Evaluation of the spatial uniformity of electronic sound masking systems in an open-plan office

Farideh Zarei

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Dr. M. Zaheeruddin ______________ Chair
Chair's name

Dr. B. Yousefzadeh ______________ Examiner
Examiner' name

Dr. H. Ge ______________ Examiner
Examiner's name

Dr. J. Lee ______________ Supervisor
Supervisor's name

Approved by Dr. Ashutosh Bagchi ______________
Chair of Department or Graduate Program Director

November 2019 Mourad Debbabi ______________
Dean of Faculty

ABSTRACT

Evaluation of the spatial uniformity of electronic sound masking systems in an open-plan office

Farideh Zarei

Providing an optimal acoustical environment is an inherent challenge in open-plan offices. In order to avoid overhearing private conversations by the office workers and reduce the distraction by the background noises, many open-plan offices adopt an electronic sound masking system that generates an artificial sound to make background noises less sensible. The sound masking system should uniformly generate the targeted masking sound over the entire office area to provide the desired influence on the acoustical environments. To evaluate the uniformity of the masking sound field in open-plan offices, this study followed the ASTM E 1573-18 method which is a standard for assessing the spatial uniformity of the sound masking systems in open plan offices. More specifically, sound maps were created with a measurement grid of 0.6 m x 0.6m, to determine the spatial variations of the masking sound levels across the office space. This study also examined the parameters that can influence the spatial uniformity in the open-plan offices by using a computer-aided simulation. Moreover, to understand the importance of a uniform sound field across the office area, the intelligibility of the speech was assessed by calculating the Articulation Index (AI). The measurement results show that the variation of the sound pressure level (SPL) across the space is within ±1.5 dBA when considering the overall A-weighted SPL and ±4.5 dB when considering the unweighted octave band SPL for the frequencies from 250 Hz to 4 kHz. From the results of the simulation it can be found that the number of sound masking loudspeakers, partition height, and the scattering and absorption coefficient of the ceiling can affect the uniformity of the masking sound. For the defined parameters, the lowest variation was achieved when the number of the sound masking loudspeakers was increased to 7, followed by when the partitions were removed and when the whole ceiling was covered by the diffuser. Among these parameters, increasing the number of sound masking loudspeakers has the most effects on improving the uniformity of the sound field across the office space. Moreover, in all the defined conditions the SPL variation for more than 90% of the space cannot be less than ±1 dBA when

considering the overall A-weighted SPL, and ±1.5 dB when considering the unweighted octave band SPL. After evaluating the variation of the speech intelligibility across the office, using the AI, the results show that when there is a higher variation in the sound field, the AI range change more. In order to have more than 60% of the office area within ±0.03 AI range, the variation of the sound field across the space should be less than ±1.5 dBA, and to have more than 80% of the office area within ±0.03 deviation for the AI value, beyond ±1 dBA deviation in the SMS should be avoided. However, as the open plan offices are much complicated than this model, achieving a tight range for the SPL uniformity of the sound masking system could not be realistic in most of the open plan offices. In this regard, more research should be done to find the necessity of defining tight tolerances and the effect of SPL variation of the masking sound on the speech inteligibility in open-plan offices.

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1. Chapter one: Introduction

1.1. Background

Nowadays, office workers spend most of their time in closed environments. Therefore, workspaces have a significant impact on employees' wellbeing and performance. There have been many previous studies to identify the crucial indoor environmental factors for the workspace. Based on the previous works, there are eight main factors, that affect the employee's performance, such as "thermal comfort, indoor air quality, office layout, lighting, acoustical condition, view, location and amenities, and biophilic design of the office environment" [1]. In terms of the occupants' productivity, among all these factors the indoor air quality, acoustical condition, and layout design of the office are more important than others [1].

There have been many attempts to improve a layout for offices. In the 1950s, Eberhard and Wolfgang Schnelle suggested a new layout for workspaces, which is called an open-plan office [2]. The open-plan office does not follow specific forms and, each office can modify their workspaces according to its need. In this regard, employees collaborate more easily [3]. Hence, open-plan offices have gained more popularity over the world.

Although the primary purpose of open-plan offices is to improve the collaboration between workers, they have some negative impact on employees' performance and their satisfaction. The two main reasons for dissatisfaction are a distraction by the background noise and lack of privacy [4], [5], [6], [7]. In open-plan offices, background noise is generated from different machines, workers talking, or their activities such as typing, turning book pages, or clattering [8]. Research has shown that in terms of annoyance, there is not much difference between background noises [9]. On the other hand, in terms of performance, the main noise source, which causes disruption in open-plan offices, is workers talking (e.g. [10], [11], [5]). When workers talking is a noise source, the disruptive impact on the other workers does not only depend on its level, but also on the speech intelligibility [12], [13]. Speech intelligibility relates to the words of the speech, which can be clearly perceived by others [14]. Therefore, when a speech is intelligible in a workspace, it can reduce employee's performance and impair their privacy [15].

There have been many attempts to find a proper way to reduce speech intelligibility. Generally, the following methods can be helpful to achieve this purpose:

1. Adding efficient absorbers such as carpets, acoustic wall panels, ceiling tiles, etc.

2. Blocking sound with solid barriers, partitions, walls, etc.

3. Covering the noise with a proper masking sound [16], [17], which reduces the sound to noise ratio and intelligibility.

Figure. 1 displays the effect of these three solutions. Figure. 1 (A) shows a low level of speech privacy. As can be seen, the background sound level of the room is low, and there are not enough absorbing materials or partitions. Consequently, the speech can be intelligible to other people. On the other hand, in Figure. 1 (B), by adding a sound masking system, the background sound level of the room increases while blocking the noise with partitions, and using the absorbing material for the ceiling, the speech sound level decreases. As a result, speech intelligibility is reduced.

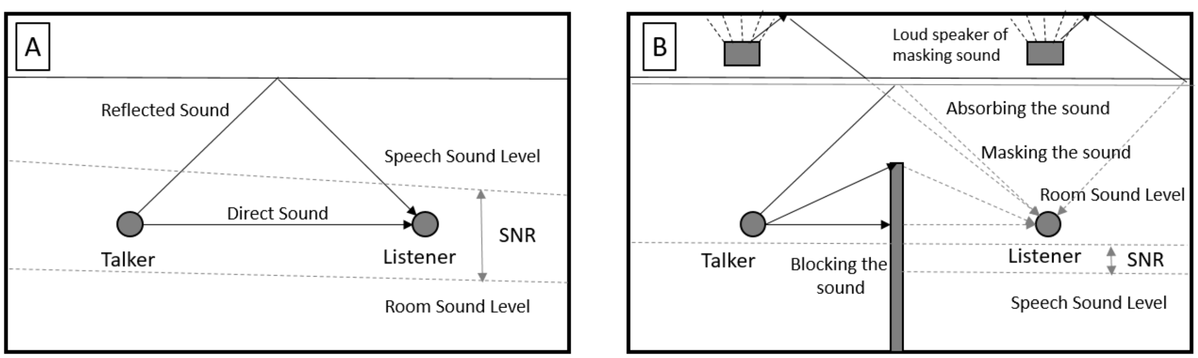


Figure 1. (A) Low level of speech privacy, (B) A proper level of speech privacy

All these methods can be used individually or together to reach an acceptable acoustic environment. However, absorbers or blocking materials are more expensive than sound masking systems are. Moreover, sound masking systems are more flexible than other methods of noise reduction. They can be placed anywhere in the office space, and the sound volume can be adjustable with the background noise level. Generally speaking, an efficient masking sound can significantly reduce the intelligibility of conversations, and as a result, it can boost productivity, increase comfort, protect speech privacy, and reduce distraction [18], [19].

1.2. Problem statement

Providing spatial uniformity of the sound field produced by the masking system in open-plan offices can be a challenge [20]. In order to create a uniform sound field, the loudspeakers of the sound masking system should be calibrated in a way that the variation across the office is as low as possible [20]. In large open-plan offices, due to architectural variations, desk partitions, and uneven distribution of sound absorbers, the chance of achieving tightly specified spatial uniformity tolerances in either overall A-weighted or one-third octave bands frequency is expected to be low. However, only a few acoustical studies have evaluated the sound field spatial uniformity in open-plan offices [21]. The ASTM E 1573-18 [20] presents a method for assessing the uniformity of the masking sound in open-plan offices but offers no guidance on acceptable tolerances for spatial uniformity. Within the sound masking industry, there has been a trend using low tolerances (as low as ±0.5 dB) in the product specifications. However, this has been driven more by marketing purposes rather than scientific evidence.

1.3. Thesis objectives

This study aims to evaluate the uniformity of the sound masking system in the open-plan office of Soft-dB's company which is located in Montréal, Québec, Canada. For this purpose, the experimental study was conducted based on the method suggested by L'Espérance et al. [21]. More specifically, sound maps were created with a measurement grid of 0.6 m x 0.6m, to determine the spatial variations of the masking sound levels across the office space. This study also examined the parameters that can influence the spatial uniformity in the open-plan office by using a computer-aided simulation. Moreover, the tolerance of variations in the masking sound level for the simulated parameters was investigated to identify the minimum achievable range.

1.4. Definition of terms

In this section, the definitions of the terms frequently used in this thesis are introduced for readers to understand this thesis more clearly. The terms are ordered alphabetically.

1. Absorption coefficient:

It is the ratio of the incident sound energy which can be absorbed by that material. The value is expressed between 0 to 1, which is dependent on the frequency and angle of the incident sound [22].

2. Articulation Index (AI):

Articulation Index (AI) is a measure to evaluate the speech intelligibility in a given environment. It is a weighted value that presents signal to noise ratio with a number between 0.00 (none intelligible) and 1.00 (completely intelligible). In order to calculate AI, ANSI S3.5-1969 [23], provides a method which gives a weighted value to the SPL difference between the background noise and maximum level of the speech sound in each 1/3rd octave band. Then all these values sum together and express as a number which is between 0 and 1. This number indicates the level of speech intelligibility.

3. Directivity:

It is defined as the variation in the sound pressure level of a source in a specific direction [24].

