Speech Privacy and Intelligibility in Open-Plan Offices as an Impact of Sound-Field Diffuseness

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ABSTRACT

The research is based on ISO 3382-3:2012, a standard for speech privacy quality measurement in open-plan offices. Predicted speech privacy and distraction distances, the quality of speech intelligibility, and the diffuseness of the sound fields were observed.

Within the past few decades, a new paradigm has emerged where reverberation control is not the only solution for good room acoustics. In certain open-plan office, quality of speech privacy and intelligibility should be similar for each workstation by creating a diffuse sound field. In many spaces, abfusor for absorption and diffusion are solution in a form of acoustic panel, furniture and other elements, such as bookshelves in offices.

The measurement in this research utilized multi-microphones. The degree of diffuseness was done by evaluating the coherences of impulse responses measured. Values of T_{30}, C_{50}, and RASTI were also evaluated. Further analysis on the sound field diffuseness was done by evaluating the coherence of early and late reflections, and also occurrences of the comb-filtering effect. Subjective evaluation of selected workstations was also conducted. The methods utilized in this research demonstrate the ability for acousticians and architects to evaluate the effect of diffuseness on speech privacy and intelligibility quality of an open-plan office layout.

Keywords: Speech privacy, Open-plan offices, ISO 3382-3:2012, Workstation.

1. INTRODUCTION

In ISO 3382-3:2012 [1], an open-plan office is described as offices and similar spaces where a large number of people can work, have a conversation, or concentrate independently in well-defined workstations. The ISO 3382-3:2012 provides technical draft of measurements of acoustical performances in open-plan offices including list of factors influencing the room acoustic condition. Factors observed in this research are the effect of sound absorption, distance between workstations, and the partition's height to the acoustical conditions. The quality of speech intelligibility, speech privacy, distractions on concentration to work, and the diffuseness of the sound field are the acoustical conditions observed.

A workstation refers to a group of adjacent desks with several chairs. It can also be in a form of a single desk with a single employee such as cubical reading desk in libraries. Sound fields observed are the acoustics 'island' within a workstation and across the workstations. It depends on the receiver's position during measurement.

Properties of the room, which include furniture, partition and equipment, play an important role in the amount of sound absorption. The height and amount of partition can define the degree of workstation enclosure. In some offices, good speech intelligibility is required for communication between employees. This can be supported by having less amount of partition for distant workstations. In contrary, less partition creates lack of speech privacy. As a consequence, in order to achieve ideal speech privacy and less distraction, a well-designed workstation layout is needed to control the amount

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of absorption as well as the ability to create a diffuse sound field where all the workstations can be expected to have the same acoustical condition.

This paper demonstrates techniques to explore the occurrences of speech privacy, speech distraction and predict their distances, the quality of speech intelligibility, and the diffuseness of the sound fields referring to ISO 3382-3:2012. The level of speech intelligibility is indicated by Reverberation Time (T_{30}), Clarity Index for Speech (C_{50}), and RASTI. The level of speech privacy and speech distraction are indicated by the privacy distance (r_P) and distraction distance (r_D). Meanwhile, coherence of pair data is used to predict the degree of diffuseness. Result of a subjective evaluation for a particular case studied is also discussed briefly to demonstrate an integrated method to evaluate the room acoustics of open-plan offices.

2. ACOUSTICAL PROBLEMS IN THE CASE STUDIED

Three open-plan offices in Jakarta, Indonesia were used as the case studied in this research. Beginning at this section, results and analysis of data measurement in one of these offices will be discussed more in depth. The shape and dimension of this selected office as well as the experiment setup is described in Figure 1.

