.75	0.375	0.708	3.68	0.194	14.8	6.59
3	6.35	0.369	0.818	2.03	0.977	33.9	15.0
4	7.51	0.397	0.778	2.52	1.27	35.9	15.9
5	10.1	0.494	0.793	2.32	3.88	50.4	22.3
6	11.3	0.392	0.745	3.01	2.34	49.5	21.9

P_x	Distance (m)	T_{30} (s)	STI	*%Al$_{cons}$*	QM	r_p	r_D (m)
7	13.9	0.659	0.714	3.56	8.46	55.9	24.8
8	15.0	0.759	0.685	4.17	11.3	55.8	24.8
9	17.6	0.991	0.668	4.57	24.1	62.5	27.7

P_x: Measurement positions. Room volume: 1109.36 m^3

The findings reveal that among the nine workstations, positions still exhibit good acoustic quality, characterized by clear speech and minimal distractions. However, it is important to note that while the (r_p) and (r_D) values can be calculated for all workstations using this technique, only workstations 1 and 2 actually exist within the room's physical dimensions.

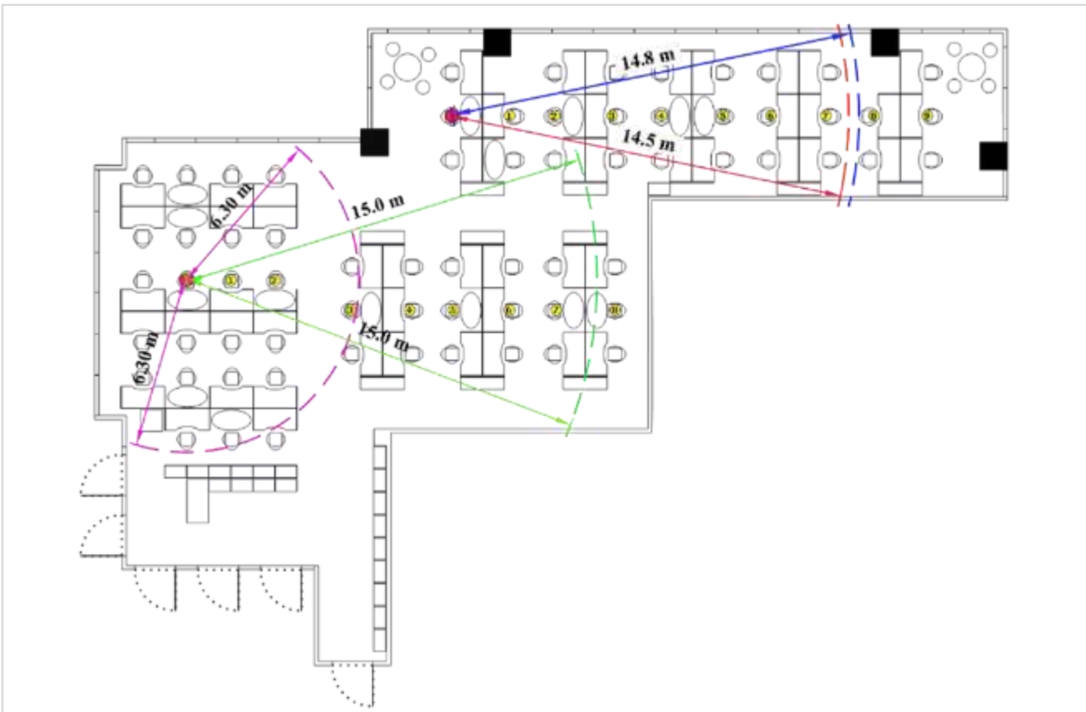

Figure 3. Illustration of the predicted speech privacy distance (r_P) using *%Al$_{cons}$*, i.e., blue line: receiver 1 and red line: receiver 2

Figure 3 represents the predicted distances, specially focusing on the workstation area, which refers to the interaction between the source and a receiver, considering various orientations of the speaker or source.