4. Equivalent A-weighted sound pressure level (L_{Aeq}):

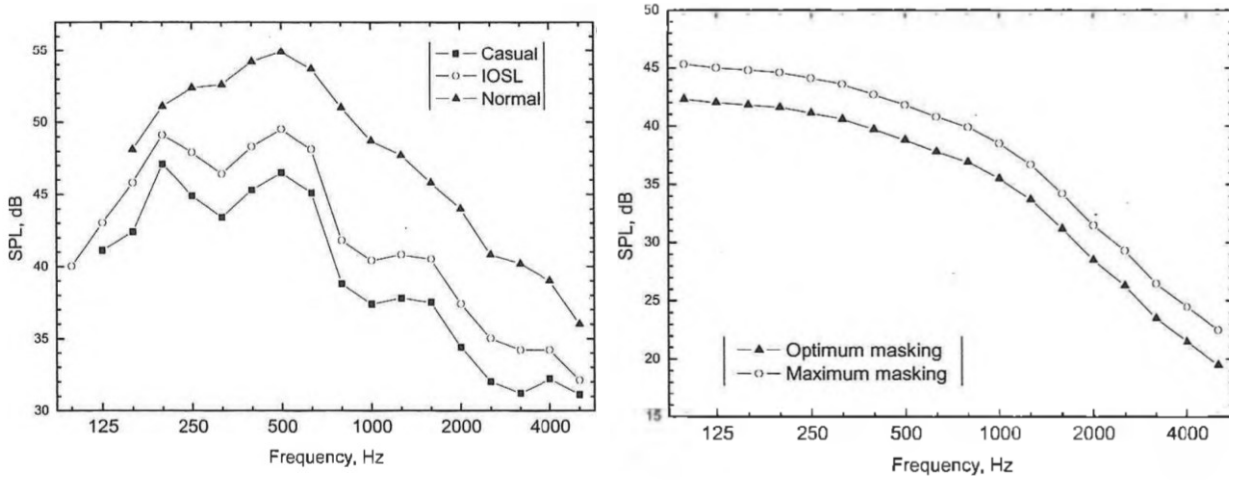
It is a constant sound pressure level that would have the same overall sound energy as the actual sound, during a specified period of time [25].

5. L_T:

It is the value of the sound pressure level when T percent of the time the sound pressure level is more than that. For instance, L_{95} means that 95% of the time over the period the sound pressure level exceeds L_{95} [24].

6. NRC (National Research Council) spectrum

The sound masking system can be effective when its spectrum is close to the background speech. Therefore, in order to control the background noise, the National Research Council (NRC) suggested an efficient spectrum in the audible frequencies for sound masking systems. This curve is called the NRC spectrum [26]. As can be seen in Figure. 2 (b), the NRC curve is between 125 Hz to 4 kHz octave band frequencies. The sound pressure level of this curve is a non-linear curve, which is defined in a way to control the acoustical condition. This spectrum is a reference for the output of the sound masking system.



(a) speech spectrum in open-plan offices, (Casual: average SPL, IOSL: intermediate SPL, Normal: normal SPL which defined in ANSI S3.5-1997 [23])

(b) Optimal sound masking spectrum (NRC-45 dBA) and maximum sound masking spectrum (NRC-48 dBA)

Figure 2. NRC sound masking curve [26]

7. Pink noise:

It is an artificial sound that contains equal energy in each frequency bandwidth [22].

8. Reverberation time (T_{60}):

The amount of time needed for the sound energy to reduce by 60 dB just after the sound source is turned off [22].

9. Scattering Coefficient:

Scattered sound is the sound that is not specularly reflected and the scattering coefficient is the part of the scattered sound energy which is uniformly diffused [24].

10. Standing waves:

Standing waves happen when a sound source is located between two parallel surfaces. It occurs when the incident sound wave interferes with the reflected sound wave, which has the same frequency, speed, and amplitude, but it has an opposite direction [27].

11. Schroeder frequency (f_s):

In closed spaces, standing waves can have a noticeable effect on the acoustical characteristics of the environment. The distribution of the standing waves is more sparsely at the low frequencies, while in the higher frequencies they distribute more densely and the space between them reduces until they overlap. The frequency between these two regions is called Schroeder frequency. The formula to calculate the Schroeder frequency is defined in the below equation [28]:

$$f_s = 2000\sqrt{\frac{T_{60}}{V}}$$

f_s (Hz): Schroeder frequency

T_{60} (s): Reverberation time

V (m^3): Volume of the room

12. Sound masking system (SMS):

It is an artificial sound with a specific level and spectrum which provides masking of the background noise to reduce distraction and increase speech privacy [22].

13. Sound pressure level (SPL):

Sound pressure is the amount of variation of the pressure in the sound wave and sound pressure level is defined with the below equation [22]:

$$SPL = 10.\log_{10}(\frac{P^2}{P_0^2})$$

SPL (dB): Sound pressure level in decibel

P (Pa): Sound pressure in Pascal

P_0: reference sound pressure level in Pascal

1.5. Thesis organization

This thesis includes five chapters that are organized to address the research objectives. Chapter two reviews all the previous studies regarding the sound masking system and all the factors that have effects on its efficiency such as masking levels, spectra, sound sources and uniformity of the masking sound through space. Chapter three describes the detailed methodology used in measurement and simulation. The results of this study and the discussion about the factors that cause these results are presented in chapter four. In chapter five, a brief summary of the study, limitations of the research and recommendations for future studies are discussed.

1.6 Abbreviations

AI: Articulation Index

ANSI: American National Standards Institute

ASTM: American Society for Testing and Materials

HVAC: heating, ventilation and air conditioning

$L_{tot,a}$: Overall A-weighted sound pressure level

L_z : unweighted octave band sound pressure level

NRC: National Research Council

NRC: Noise Reduction Coefficient

NSERC: Natural Sciences and Engineering Research Council

PAI: Partial Articulation Index

PTB: Physikalisch-Technische Bundesanstalt

SMS: Sound masking system

SPL: sound pressure level

STR: Structural speaker

2. Chapter two: Literature review

This section aims to highlight the findings from the previous studies for the sound masking systems and the parameters of the sound masking systems for optimal acoustic environments in open-plan offices.

2.1. Sound masking system

Sound masking happens when perceiving one sound is affected by the other sound [29], [30]. The masking occurs when the neural activity for perceiving the first sound is reduced by the neural activity by the other sound. The masking is more efficient when the frequency of the masking sound is similar to the frequency of the targeted sound [31].

Generally, there are two ways to mask a sound. One way is to use a sound with greater power as a masker. This way of masking is referred as energetic sound masking. The other sound masking mechanism is referred as informational sound masking, using the later sound to cover the meaning of the first sound. For the information sound masking, listeners perceive both sounds, but it is hard for them to recognize the meaning of the sounds. Wang et al. [32] conducted an experimental study to find out which type of masker is more efficient for employees' concentration. They concluded that the stationary energetic masking sound performed better than the informational sound masking.

2.2. Sound source level for sound masking system

Masking sound should be loud enough to be able to cover the background noise. However, if the sound level of the masking sound is too high, it can also cause annoyance and create adverse effects [33]. So far, there have been some studies to find the proper level for sound masking systems (e.g. [34], [35] and [36]). Based on these studies, the sound pressure level of the masking system is better to be less than 48 dBA. The reason is that people tended to raise their voices during their conversation when the masking sound is over 48 dBA. As a result, speech privacy is reduced. Moreover, when the sound masking is more than 48 dBA, it is annoying and not desirable for the occupants.

Furthermore, the minimum level of the sound masking system should be defined in a way that can be efficient enough to mask the ambient noise while creating a smooth acoustical condition in the space. L'Espérance et al. [37] suggested using 42 dBA as the minimum level for sound masking systems. Based on their experimental studies, this level can provide a basic level of confidentiality.

National Research Council (NRC) also did an experimental study to find the proper range of the SPL for the sound masking system in open-plan offices. They recommended a proper range for the SPL of masking systems is between 45 dBA and 48 dBA. Due to their study, the most preferred level for the ambient noise in open-plan offices is 45 dBA and when the SPL exceeded 48 dBA it was reported as annoying [38].

2.3. Sound source spectra for sound masking system

Choosing an appropriate spectrum for masking sound should be in a way that provides a balance between employees' efficiency and satisfaction. Studies have shown that the most efficient masking sound is the one that has the same frequency with the targeted sound (e.g. [35] and [39]). So far, researchers suggested different kinds of spectrum for masking the background noise. For instance, Veitch et al. [18] studied the proper spectrum for the pink-noise masking sound. They found that an appropriate spectrum that considers both comfort and privacy is the one in which the sound pressure level decreased by 5 dB per octave bands between 125 Hz to 8000 Hz. Hongisto et al. [40] also studied the preferred spectrum of sound masking systems. They found that the participants preferred a pseudo-random sound with a slope of -7 dB per octave doubling rather than a slope with -5 dB per octave doubling.

2.4. Sound source types for sound masking systems

Conventional masking sounds that are used in open-plan offices are continuous pseudorandom [41], [42]. These noises are commonly used as a masker in open-plan offices because they have similar spectra with ventilation noise. However, these days, for the source of sound masking system the pseudorandom noises are not acceptable anymore. Because of the hissing or rumbling quality, these sounds are uncomfortable for the occupants. There is some research to support this idea. For instance, Benway et al. [43] found that although masking noises by pink sound is efficient in decreasing speech intelligibility, enhancing privacy and improving acoustical comfort, employees complain that they perceive pink noise like an airplane environment, and they feel fatigued over time.

Moreover, there is some research about masking speech by babble sound to reduce the intelligibility of the speech. The results showed that by increasing the number of talkers of the masker sound, the performance of employees will be increased [44]. For instance, Zaglauera et al. [15] did an experimental study to test the performance of workers in the short-term memory test. They concluded that the employees' performance will improve when the number of talkers in babble masker increases. However, the employees' performance in silent conditions was much better. Generally, it can be concluded that although the greater number of talkers can mask the background speech, it will increase the employees' annoyance.

In recent years, there are some studies about using natural sounds such as the sounds of water, birds, wind, and forest as a masker in work environments. These sounds are usually perceived as a pleasant sound and used to reduce stress [45]. There are some investigations on using natural sound as a masker in open-plan offices. For example, Hongisto et al. [46] indicated that although the spectrum of nature sound might not be smooth, they are more acceptable than the other pseudo-random noises since they belong to the natural environment. Moreover, Yu et al. [42] indicated that due to the listener's mood or their ability to focus, nature sounds such as the sound of wind, fire, or rain are more efficient for masking background noises in the office environment. Furthermore, Haapakangas et al. [47] conducted another study in this field, and they explained that by considering acoustical satisfaction in open-plan offices, water sound was more acceptable than instrumental or vocal music, pseudo-random noise, and ventilation, although all of these maskers had the same SPL and spectrum slope. Moreover, when natural elements like plants, nature photos, nature views, and natural colors are employed in the workspace, the water-masking sound becomes more preferable than the other masking sounds [48].