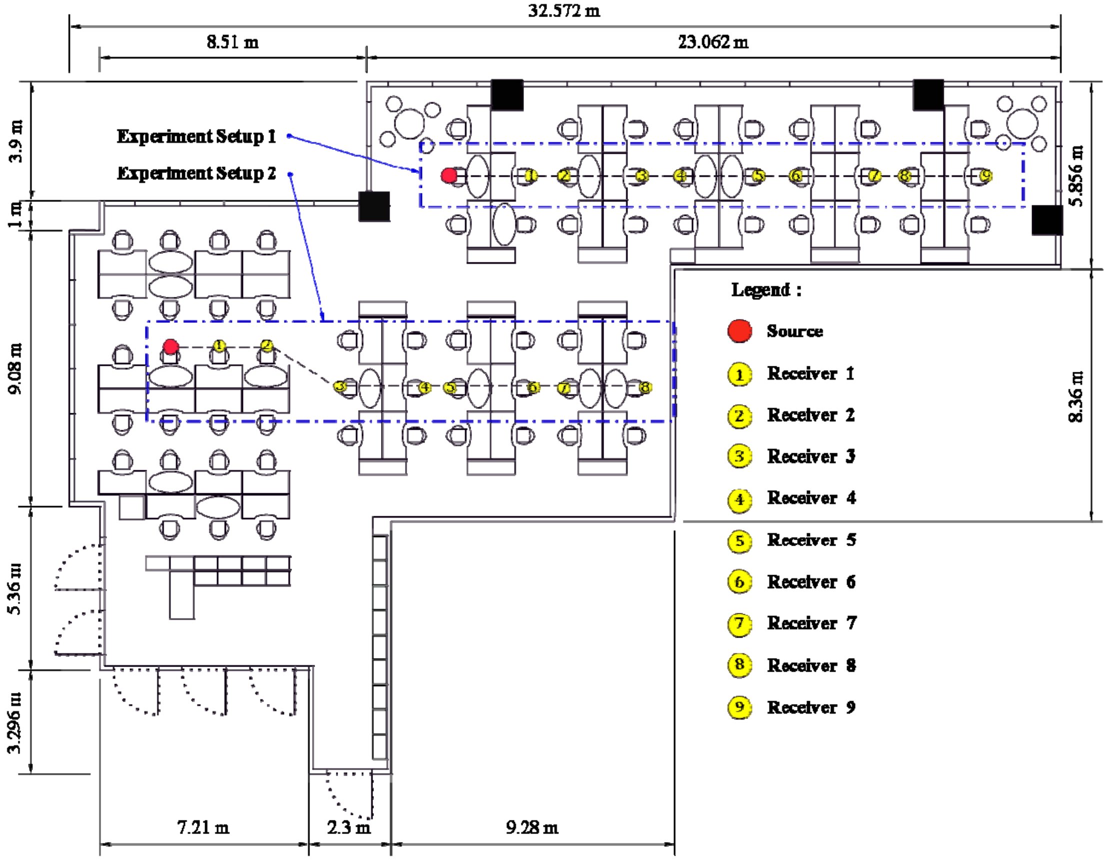

Figure 1 – Layout and experiment setting 1 and setting 2 of the first open-plan office.

In many working situation, it is desirable for employees involved in a conversation to avoid involuntary spread of speech of a private nature. For other employees, speech from an unwanted source can be intrusive and create distraction [2]. Aside to speech privacy and speech distraction, some open-plan layout are intentionally designed to serve the purpose for direct communication among workstations where small meetings across the space are often held [3]. Therefore, the office is expected to have good speech intelligibility throughout the entire space.

In Figure 2, the nature of the acoustical tasks and problems in the open-plan office are illustrated [4]. Scenario activities can be described as (1) A speaker requires high speech privacy with the listener in workstation 1 and avoids the spread of confidential conversation to listener in workstation 2, (2) A listener in workstation 2 can be distracted by the conversation between speaker and listener in workstation 1, and (3) A listener in workstation 2 often requires the ability to clearly understand the speech content from the speaker in workstation 1. These scenarios will be known as 'islands' (a source to receiver sound field or acoustics interactions).

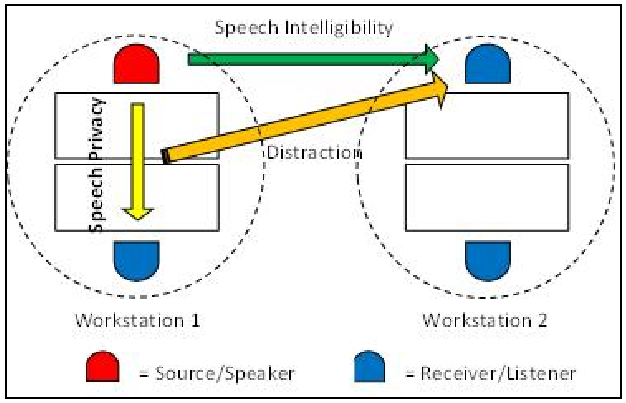

Figure 2 – Speech scenarios in the open-plan office [4].