The comparison between the $L_{p,A,S,4m}$ values obtained from the ISO 3382:3 measurement procedure and the values derived from Equation (3) using the room data reveals considerable agreement. Both methods indicate $L_{p,A,S,4m}$ values $\geq$ 50 dBA, which suggests a poor acoustic condition. However, there is a notable disparity between the regression model for $D_{2,S}$ obtained from Equation (2), which yields a value $\geq$ 7 dBA indicating a good acoustic condition, and the results from the ISO 3382:3 method based on Equation (1), which indicate a value < 5 dB, indicating a poor condition.

By utilizing the *%Al$_{cons}$* values derived from Equation (3) and Equation (5), the predicted speech privacy distances can be used to categorize two conditions: 'Private' (P) and 'Not Private' (NP) for all setups. The same approach can be applied to determine distraction distances. The P and NP islands list for the examined case is reported elsewhere (Utami et al. 2013).

In an open-plan office with a favorable acoustic condition, 'Distracted' (D) or 'Not distracted' (ND) islands should be present. This condition is estimated by calculating the distraction distance using the same method as the privacy distance with *%Al$_{cons}$*. Table 3 demonstrates that in experiment Setup-1, there are more 'Distracted' (D) islands than 'Not Distracted' (ND) ones, indicating a poor acoustic condition. Approximately 79% of the 'islands' experience working distractions, while only 6% allow for private communication. This low level of speech privacy suggests a working environment with compromised worker communication. As mentioned earlier, background noise and distractions can lead to poor speech intelligibility, which is why STI is utilized, as conducted by Ebissou, Parizet, and Chevret (2015).

However, it is worth considering that background babble can also serve as natural masking for disruptive speech, as found by Zaglauer, Drotleff, and Liebl (2017). To enhance privacy and increase workers' concentration, sound systems that mask various sounds have been implemented (Haapakangas et al. 2014; Jahncke et al. 2011). Jahncke, Hongisto, and Virjonen (2013) recommend modifying room acoustics in open-plan offices to improve the quality of STI, particularly for cognitive work that demands concentration and a high short-term memory load.

Table 3. Distraction conditions in experiment Setup-1

Listener		Observer position or involuntary listener								
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1	2.59	-	D	D	ND	ND	ND	ND	ND	ND
2	3.75	D	-	D	ND	ND	ND	ND	ND	ND
3	6.35	D	D	-	D	D	D	D	ND	ND
4	7.51	D	D	D	-	D	D	D	D	ND
5	10.1	D	D	D	D	-	D	D	D	D
6	11.3	D	D	D	D	D	-	D	D	D
7	13.9	D	D	D	D	D	D	-	D	D
8	15.0	D	D	D	D	D	D	D	-	D
9	17.6	D	D	D	D	D	D	D	D	-

D: Distracted; ND: Not Distracted; Listener: microphone positions during experiment

Conclusion

The overall assessment of the acoustic conditions in an open-plan office using regression models for $D_{2,S}$, and $L_{p,A,S,4m}$ as described in Equations (2) and (3), reveals that modified techniques can be used to predict the acoustic quality of a modern layout of open-plan office. In this case, the $D_{2,S}$ values indicates a good acoustic quality ($\geq$ 7 dB). However, the $L_{p,A,S,4m}$ are still not meting the required good acoustic quality (< 50 dB).

Moreover, by utilizing the $\%Al_{cons}$ equations, this paper demonstrated how to predict distraction distances and categorized each listener position in two conditions, 'Distracted' (D) or 'Not distracted' (ND) workstation. The results showed that, in experiment Setup-1, there are more 'distracted' (D) islands than 'not distracted' (ND) ones, indicating a poor acoustic condition. Approximately 79% of the 'islands' experience working distractions, while only 6% allow for private communication.

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Sentagi Sesotya Utami contributed to the research concepts preparation, methodologies, investigations, data analysis, visualization, articles drafting and revisions.

Joko Sarwono contribute to the research concepts preparation and literature reviews, data analysis, of article drafts preparation and validation.

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