The other proper masking sound in offices is relaxing music because it is spontaneously used by employees, and in some conditions, it can elevate their mood [49]. Listening to music can improve emotions and affects heart activity, respiration, blood pressure, and nervous system activities [42]. Many studies proposed that listening to relaxing music can decrease physiological stress, especially sedative music that has a slow tempo (60 to 80 bpm) and a smooth dynamic range [45]. However, extra attention is needed to choose proper music as a masking sound in workspaces. Since the level of the music changes continuously at each frequency and may not contain needed frequency components to mask human speech [45]. Therefore, the music signal may not be proper for covering speech sounds.

2.5. Spatial uniformity of sound masking system

One of the most important factors for having an efficient sound masking system is providing a uniform sound field across the workspace [10]. Spatial uniformity can be quantified by how SPL vary across a defined space [20]. The sound masking system should uniformly generate the targeted masking sound over the entire office area to provide the desired influence on the acoustical environments. When the masking sound is not uniform throughout the office, it will distribute uneven SPL across the office space. As a result, the sound of the masking system will be loud and annoying in some areas while in other areas, the background noises are still not efficiently masked. The ASTM E 1573-18 [20] presents a method for assessing the uniformity of the masking sound in open-plan offices. In this method, the overall A-weighted SPL ($L_{tot,a}$) and unweighted octave band SPL (L_z) should be measured at several locations. Then the measured values should be compared with the target spectrum to find the tolerance of the deviation. However, the ASTM E 1573-18 [20] offers no guidance on acceptable tolerances for spatial uniformity. The spatial uniformity of sound masking system is typically specified as a spatial tolerance by system specifications [50]. Recently, there has been a trend of insisting tight tolerances as low as ±0.5 dB in masking sound system product specification. Even though one can agree that the nonuniform masking sound can disturb employees' tasks, those tight spatial tolerances and their effect on employees' speech privacy have not been examined scientifically with actual measurement data.

Moreover, there are many parameters that can affect the spatial uniformity of the masking sound in an office including locations and directions of loudspeakers, number of the speakers, location, and height of the obstructions, the amount of sound absorber and diffusers in the office and their location, and noise from air-ventilation equipment [51]. In terms of the location and direction of the loudspeakers, some research has been done. Based on the results of the previous studies, when the loudspeakers are located under or within the ceiling, they are directly facing the office space and make a hot spot in their axes. This approach is usually used when the ceiling height is too high or when the suspended ceiling is entirely or partly absent. On the other hand, in most open-plan offices, loudspeakers are placed in the plenum above the suspended ceiling. In this approach, the sound is mixed well in the plenum, which causes a uniform propagation of the sound in the whole office space [21]. However, in terms of the other parameters that affect the uniformity of the sound masking systems in open plan offices there is not much research in this content.

In order to assess speech intelligibility across the open plan offices, there are some research which used the Articulation Index (AI). [51]. Articulation Index (AI) is a metric between 0 and 1, to predict the speech intelligibility by using the difference between one-third octave band signal-to-noise ratios of standard speech and given background noise spectra at specific locations. The calculation procedure is standardized in ANSI/ASA S3.5 [23]. The ANSI/ASA S3.5 also defines Privacy Index for predicting speech privacy as inverse of the AI.

In order to describe how the different values of the AI can be perceived by the occupants of an open plan office, different studies have been done in this content. From the results of these studies, it can be found that when the AI value is less than 0.05, confidential privacy can be occurred [33], [53]. Confidential privacy is a condition that the speech can be detected but almost all the speech words are not intelligible from the adjacent area [54]. The other condition which has a lower level of the speech privacy is referred to the acceptable or normal privacy. In this condition, the AI value is between 0.05 and 0.15 [55], [56]. In the normal privacy condition, the speech is not distracting and there must be an effort to understand it [54].

J.S. Bradley [17] used a previously simulated model to assess the effect of the office design parameters on the speech intelligibility. He found that the following parameters can affect the speech privacy in open plan offices: sound absorption and height of the ceiling, the height, size, the absorption and transmission of the partitions between the workstations, floor absorption, and the type of the ceiling lighting. Among all these parameters, ceiling absorption, height and size of the partitions had the most effect on achieving the acceptable speech privacy. The results of his study reveal that the acceptable privacy cannot be achieved unless all the design factors be close to their optimum values. Moreover, he found that the level of the sound masking system, level of the speech sound, and the location and direction of the talker are the other factors that can affect the speech privacy.

In order to find the effect of masking sound level variation on speech intelligibility, Moeller [50] did an experimental study. In his case study, the distance between the workstations was 4.7 m and the partition's height was 1.6m. When there was no masking sound the background sound level was 40.6 dBA. In this condition, by calculating the AI, he found that employees can understand around 85% of the background speech. By increasing the masking sound level comprehension drops. By setting the masking sound level to the maximum level of comfort which is 48 dBA [38], when having a ±0.5dBA deviation, the comprehension of the background speech is not more than 25%. However, for the ±2dBA range, the employees can understand 59% of the background conversation which is not much better than the unmasked condition.

Thus, this study aims to evaluate the uniformity of the sound masking system and its effect on speech privacy in an open-plan office in Montréal, Québec, Canada. The measurement was carried out with a resolution grid of 0.6 m x 0.6 m to determine spatial variations of the masking sound levels across the office space by following the method used in L'Espérance et al [21]. This study also examines the parameters that can influence the spatial uniformity in the open-plan office by using a computer-aided simulation. To propose an acceptable spatial variation of the masking sound levels, Articulation Index (AI) was utilized to examine speech intelligibility over the open-plan office space.

2.6. Summary

This chapter discussed all the factors which affect the efficiency of the sound masking systems. From the previous studies, it can be concluded that an efficient sound pressure level for the sound masking system in open-plan offices should be more than 42 dBA to be efficient and less than 48 dBA to be pleasant and acceptable. In terms of a proper spectrum for the sound masking system, the sound that its spectrum is close to the speech spectrum, like a sound which has a slope with -7 dB per octave doubling, is the efficient one. In the industry, the sound masking curve is usually suggested by the acousticians. For this research, the spectrum which is provided by the National Research Council (NRC) was considered as a reference curve. In order to specify a proper type of sound for the masking system, more research is needed to be done in this content. The other important factor for having an efficient sound masking system is providing a uniform sound field through the workspace. Uniformity of the masking system depends on many factors such as location and direction of loudspeakers, number of loudspeakers, location, and height of the obstructions such as partitions, the amount of sound absorber in the office and their location, HVAC (heating, ventilation and air conditioning) sound, etc. In the current study, some of the critical parameters, which can affect the uniformity of the sound masking system, is evaluated by using a simulated model of the open-plan office. The following sections explain the procedure more into detail.

3. Chapter three. Research design and method

The acoustic measurement and geometrical room acoustic simulation were carried out to investigate the spatial uniformity of masking sound in the open-plan office in Montreal. The measurement followed procedures as stated in the ASTM E1573-18 [20]. With the obtained measured data, the room acoustic simulation was utilized to investigate how three physical parameters (a number of sound masking speakers, partition height, and ceiling's scattering & absorption property) affect the spatial uniformity of masking sound.

The data which are required for the measurement and simulation are as follow 1. detail information about the office space, including office layout, dimension, scattering coefficient of the surfaces, room material, and their absorption coefficient 2. Information about the sound masking system including the type of the speaker, number of the loudspeaker, location, direction, directivity, SPL and, the spectrum of the sound source, 3. Information about the HVAC system including, duct location and the location of the air return grill and diffuser.

All the details about the input data are explained in the first section of this chapter. In the next part, after describing the calibration method which was used for the loudspeakers of the sound masking system, the measurement procedure is explained in detail. When the measurement completed, the sound maps were generated by using RAP-ONE II software to display the overall A-weighted SPL distribution and the variation of the SPL through octave bands from 250 Hz to 4 kHz across the open-plan office. The criteria which were used for the measurement were based on the ASTM E1573-18 standard [20].

The simulation method and all the scenarios, which are defined to assess the effects of a specific factor on the uniformity of the sound masking system across the office space is described. The simulation was conducted with CATT Acoustic v9.1e software [52] which can generate sound maps for a defined condition. In both sections, measurement, and simulation, the percentage of the positions within a certain tolerance was calculated by using the Microsoft Excel-2019 (the calculation process is explained in the appendix). The outputs of this research are discussed in chapter 4. In the last part, to evaluate the effect of the uniformity of the sound field on speech intelligibility in the open-plan office, Articulation Index (AI) was calculated.

3.1. Office layout

The measurement was conducted in an open-plan office, located in Montreal, Canada. The L-shape open-plan office space has a floor area of approximately 68.5 m^2, with a height of 2.7 m. Materials in the room include acoustical ceiling tiles, thin carpet, double-glazed windows (south side), and gypsum walls. Ventilation ducts and sound masking loudspeakers are placed in the one-meter high plenum above the ceiling. Figure. 3 presents the office plan with locations of the measurements and sound masking speakers, workstations, partitions, air diffusers and a return grill. There are two fixed desks located on the right side of the office, with 1.4 m high absorbent desk partitions which separate the workstations . The other four tables on the left side do not have partitions between the workstations. On the right side of the office, there are two closed offices. The walls between the open-plan office and the closed office are continued up to the slab deck. Each room has its loudspeaker to control the noise in the office. During the measurements, the doors of the closed offices were closed, the loudspeakers in the closed offices were turned off, and only the uniformity of the sound in the open area was measured.

In this office, there are four loudspeakers mounted above the ceiling in the plenum. The locations of the loudspeakers are marked in Figure. 4 as orange circles. Moreover, an air return grill is located in the bottom right corner (southeast) of the room, and two supply diffusers of the HVAC system are located in the middle of the space. The locations of the air return grill and supply diffusers are also presented in Figure. 4.