3. RESEARCH METHOD

3.1 Measurement Procedure and Parameters

Data obtained from the measurement are *.wav* files of impulse responses from certain positions of sound source and receivers. According to ISO 3382-3:2012, positions of sound source and receivers should be at least 1.2 m above the floor and 0.5 m from the workstations. An omnidirectional sound source is used since a speaker orientation inside the room can varied to any direction. The average condition for all direction is the best approximation. It is placed at least 2.0 m from walls or other reflecting surfaces.

The source and receivers were positioned at a straight line (see Figure 1) in order to understand the impact of partition and increasing workstation distance to the speech privacy and speech distraction by using regression analysis from STI measured. Data are A-weighted SPL obtained from pink noise generated by the source and parameter acoustics T_{30}, C_{50}, STI, and RASTI from impulse responses at several workstations. Meanwhile, to evaluate the sound-field diffuseness, an experiment setup with two microphones on top of each other by 0.8 meter apart that simultaneously recorded the room impulse responses, is used as shown in Figure 3.

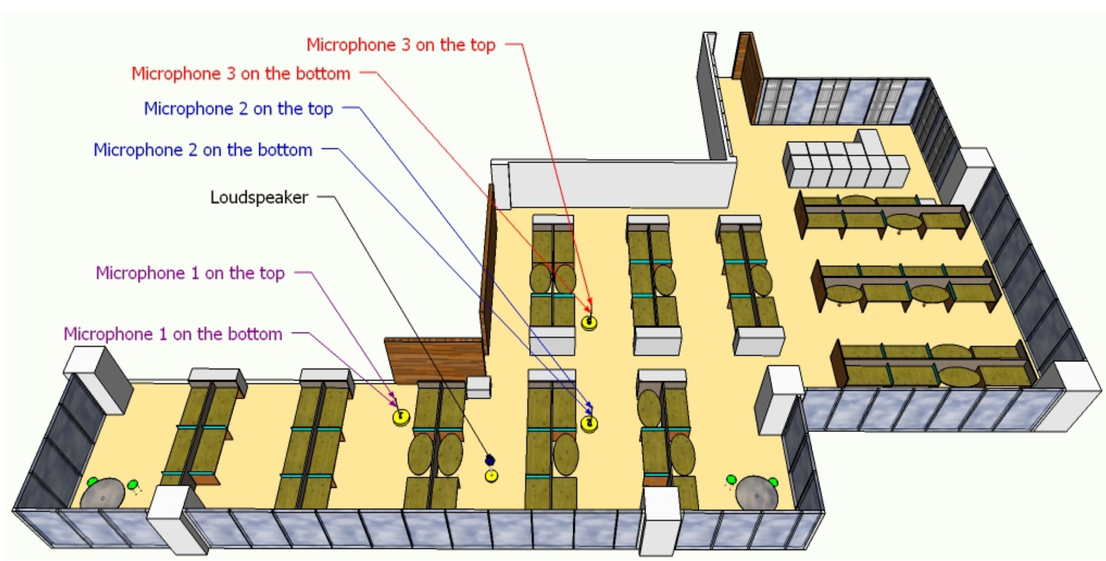

Figure 3 – Layout of experimental setting 3 for diffuse sound-field analysis.

Reliable measurements can only be achieved in unoccupied furnished room to create less background noise variation. However, normal daytime background noise, whether it is caused by ventilation, traffic noise or an artificial masking sound system are unstable sources, which requires several measurement to obtain the average acoustical conditions.

3.1.1 Speech Privacy Distance (r_P) and Distraction Distance (r_D) based on ISO 3382-3:2012

Based on the ISO 3382-3:2012, the acoustical condition of an open-plan office can be characterize as private and non-private. Privacy distance is the distance from sound source where STI falls below 0.2. The distraction to perform a work on a certain listener position can be avoided when STI is below 0.5, related to the distraction distance (r_D). Above the distraction distance, concentration starts to improve rapidly. In ISO 3382-3:2012, spatial decay rate of A-weighted SPL of speech ($D_{2,S}$) [1] indicates the effectiveness of materials and partitions within the room for sound absorption. It is the rate of A-weighted SPL change from a source to receivers as the distance increased obtained from the linear regression analysis of the A-weighted SPL to receiver’s distance from the source. Detail values of the parameters above to characterize the acoustical conditions are listed in Table 1.