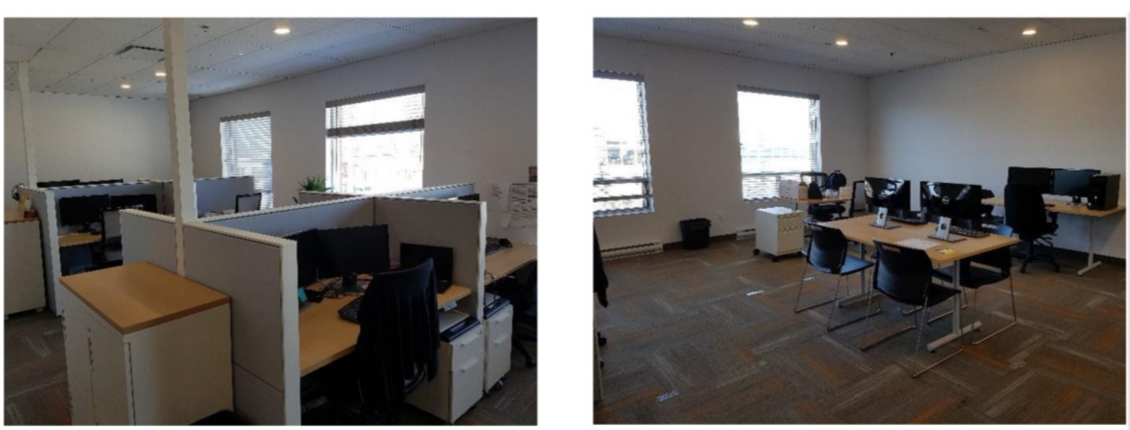


Figure 3. Pictures of the open-plan office in Montreal for the spatial uniformity measurement

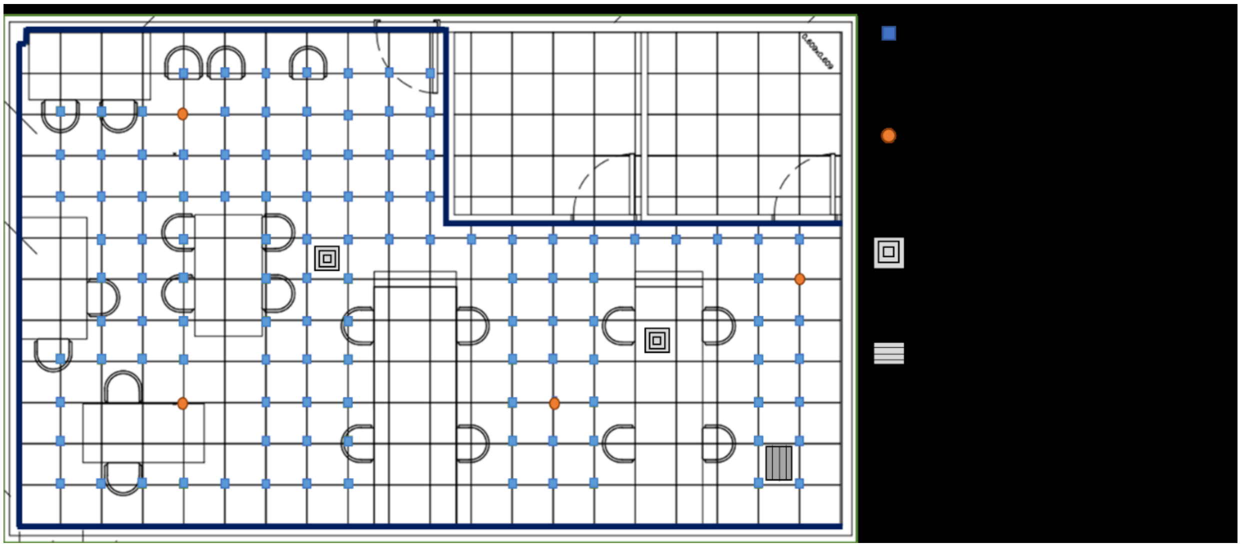


Figure 4. The layout of the open-plan office including the location of the loudspeakers, measured points, locations of the air return grill and diffusers of the heating, ventilation and air conditioning (HVAC) system

3.2. Sound masking system setup

A proper sound level for the sound masking system is between 42 dBA to 48 dBA, which depends on the background noise as discussed in the literature review chapter. Therefore, the speakers in the office were typically set between 42 dBA and 47 dBA. However, as the HVAC system from an air ventilation unit cannot be stopped during the measurement, the sound level from each of the loudspeakers was raised by the same amount in each one-third-octave frequency band to a level sufficiently above the HVAC noise which was approximately 53 dBA overall for the frequency range between 100Hz and 5000Hz to avoid any influences by the noise from HVAC noise.

The class 1 sound level meter (SLM) of Mezzo Precision was used for the tuning of the sound masking system and measuring the sound pressure level across the office. But, before the measurement, the sound level meter was calibrated by using an acoustic calibrator. For this purpose, after installing the calibrator on the microphone, the calibration was run until the SPL, and the sensitivity of the measurement was acceptable (it took around 10 seconds).

The area that can be covered by each speaker is called zone. The radius of the zone depends on the ceiling height and the kind of the speaker. The method of calibration for the speakers was a fixed-point calibration for each loudspeaker. Generally, there are two methods for calibrating the sound masking system: using a single-fixed location at the center of each zone, or sweeping the microphone through the zone. For the fixed location calibration method, each loudspeaker is calibrated to the specified sound masking spectrum at a single fixed location. Depending on the number of speakers per zone, this may be directly below the loudspeakers (one speaker per masking zone) or centrally-located between the loudspeakers (two or more speakers per masking zone). For the sweep calibration method, all the loudspeakers in a zone are calibrated based on matching the average sound masking level measured across the whole zone to the specified masking curve. With decreasing zone size, it becomes more difficult to calibrate the system using a sweep method due to the bleed-in from adjacent zones in one- or two-speaker masking zones, so the manufacturer will tend to base the calibration on the fixed-point method. Whilst this allows for faster calibration for small zones, it is suspected that this can lead to significant variation between the central calibration position, and measurement positions (i.e. workstations) away from the calibration position.

Due to the specifications for the STR (Structural speaker) loudspeaker, the area that can be covered by the speakers is equal to the height of the deck plus three feet. As the speakers in the plenum of the office were STR and the deck height of the office is 3.6 m, each speaker can cover 4.5 m [57]. In order to calibrate each zone a single position directly below each loudspeaker was chosen. The calibration was conducted at 1.2 m height above the floor level, which is the ear height of a seated person. For starting the calibration, the room was kept as quiet as possible, and the only sound in the room was the sound of the sound masking and HVAC system. Then the microphone, which was pointed at 45 degrees above the horizontal plane, was rotated across a 1 m diameter circle with a center at the right below the point of each loudspeaker for at least 10 seconds.

For this calibration, the NRC-53 dBA spectrum was considered as a reference value. The SPL values of this curve are presented in Table 1. To match the NRC optimal sound masking curve, one speaker can be calibrated perfectly; however, by calibrating the second speaker, the sound in the first zone can change again. Therefore, the calibration was repeated several times to achieve an acceptable average sound pressure level across the whole space. As a result, none of the speakers were calibrated perfectly but, the difference between the NRC-53 curve and the sound pressure level below each speaker is less than 1 dB for all the speakers considering 100 Hz to 5kHz for the 1/3 octave band frequencies and for the overall dBA values. The results of the calibration are displayed in Table 1.

Table 1. Calibration results at the points below the loudspeakers (spk) and the differences between the NRC-53 curve and the measured values

Frequency range	**Measured value (dB)**				**NR-53**	**Difference (dB)**			
	Spk. 1	Spk. 2	Spk. 3	Spk. 4		Spk. 1	Spk. 2	Spk. 3	Spk. 4
100 Hz	55.2	54.7	54.6	54.4	54.9	0.3	-0.2	-0.3	-0.5
125 Hz	54.4	54.2	54.8	54.1	53.9	0.5	0.3	0.9	0.2
160 Hz	53.5	52.8	53.5	52.3	52.7	0.8	0.1	0.8	-0.4
200 Hz	52.9	51.9	52.1	52.3	51.9	1	0	0.2	0.4
250 Hz	51.7	51.2	51.3	50.5	50.7	1	0.5	0.6	-0.2
315 Hz	49.8	50.3	50	48.8	49.4	0.4	0.9	0.6	-0.6
400 Hz	49.3	48.4	48.2	48.6	48.4	0.9	0	-0.2	0.2
500 Hz	47.9	47.2	47.1	47.5	46.9	1	0.3	0.2	0.6
630 Hz	45.9	45.8	46	45.5	45.4	0.5	0.4	0.6	0.1
800 Hz	44.2	43.2	43.7	43.7	43.4	0.8	-0.2	0.3	0.3
1000 Hz	42.2	42.2	42.4	42.4	41.7	0.5	0.5	0.7	0.7
1250 Hz	39.4	39.4	40	39.1	39.4	0	0	0.6	-0.3
1600 Hz	37.6	37.4	37.3	37.3	37.4	0.2	0	-0.1	-0.1
2000 Hz	35.6	35.6	35.5	34.6	35.4	0.2	0.2	0.1	-0.8
2500 Hz	33.2	33	33	32.8	32.9	0.3	0.1	0.1	-0.1
3150 Hz	31	30.3	30.6	30.5	30.4	0.6	-0.1	0.2	0.1
4000 Hz	28.4	27.1	27.8	27.3	27.4	1	-0.3	0.4	-0.1
5000 Hz	25.4	24.1	24.7	24.5	24.4	1	-0.3	0.3	0.1
100-5000 Hz	53.36 dBA	52.94 dBA	53.18 dBA	52.78 dBA	52.68 dBA	0.7 dBA	0.3 dBA	0.5 dBA	0.1 dBA

3.3. Measurement

The ASTM E1573-18 standard states that the minimum number of the measured points for spaces with the area less than 465m^2 should be five, and there should be at least one measurement point for every 93 m^2 for the larger space than 465 m^2. In this study, 117 locations were measured to evaluate the spatial uniformity of the masking sound levels across the office. All the measured locations are presented in Figure. 4 as small squares. The distance between the measured points was 0.6 m except the locations near the furniture where is at least 1 m distant from any reflective surfaces [20]. A class-1 Mezzo Precision sound level meter (SLM) was used and calibrated before and after the measurement. A broad set of data, including the equivalent, maximum, minimum, and statistical SPLs (L95, L10, etc.) were obtained. The measurement procedure followed as stated in ASTM E1573-18 [58].

Prior to the spatial uniformity measurement, the background noise level of the office was measured and sound level from the loudspeakers was calibrated accordingly. Figure 5 presents the average SPL of the background noise and masking sound. The masking sound spectrum proposed by Bradley [17] was used in this study. According to ASTM E1573-18, the difference between the SPLs of the masking sound and background noise should be greater than 10 dB in all one-third octave bands. As the heating, ventilation and air conditioning (HVAC) system cannot be turned off during the measurement, the SPL from the sound masking speaker was raised to overall 53 dBA by the same amount in each one-third-octave band from 100Hz and 5000Hz to avoid any influence by the noise from HVAC system, even though the optimal sound level for the sound masking system in open plan offices is between 42 dBA to 48 dBA [36]. However, some locations near the air diffuser and return grill still failed to achieve the minimum 10 dB difference possible due to the HVAC noise. Totally, 40 points were influenced by the background noise; therefore, only 77 positions are considered for the analyzing.

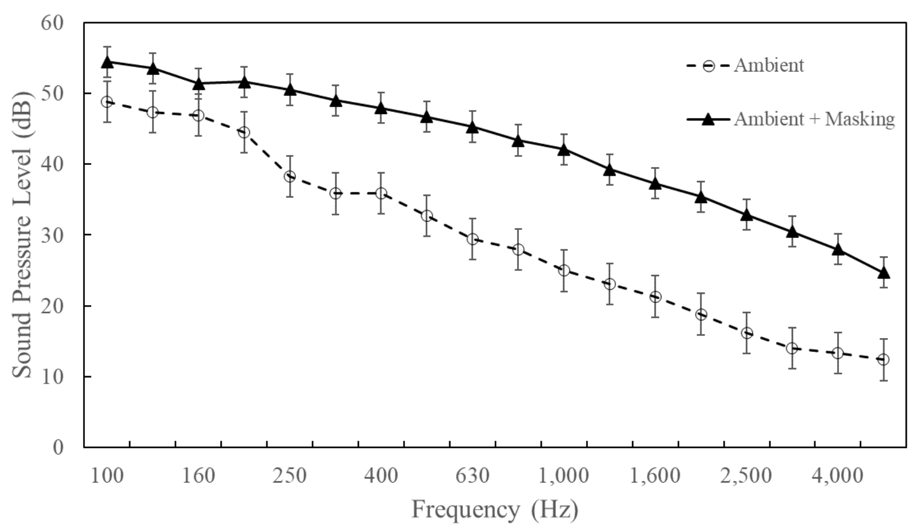


Figure 5. Average SPL of the whole space without the masking sound (Ambient) and with the masking sound (Ambient + Masking)

After calibrating the loudspeakers, the sound pressure levels are measured at 117 locations over the open-plan office. At each location, the SPL was measured while sweeping the SLM around a circle of 1 m radius centered on the location for 10 seconds. The microphone of the SLM was pointed at 45 degrees above the horizontal plane. The height of the microphone was 1.2m, which is the height of the ear of a seated person. The same measurement was repeated two more times with the same tester and the same SLM, and the measurement was repeated once again with a different tester and different SLM. When the measurement was completed, to understand how the masking sound distribute across the office space, the noise maps were generated by using RAP-ONE II software, which can create a sound map by using Kriging interpolation. Kriging interpolation is a method of spatial interpolation that can be used when there is a limited set of data, and it can determine the value of the variable for the rest parts of the space. In this method in order to predict the unmeasured values, the surrounding measured points are given a weight based on their arrangement and the distance between the measured and unmeasured positions [59].

3.4. Simulation

The simulation was conducted by using the CATT Acoustic v9.1e software [60] which combine three prediction methods: 1. mirror image-source, 2. ray-tracing, and 3. cone-tracing. In the "Early part detailed Mirror Image-Source Model (ISM)" the whole image sources of the surrounded surfaces are calculated based on the defined amount of time and the maximum number of the reflections. From each of the image sources, both diffuse and specular rays reflect in a way to avoid exponential increasement of the reflected waves. The other method which is "Audience area mapping" is similar to the ray-tracing method. In this method, the rays are reflected from the surrounding surfaces on the basis of Lambert's Law. The ray-tracing method is used to calculate energy parameters (e.g. Clarity (C80)), using a grid throughout the audience space. Therefore, this method is not proper for auralization. The third method is "Full detailed calculation". This method combines mirror image-source, ray-tracing and cone-tracing algorithms. In this method, the mirror image-source is used to calculate the first two specular reflections. Moreover, the ISM method is used to calculate the first order of diffuse reflections. The approximate cone-tracing method is conducted for the higher order of the reflecting rays. In this method, the calculation of the ray directions is randomised.

The process that CATT-Acoustic software used for the simulation includes the following parts: Modeling of the room, defining the absorption coefficient and the scattering coefficient of the materials, defining the settings for the sources and receivers, setting the process of the calculation. In the following sections, after describing all the settings which were conducted for the simulation, the scenarios which were defined to evaluate the factors which affect the uniformity of the sound masking system are explained in detail.

In CATT-Acoustic the geometry of the model can be imported from some other software such as AutoCAD. But for this research, the data for the geometry of the model was imported manually. Although this is a more time-consuming method, the users have more control of the location of the corners and surfaces and they can easily change them if necessary. The geometry model in CATT-Acoustic should not be simulated in very detail. The reason is that a detailed model increases the reflection orders and as a result the accuracy reduced. However, there is not a specific standard which recommends the proper level of the detail for the model. For the modeling of the current study, the geometry of the open-plan office is simplified based on a cut-off dimension of 50 cm for computational efficiency. Figure. 6 illustrates the 3D geometrical model of the office including layout, the location of the loudspeaker and the workstations.

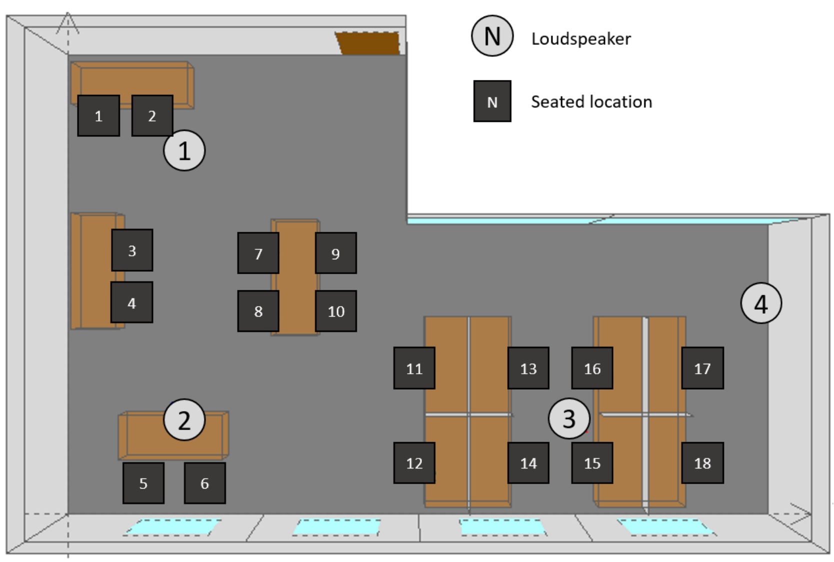


Figure 6. Office layout and the location of the sources and receivers

For each material and furniture absorbing coefficient was defined in 125 Hz - 4k Hz based on the used materials in the office. Table 2 displays the types and absorption coefficients that were conducted in the simulated model. All the values are obtained from the PTB (Physikalisch-Technische Bundesanstalt) database [61].

There is not much information about the scattering coefficient of building materials [62]. Therefore, in this simulation, although small changes in the scattering coefficient of building material can have a big effect on the reverberation time of the room, a frequency-independent scattering coefficient was considered for all the big flat surfaces. Therefore, as the walls, floor, deck, and ceiling of the office are flat and big enough compared to the wavelength of the sound from the masking system, the scattering coefficient of all of them was defined as 10%. Moreover, the auto edge scattering setting was considered for the protruding and recessed elements, such as partitions or desks [63].

Table 2. absorption coefficient of the materials in the open-plan office [56]

Element of the building	**Material**	**Absorption coefficient of the materials in 125Hz to 4kHz frequencies**					
		125 Hz	250 Hz	500 Hz	1k Hz	2k Hz	4k Hz
Exterior walls	2 layers of 16mm gypsum board	28	12	10	17	13	9
Interior walls	1 layer of 13mm gypsum board	18	32	70	99	50	29
Floor	10 mm soft carpet on concrete	9	8	21	63	27	37
Ceiling	16 mm thick Armstrong type 755B Minaboard mineral fiber tiles	5	19	57	74	71	76
Deck	Smooth unpainted concrete	1	1	2	2	2	5
Glasses between the interior spaces	Double glazing, 2-3 mm glass, 10 mm gap	10	7	5	3	2	2
Windows	Double glazing, 2-3 mm glass, >30 mm gap	15	5	3	3	2	2
Door	Solid wooden door	14	10	6	8	10	10
Tables	plywood	14	10	6	8	10	10
Partitions	25mm Fibreglass bitumen bonded mat	10	35	50	55	70	70

The speakers of the masking system in the open plan office are STR (Structural speaker), which is shown in Figure 7. These speakers are aimed upward and installed in the plenum. In the simulation, the size and orientation of the speakers were defined identically with the actual STR loudspeakers.

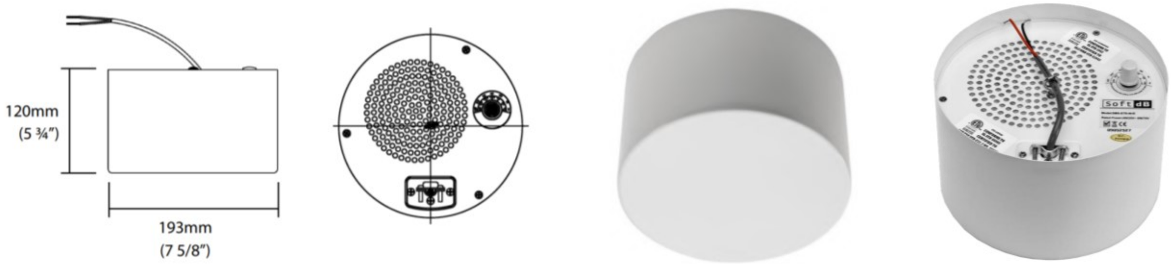


Figure 7. Sound Masking System Structure Loudspeaker (SMS-STR) [57]

Moreover, the directivity of the loudspeakers in the simulated model is also based on the specification information of the STR speaker. Figure. 8 displays the vertical polar graph and the frequency response of the STR loudspeaker.