Table 1 –Criteria of the Room Acoustics of Open-Plan Offices based on ISO 3382-3:2012 [1]

Acoustical Condition	Room Acoustics Parameters		
	Spatial Decay Rate of A-weighted SPL of Speech	A-weighted SPL of Speech at 4 Meters	Distraction Distance
Good	≥ 7 dB	≤ 48 dB	≤ 5 m
Poor	< 5 dB	> 50 dB	> 10 m

3.1.2 Method using Articulation Loss of Consonant ($\%Al_{cons}$)

The values of $\%Al_{cons}$ is required to predict speech privacy distance and distraction distance. The distance is measured from the position of the speaker/source observed. From a listener’s (receiver’s) point of view, the speech from the source can be private if the speech privacy distance obtained from the $\%Al_{cons}$ equation (Eq. (2)), is larger than the source to receiver’s distance. If a second listener is within the predicted speech privacy distance, then the conversation between speaker and the first receiver is no longer private from the second listener’s point of view.

The $\%Al_{cons}$ is defined as the percentage of consonant loss during a speech. First algorithm to calculate is shown in Eq. (1). Another equation to calculate $\%Al_{cons}$ is shown in Eq. (2) below [5].

$$\%Al_{cons} = (170.5405)*e^{((-5.419*STI))} \quad (1)$$

$$\%Al_{cons} = (200*r^2*T_{60}^2*(1+n))/VQM \quad (2)$$

where : r = Distance between speaker and listener
T_{60} = Reverberation time
n = Amount of source (here n=1)
V = Room volume
Q = Directivity of sound source
M = The amount of room absorption

The STI values obtained from the measurement are inserted into Eq. (1) to obtain $\%Al_{cons}$ for each receiver’s position. This is then inserted into Eq. (2) to obtain the QM value. After QM is obtain, the next step is to calculate $\%Al_{cons}$ with Eq. (1) by setting the STI value 0.2, which is the value where speech privacy distance might occur and 0.5 to avoid speech distraction, as described in ISO 3382-3:2012.

Using this last $\%Al_{cons}$ value and plugging it to Eq. (2) with the QM obtained above, the privacy distance and distraction distance for a conversation island (a speaker and a listener) can be predicted for each position/receiver observed.

3.2 Speech Intelligibility

Having less partition in an open-plan office may provide easiness for speech activities among workers. The ability to understand the speech content defines the conversation quality, which can be degraded by the excessive reverberation and a high noise level. Reverberation time using T_{30} is the first parameter used to predict speech intelligibility, especially to compare between workstation positioned at the corner of the room, near transparent facade and those positioned at the center of the large opened space. At octave band 1000 Hz, a value of 0.7 indicates good speech intelligibility for an office. The C_{50} is used as the next parameter using the same impulse response data. Comply to the ISO 3382-3:2012, RASTI as a more practical version of STI is used as the third parameter to evaluate the acoustical performances for speech intelligibility [5].

3.3 Sound-Field Diffuseness

This research, sound-field diffuseness was indicated by value of coherence of two signals impulse response. Determination of value of coherence was conducted using Matlab calculations. Sound-field diffuseness is well indicated by value of coherence is high (near to 1) between two signals impulse response. Meanwhile, sound-field diffuseness is poor indicated by value of coherence is low (near to 0) between two signals impulse response. Sound-field diffuseness was done by evaluating the coherence of early and late reflections. Early reflections coherence comes from early reflections signal, i.e. signal at $t < 50$ ms, while late reflections coherence comes from late reflections signal, i.e. signal at $t > 50$ ms.

4. RESULTS AND DISCUSSION

4.1 The Level of Speech Privacy

The predicted speech privacy distance for all experimental setups, calculated using the %Alcons in Eq. (1) and Eq. (2) can be interpreted as private or non-private conditions. It describes the condition of sound fields given the receiver's positions in office A for a particular measurement setup as shown in Figure 1. In Table 2, the most right column consist of main listener's position or where the microphones were positioned during the experiment for experimental setting 1. The row heading is the secondary listener or where speech privacy condition is observed. It is shown that a private conversation may occur between the source and main listener 1 and main listener 2, if it is being heard from receiver position or secondary listener 8 and 9. This is influenced mostly by the distance of receivers 8 and 9, which are far from the sound source. As the sound travels, the energy is absorbed by partitions of the workstations.

Table 2 – Speech Privacy Conditions of Open-Plan Office A with Experimental Setting 1

Main listener	Observer point or Secondary Listener								
	1	2	3	4	5	6	7	8	9
1	-	Non private	Non private	Non private	Non private	Non private	Non private	Private	Private
2	Non private	-	Non private	Non private	Non private	Non private	Non private	Private	Private
3	Non private	Non private	-	Non private	Non private	Non private	Non private	Non private	Non private
4	Non private	Non private	Non private	-	Non private	Non private	Non private	Non private	Non private
5	Non private	Non private	Non private	Non private	-	Non private	Non private	Non private	Non private
6	Non private	Non private	Non private	Non private	Non private	-	Non private	Non private	Non private
7	Non private	Non private	Non private	Non private	Non private	Non private	-	Non private	Non private
8	Non private	Non private	Non private	Non private	Non private	Non private	Non private	-	Non private
9	Non private	Non private	Non private	Non private	Non private	Non private	Non private	Non private	-

As for experimental setting 2, there are no private distance that might provide private conversation within the entire space.

Figure 4 and Figure 5 are examples on how to present the predicted speech privacy and distraction distance using the %Al$_{cons}$ method discussed in subsection 3.1.2. Since the source is an omnidirectional to model all possibilities of the speaker orientation, then the privacy and distraction distance is presented as the radius of circle, representing a horizontal area of the 'sound field' (the interaction between source and a receiver).

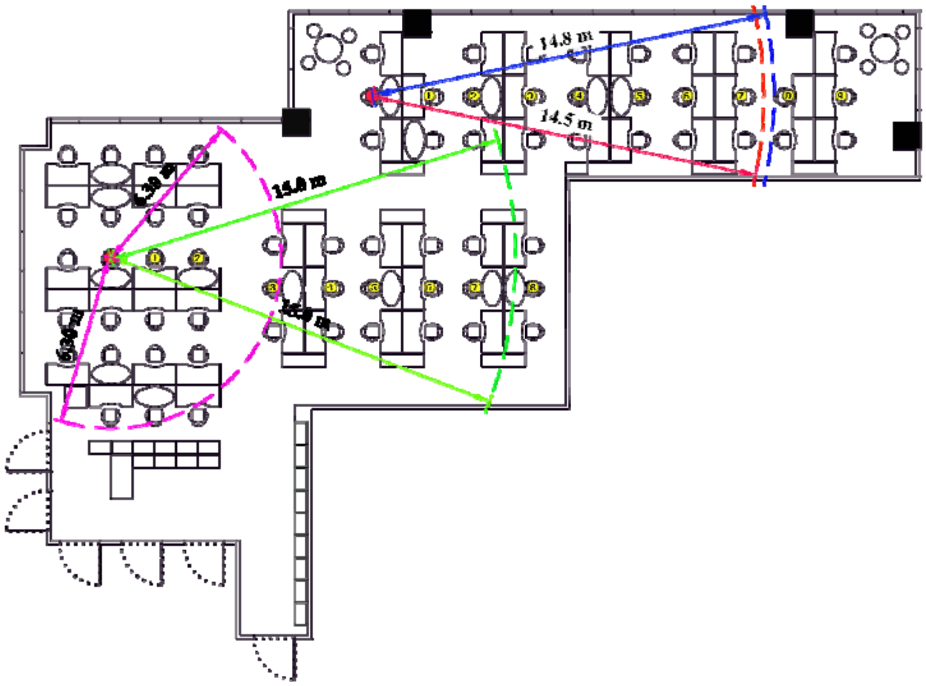

Figure 4 – Predicted speech privacy distance (r_P), calculated using the %Alcons in Eq. (1) and Eq. (2).