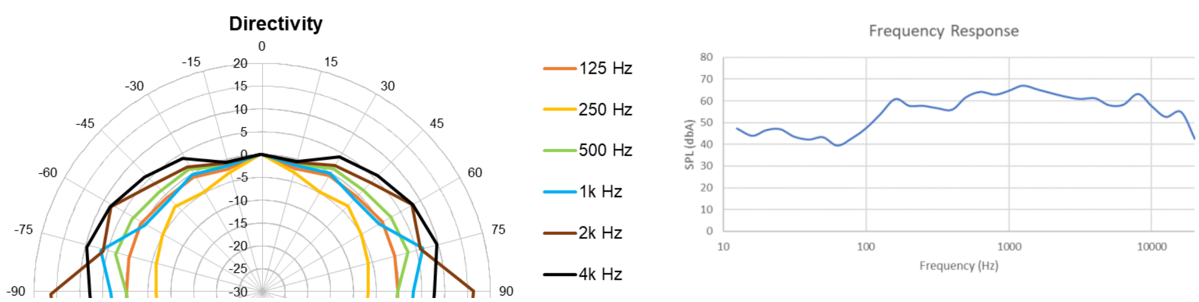


Figure 8. Directivity and the frequency response of the STR loudspeaker [57]

In CATT-Acoustic, the sound power of the speakers can be defined as SPL values measured at 1m distance apart from the source. Therefore, the sound pressure levels of the speakers were defined based on the NRC-53 dBA curve (for 100Hz to 5kHz frequencies). The NRC-53 SPL is presented in Table. 3. Table 3 also, displays the sound pressure level of the points at 1.2m height blow the speakers. As can be seen, the result of the simulation shows that the differences between the SPL and the NRC-53 dBA curve through all the frequencies is less than 0.3 dB.

The sound power level of the speakers were defined in the similar way of the calibration procedure during the measurement to have the sound spectrum measured at the location directly below the speaker follow the NRC reference spectrum from 125 Hz to 4 kHz octave bands. The

NRC-53 SPL is presented in Table. 3. Table 3 also, displays the sound pressure level of the points at 1.2m height blow the speakers. As can be seen, the result of the simulation shows that the differences between the SPL and the NRC-53 dBA curve through all the frequencies is less than 0.3 dB. After calibrating the loudspeakers, the SPLs at the 117 locations as designated in the measurement were simulated.

Table 3. SPL results of the simulation and their differences with NRC value from 125Hz to 4k Hz octave band for the calibrated points which are right below each speaker

Loudspeaker		**Frequency (Hz)**					
		125	250	500	1000	2000	4000
Speaker 1	NRC (dB)	58.7	55.56	51.84	46.57	40.38	32.84
	SPL (dB)	58.79	55.52	51.64	46.67	40.65	33.14
	difference (dB)	0.1	0.0	0.2	0.1	0.3	0.3
Speaker 2	NRC (dB)	58.7	55.56	51.84	46.57	40.38	32.84
	SPL (dB)	58.7	55.9	51.8	46.5	40.5	33.1
	difference (dB)	0.0	0.3	0.0	0.1	0.1	0.3
Speaker 3	NRC (dB)	58.7	55.56	51.84	46.57	40.38	32.84
	SPL (dB)	58.91	55.84	51.88	46.32	40.18	33
	difference (dB)	0.2	0.3	0.0	0.2	0.2	0.2
Speaker 4	NRC (dB)	58.73	55.56	51.84	46.57	40.38	32.84
	SPL (dB)	58.56	55.72	51.72	46.87	40.1	32.52
	difference (dB)	0.2	0.2	0.1	0.3	0.3	0.3

The number of rays which was chosen for the calculation was 50000. This number seems to be sufficient for the accuracy of the simulation; because by increasing the rays' number there was not a significant difference in the simulation results. The length of the impulse response was 2000 ms.

In order to assess the effects of different factors on the uniformity of the sound masking system through the office, three physical parameters were investigated to find how they influence the spatial uniformity of the masking sound field. In the following, the scenarios are explained more into detail.

3.4.1. Scenario 1: Effects of loudspeaker numbers

It is expected, by increasing the number of speakers of the sound masking system, the uniformity through the office space increases. In this scenario, the number of loudspeakers was adjusted from one to seven. The location of the loudspeakers in each condition was chosen in a way to cover the most part of the space. For this purpose, when the number of the speakers are not enough to cover the whole space, they are placed in a way to cover the center part of the office, and by increasing the speakers, they are located in a way that edge of the coverage circle of the speakers can at least touch each other. For the condition with more speakers, the area that can be covered by each speaker has an overlap with the adjacent speakers. It was expected that the spatial uniformity improves by increasing the number of the loudspeakers. In all of these conditions, only the number of speakers was changed, and the rest settings have remained the same.

3.4.2. Scenario 2: Effects of partition height

In this scenario, the effect of the partitions' height through the office space on the SPL uniformity of the sound masking system was evaluated. The effect of the partition height on the spatial uniformity was analyzed. The partition's height in the actual open-plan office is 1.4 m. In this scenario, the five different heights of 0 m, 1.1 m, 1.4 m, 1.7 m and 2 m were used for the acoustic simulation. By changing the partitions' height, the SPL of the points below the speakers was changed. Therefore, new SPL for the speakers was defined in a way to achieve less than 0.3 dB differences between the SPL at those points and the NRC-53 dBA curve.

3.4.3. Scenario 3: Effects of ceiling absorption and scattering coefficient

In this scenario, the acoustic characteristics of the ceiling surface was manipulated to find out how it affects the masking sound field. The more diffusive the ceiling panel is, the more uniform masking sound field was expected. The six different ceiling combinations of scattering and absorption conditions were investigated as follows: 1. Noise Reduction Coefficient (NRC) 0.3 and no diffuser, 2. NRC 0.3 and 50% diffuser for the area of the ceiling, 3. NRC 0.3 and 100% diffuser, 4. NRC 0.8 and no diffuser, 5. NRC 0.8 and 50% diffuser for the area of the ceiling, and 6. NRC 0.8 and 100% diffuser. In the defined conditions, the scattering coefficient of the ceiling was changed based on an actual acoustic diffuser (Waveform Harmonix-K) [64]. As can be seen in Figure. 9, Waveform Harmonix-K has an asymmetric based shape, which can create a uniform sound field across the space. This material can be installed on the acoustic ceiling tiles and it is usually used where acoustical control is needed such as: auditorium, worship space, studios [64]. Figure. 10 present the acoustical data of this material. To assess the effect of the ceiling absorption coefficient on the sound field, the NRC value of the acoustic ceiling tile (ACT) which is 0.8, and Waveform Harmonix-K, which is 0.3 was considered for this scenario. For the condition that 50% of the ceiling is covered by the diffuser, the diffuser was located at the center part of the ceiling and there is a 0.5 m space from the surrounded walls. The material for the rest parts was ACT.

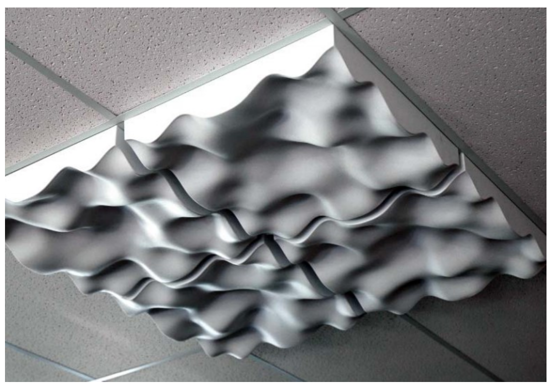
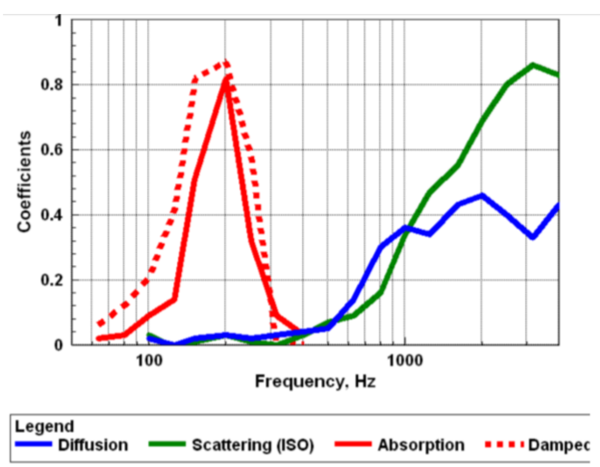


Figure 9. Waveform Harmonix-K [45]



f (Hz)	Diffusion	Scattering (c)	Absorption
100	-0.01	0.32	0.46
125	-0.04	0.18	0.48
160	-0.04	0.07	0.50
200	0.00	0.05	0.38
250	0.00	0.03	0.23
315	0.03	0.03	0.18
400	0.03	0.03	0.22
500	0.03	0.04	0.26
630	0.03	0.06	0.24
800	0.04	0.08	0.24
1000	0.06	0.11	0.27
1300	0.12	0.21	0.25
1600	0.18	0.35	0.22
2000	0.28	0.52	0.20
2500	0.29	0.66	0.22
3150	0.47	0.84	0.17
4000	0.45	0.94	0.14

Figure 10. Waveform Harmonix-K [45]

3.4.4. Articulation Index

In order to evaluate the effect of the uniformity of the sound field on speech intelligibility in the open-plan office, Articulation Index (AI) was calculated. The normal speech spectrum of a male from ANSI S3.5-1997 [23] [65] was used for the AI calculation. In the simulation, a speech source was assumed to be located at the other side of the workstation in the office. To simplify the calculation, a single simulation with the same condition of the measurement was carried out to calculate the speech spectrum at a receiver location. Then, the same speech spectrum was used for the AI calculation. The reference male speech spectrum and the used spectrum at a receiver correspond to 59.5 dBA and 54.3 dBA respectively. During the measurement the SPL of the masking system was raised to 53 dBA to avoid any influence from the HVAC system. However, in the real condition the maximum acceptable level for the masking system is 48 dBA [56]. Therefore, the background sound in the AI calculation was the measured masking sound at each position mines 5 dBA.

3.5. Summary:

This chapter provides detailed information about the measurement and simulation method to achieve the objectives of this research. In the first part, the measurement was conducted to assess the spatial uniformity of the sound field generated by a one-speaker per zone sound masking system in an open-plan office, where each of the loudspeakers was calibrated separately at a fixed point directly under the speaker. In the second part of this research, different factors that affect the uniformity of the masking sound were evaluated by using the simulation. Three scenarios were simulated and, in each scenario, one factor which can affect the SPL variation was assessed. After the simulation was completed, the effect of the office design parameters (number of the SMS loudspeaker, partition height, absorption and scattering coefficient) on the variation of the sound field and speech intelligibility across the open plan office was examined.

4. Chapter four. Results and discussion

The results of this study are analyzed in three sections. In Section 4.1, the measurement results are discussed in detail and the results from the simulation are presented in Section 4.2. In section 4.3 by examining the speech intelligibility over the open-plan office, the acceptable spatial variation of the masking sound levels was achieved.

4.1. Measurement Results

Figure. 11 displays the HVAC influenced positions as an orange multiplication sign. As can be observed, most of the excluded positions are on the upper side of the office, which can be the result of the sound from the HVAC ducts, located around that part in the plenum. When looking at all 117 measured positions, 40 points were influenced by the background noise; therefore, only 77 positions are considered.

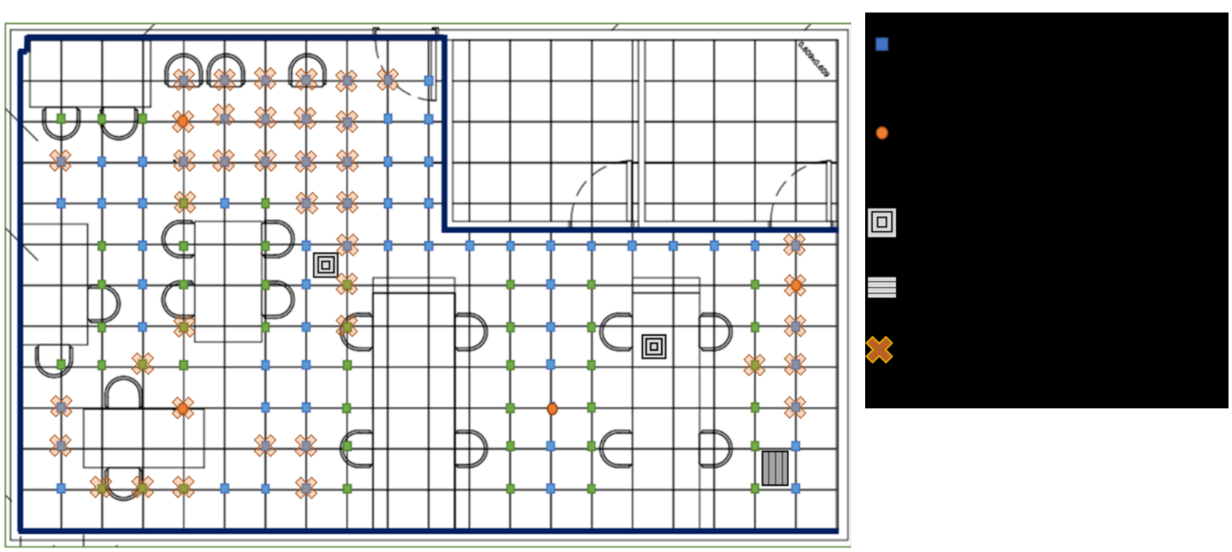


Figure 11. Positions of the excluded measured points which are affected by the background sound

Table 4 presents the percentage out of 77 locations within a certain tolerance in dB. The tolerance is set from the reference spectrum (NRC-53 dBA from 250Hz to 5 kHz) and 51.96 dBA of overall A-weighted SPL. For the $L_{tot,a}$, 61% the positions are within ±0.5 dBA and all locations fall into the tolerance range of ±1.5 dBA. When considering the L_z for the 250 Hz to 5 kHz one-third octave bands, none of the measured points can be within ±0.5 dB and all locations are within ±4.5 dB.

Table 4. Percentage of the measured positions within specified tolerance in dB from the targeted sound level by utilizing Ltot,a and Lz from 250 Hz to 5 kHz (considering the points which are not affected by the HVAC sound in the 1/3rd octave bands). The total number of the locations is 77.

Tolerance (dB)	±0.5	±1	±1.5	±2	±2.5	±3	±3.5	±4	±4.5
$L_{tot,a}$	61%	99%	100%						
L_z (250 – 4 kHz)	0%	4%	22%	55%	69%	87%	95%	99%	100%

In order to understand how the masking sound, distribute across the office space, the $L_{tot,a}$ distribution at 1.2m height is displayed as a bar chart in Figure. 12. As the NRC value for 250 Hz to 5kHz is 51.96 dBA, all the positions are within ±1.5 dBA range. Moreover, the difference between the lower SPL (L95% = 51.20 dBA) and the higher SPL (L5% = 52.55 dBA) is 1.35 dBA and the standard deviation is 0.51 dBA.

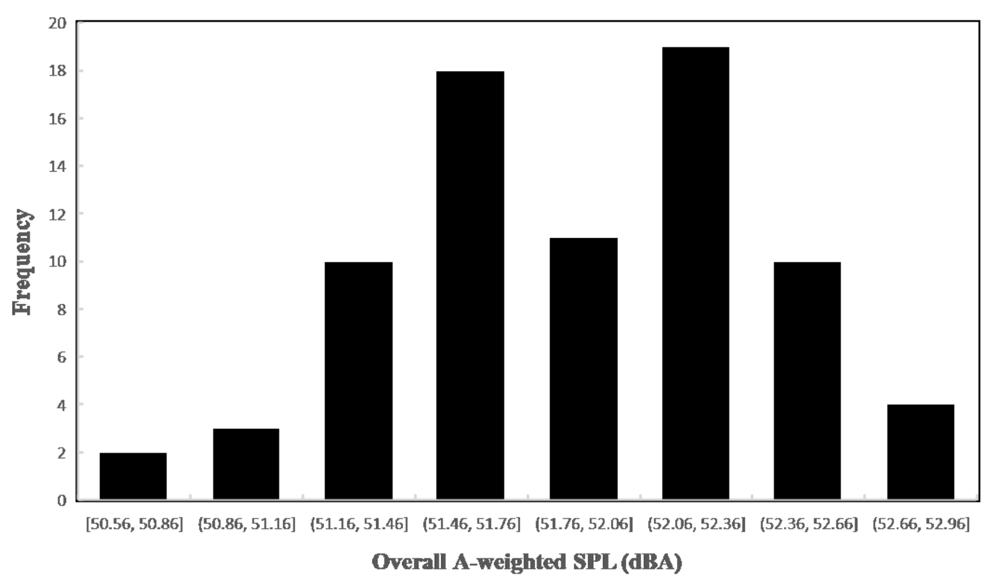
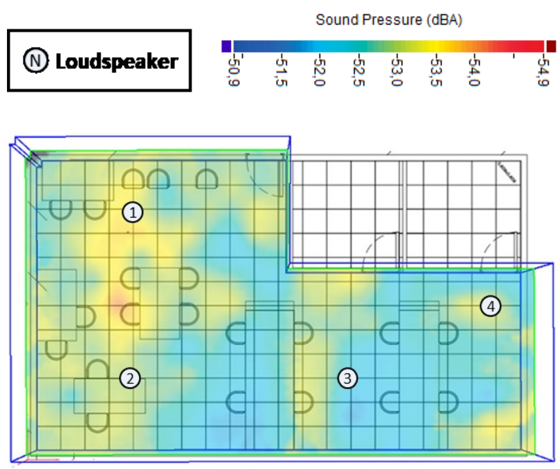
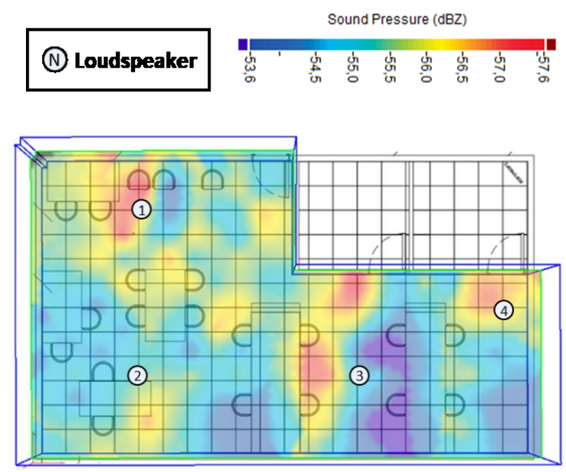


Figure 12. Distribution of the $L_{tot,a}$ for all the measured point across the office

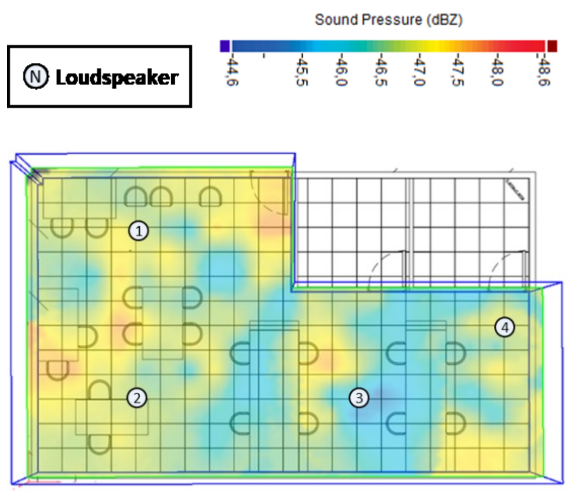
Figure 13 illustrates the sound maps a varying ±2 dB color scale, centered on the NRC-53 dBA for the $L_{tot,a}$, 250 Hz, 1 kHz and 4 kHz octave bands. In Figure. 13 (b) and (d), the positions with dark purple or dark red are out of the ±2 dB range. At 1 kHz the color map shows a more uniform distribution of the masking sound over the space in comparison with the higher and lower frequencies. In the 250 Hz, the SPL is mostly lower than the reference value, while in the 4 kHz, the SPL for most of the space is more than the reference value. Moreover, in the 250 Hz color map, the number of the positions which are out of ±2 dB range (18%) is more than the other maps. When looking at the color map for the $L_{tot,a}$, the blue area which is lower than the reference spectrum is mostly on the right side of the office which could be a result of absorption by the desks partitions. On the other hand, the yellow area is mostly found on the positions between the two speakers on the left side where the variation is more than the reference spectrum. It is good to mention that this is the side with no desk partitions.