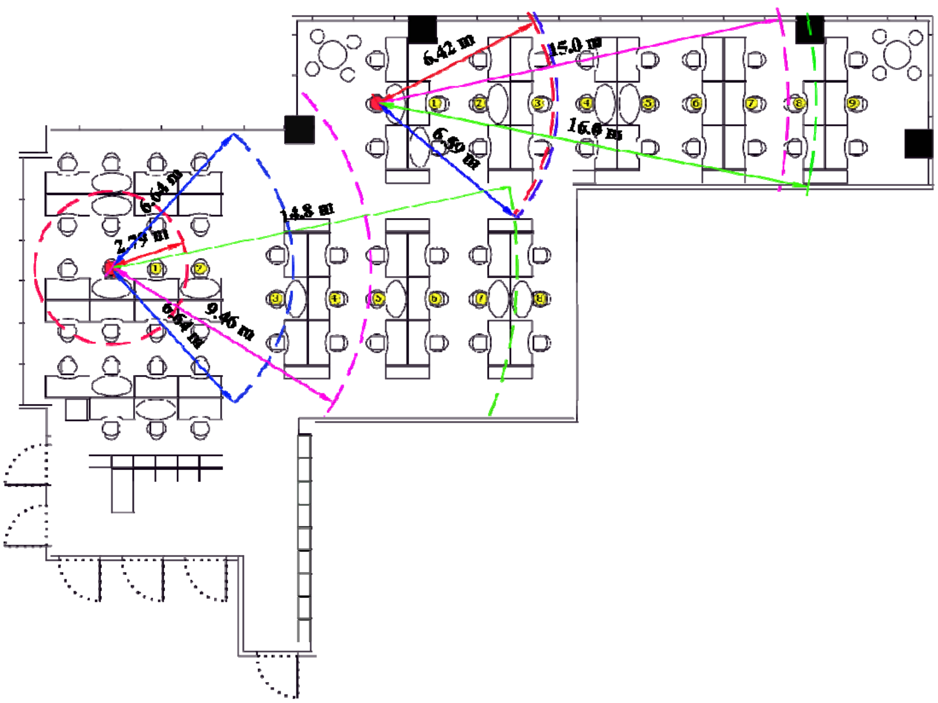

Figure 5 – Predicted speech distraction distance (r_D), calculated using the %Alcons in Eq. (1) and Eq.

(2).

Table 3 – Values of predicted speech privacy and speech distraction distance, calculated using the %Alcons in Eq. (1) and Eq. (2).

Receivers	Distance from Sound Source (m)		Privacy Distance (m)		Distraction Distance (m)	
	Setting 1	Setting 2	Setting 1	Setting 2	Setting 1	Setting 2
Receiver 1	2.59	1.00	14.5	6.30	6.42	2.79
Receiver 2	3.75	2.53	14.8	15.0	6.59	6.64
Receiver 3	6.35	4.95	33.9	21.3	15.0	9.46
Receiver 4	7.51	7.40	35.9	33.5	16.0	14.8
Receiver 5	10.1	8.48	50.4	40.2	22.3	17.8
Receiver 6	11.3	11.1	49.5	50.3	21.9	22.3
Receiver 7	13.9	12.2	55.9	51.3	24.8	22.8
Receiver 8	15.0	14.6	55.8	64.4	24.8	28.6
Receiver 9	17.6		62.5		27.7	

The low speech privacy level in both scenarios (experiment setup within the open-plan office) is influenced by the good speech intelligibility throughout the space for both scenarios. Good speech intelligibility provides the condition where speech information reaches the listener's without significant distortion. This condition is explained further in the following section.

4.2 The Level of Speech Intelligibility

The level of speech intelligibility was indicated by parameters reverberation time (T_{30}), clarity index for speech (C_{50}), and rapid speech transmission index (RASTI). Values of reverberation time (T_{30}) are within the range of 0.6 s to 1 s, by means several are in the ideal range for T_{30} in office, which is 0.6 s – 0.8 s.

All the C_{50} measured are above the minimum value that indicates good speech intelligibility, which is -2 dB [5]. Values of RASTI are within the range of 0.65 – 0.85 or the range that indicates very good speech intelligibility [5]. These values of parameters supported evidence that the office observed in this research using the two experiment settings scenarios have good speech intelligibility.

4.3 Diffuseness of Sound Field

Diffuseness of a sound field can be indicated by the coherence of two measurement data from two microphones with values from 0 to 1, with coherence near 1 is a condition of diffused. Similarity between the data at two receivers can be found for the entire data length or only partially, for example on the early part of the signals. Microphones at the upper position (1.2 m above the floor) of the sound field observed (see Figure 3) are noted with the letter A. Meanwhile, microphones at the lower position (0.6 m above the floor) are noted with the letter B.

The coherence of full data response (Coh_{full}) and the coherence of late reflections (Coh_{late}) in Table 4 of experimental setting 3 are all above 0.5. Therefore, this indicates a possibility of having diffused sound fields. Furthermore, in a diffused sound field, the sound is expected to be heard equally throughout the sound field observed. If this condition exists in an open-plan office, then it provides easiness for the office management to rearrange the workstation layout for having a good room acoustics.

In Table 4, all the coherence values indicate a diffused condition, therefore, it is expected that the parameter's values at paired-positions observed are also similar, in such that the speech intelligibility quality are also the same. Coherences of data from far apart receivers (distant workstations) can also show the similarity of speech privacy condition. However, this was not observed in this research.

Table 4 – Values of Full Coherence (Coh_{full}) and Late Reflection Coherence (Coh_{late}) of scenario 5

Scenario 5		
Receivers	**Coh_{full}**	**Coh_{late}**
1AB	0.706	0.658
2AB	0.764	0.644
3AB	0.669	0.532
12A	0.748	0.583
13A	0.585	0.556
23A	0.698	0.542
12B	0.783	0.636
13B	0.686	0.564
23B	0.658	0.661

In order to understand the results as shown in Table 5a – 5c, one has to follow setting in Figure 3. Similarity of T30 and RASTI values are almost found in all the sound-field measured, given in Table 5a – 5c. The colored area in the middle is the sound-field observed where the rectangular sound-field has four microphones on its corners. There are values of T_{30}, C_{50}, and RASTI for each microphones illustrated in Table 5a – 5c as well.

With coherences nearly and above 0.6, all the speech intelligibility parameters are almost the same expect for C_{50} although all the C_{50} values still indicate a good clarity.

Table 5a – Coherences and Speech Intelligibility Quality for Sound Field 1 in Figure 3

T_{30}	0.345		Coh_{full}		0.368	T_{30}
C_{50}	8.83				10.9	C_{50}
RASTI	0.820	**1A**	0.748	**2A**	0.790	RASTI
Coh_{full}		0.706	Sound-field observed	0.764	Coh_{full}	
T_{30}	0.347	**1B**	0.783	**2B**	0.361	T_{30}
C_{50}	9.19		Coh_{full}		10.8	C_{50}
RASTI	0.760				0.784	RASTI

Table 5b – Coherences and Speech Intelligibility Quality for Sound Field 2 in Figure 3

T_{30}	0.345		Coh_{full}		0.411	T_{30}
C_{50}	8.83				13.0	C_{50}
RASTI	0.820	**1A**	0.585	**3A**	0.774	RASTI
Coh_{full}		0.706	Sound-field observed	0.669	Coh_{full}	
T_{30}	0.347	**1B**	0.686	**3B**	0.376	T_{30}
C_{50}	9.19		Coh_{full}		7.94	C_{50}
RASTI	0.760				0.780	RASTI

Table 5c – Coherences and Speech Intelligibility Quality for Sound Field 3 in Figure 3

T_{30}	0.368		Coh_{full}		0.411	T_{30}
C_{50}	10.9				13.0	C_{50}
RASTI	0.790	**2A**	0.698	**3A**	0.774	RASTI
Coh_{full}		0.764	Sound-field observed	0.669	Coh_{full}	
T_{30}	0.361	**2B**	0.658	**3B**	0.376	T_{30}
C_{50}	10.8		Coh_{full}		7.94	C_{50}
RASTI	0.784				0.780	RASTI

5. CONCLUSIONS

The results in this research have provided the evidence that sound absorption, distance between workstations, and partitions do influence the level of speech intelligibility, speech privacy, and distraction to concentration at work. This can be seen in the different value obtained from each experiment scenario. The C_{50} from workstation close to the source to the ones further away declines by 76.9% and 24.9%, for scenario 1 and 2 respectively. RASTI declines by 18.7% and 0.7%. The speech privacy declines by 6% and 0%. Meanwhile, the difference in percentage of distraction to concentration at work reaches up to 79% and 100%. However, sound absorption, distance between workstations, and partitions were not proven to influence diffuseness of sound field observed. This was shown in coherence values which were relatively similar with a small standard deviation between coherence values, which is 0.045.

In order to use the coherences for predicting uniformity speech privacy quality throughout the office (far apart workstations), a multi-microphone array that can record data simultaneously for more than 4 positions is required. The techniques, parameters and the method of analysis utilized in this research can be used as a design approach for rearranging the workstation layout in an open-plan office, in order to have a good room acoustics.

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