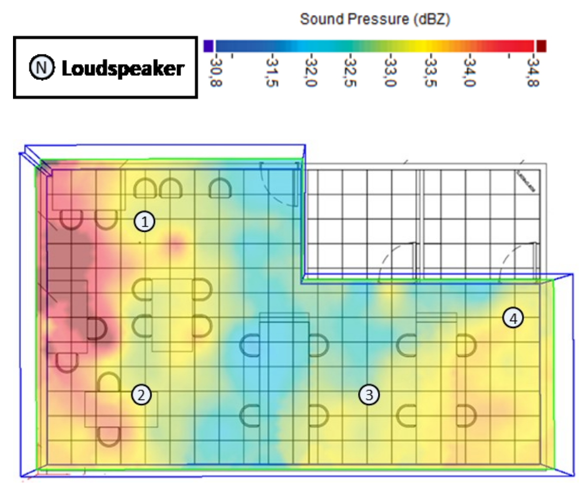
(a) $L_{tot,a}$



(b) 250 Hz



(c) 1000 Hz



(d) 4000 Hz

Figure 13. distribution maps using ±2 dBA ranges for (a) Ltot, (b) 250 Hz, (c) 1 kHz, and (d) 4 kHz

4.2. Room acoustic simulation results

A proper way to check the precision and validation of the acoustic modeling is to compare the simulation results with the measurement. Table. 5, compared the results of the simulation with the measurement for the Overall A-weighted SPL and SPL throughout all the defined frequencies. As the simulation was conducted without considering the HVAC effect through the octave bands, the measurement results in Table. 5 are for the condition that the points which are influenced by the HVAC are excluded when considering 250 Hz to 4 kHz octave bands. A quick glance at the results reveals that in both measurement and simulation, the results present the same trend, but the percentage of the points in each defined tolerance is not the same. When comparing the results in the octave bands, for the overall A-weighted SPL, the measurement and simulation results are almost similar. In both of them all the points are within ±2 dBA and more than 90 percent of the points are within ±1.5 dBA. For the variation of the SPL through the defined frequencies, in the simulation all the points are within ±3.5 dB and more than 90 percent of the positions are within ±2.5 dB; however, for the measurement results, these values are ±5 dB and ±3.5 dB respectively. The main reason for this difference might be the number of points which are excluded from the analysis in the measurement. While in the simulation all the 117 points are considered for studying the uniformity of the sound field in the office space, there are only 40 points in the measurement results which are not affected by the HVAC sound. Therefore, as some points which are studied in the simulation are not considered in the measurement, the results are not the same.

Table 5. Percent of the measured positions within a certain tolerance for the measurement and simulation

Tolerance	Overall A-weighted		Throughout all the frequencies	
	Measurement	Simulation	Measurement	Simulation
	Octave bands (40 point)	Octave bands (117 point)	Octave bands (40 point)	Octave bands (117 point)
±0.5	20%	28%	3%	6%
±1	50%	68%	23%	28%
±1.5	93%	89%	48%	56%
±2	100%	99%	68%	70%
±2.5		100%	80%	93%
±3			88%	99%
±3.5			93%	100%
±4			95%	
±4.5			98%	
±5			100%	

After the simulations were completed, the same method as the measurement part was used to analyze the data. In the following, the results of the defined scenarios are discussed in detail. It is good to mention that, as the noise maps which were created with the CATT-Acoustic software are based on the 1/1 octave bands, all the calculations and color maps in the following parts are reported for 125 Hz to 4 kHz octave bands.

4.2.1. Effects of the defined scenarios (number of the SMS loudspeaker, partition height, absorption and scattering coefficient)

The simulation results reveal that in the lower tolerances, there are more differences between the conditions. Therefore, to have a better comparison between the defined scenarios, the SPL variation for more than 90% of the positions are considered in each condition. Table. 6 presents the variations of the SPLs, when varying the number of the masking sound loudspeakers, the desk partitions' height and ceiling absorption and scattering properties. When looking at the result, for the condition that only one masking loudspeaker installed in the office, the SPL variation for both $L_{tot,a}$ and L_z is much more than the other conditions. For the $L_{tot,a}$, 90% of the points are within ±8.5 dBA and for the L_z the SPL variation fall in to the ±12 dB. By adding one more speaker the uniformity of the masking sound enhanced noticeably and the SPL variation for more than 90% of the space can be within ±3.5 dBA for the $L_{tot,a}$ and ±6 dB for the L_z . For the condition that the office has three speakers for the masking system, the SPL variation is much lower than the previous conditions. The variation for 90% of the points fall in to the ± 2.5 dBA range for the $L_{tot,a}$ and ±4 dB for the L_z . When looking at the current condition (four speakers in the office), for the $L_{tot,a}$ more than 90% of the points are within ±2 dBA, and when considering the L_z the tolerance is ±2.5 dB. By adding more speakers, the uniformity of the SMS has a slight improvement. When having seven speakers in the office, 90 percent of the positions can be within ±1 dBA, and considering SPL variation for the L_z, more than 90 percent of the positions fall into ±1.5 dB tolerance.

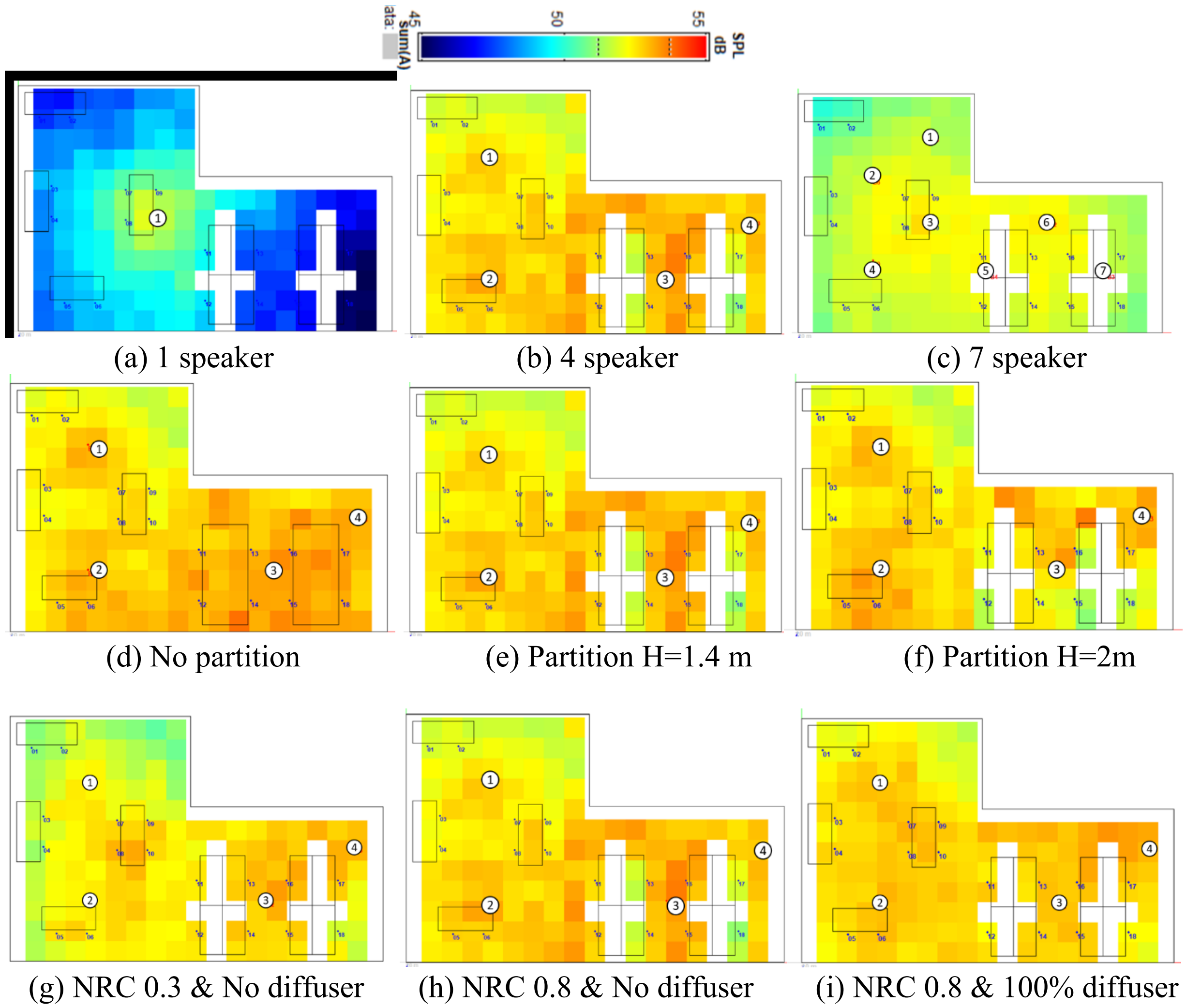
The simulation results for changing the partition height reveals that by having a lower partition the uniformity of the sound field improves and removing the partitions provide a more uniform sound field compare to the other conditions. However, for the partition with 1.4 m height and lower, the changes in the uniformity of the sound field is not noticeable. In all these conditions the SPL variation for more than 90% of the positions are less than ±2 dBA range for the $L_{tot,a}$ and ±3 dB for the L_z. Having higher partitions than 1.4m reduce the uniformity of the sound field, but there is not much different between 1.7m and 2m partitions height. In both of these conditions the SPL variation for more than 90% of the positions is within ±2.5 dBA for the $L_{tot,a}$ and less than ±6 dB for the L_z.

Comparing the results of the scenario which assess the effect of the ceiling absorption and scattering coefficient on the sound field, there is up to ±1.5 dBA improvement in the $L_{tot,a}$ variation and ±2.5 dB when considering the L_z, across 90% of the office space. The best condition which provide the least variation of the SMS across the space is for the condition that the NRC of the ceiling is 0.8 and the ceiling material was replaced by the diffuser. In this condition, more than 90 percent of the positions are within ±1 dBA range for the $L_{tot,a}$ and ±2 dB for the L_z. The results also show that by changing only the absorption coefficient of the ceiling, there is not much different in the SPL variation, when considering the $L_{tot,a}$. But, when comparing the SPL variation through the octave bands, a ceiling with NRC 0.8 can provide a more uniform sound field across the space.

Table 6. Effect of the varying loudspeaker numbers on 90 percent of the positions for the $L_{tot,a}$ and Lz for the frequencies from 250 Hz to 4 kHz

	Number of the positions		Tolerance	
	$L_{tot,a}$	L_z (250 – 4 kHz)	$L_{tot,a}$	L_z (250 – 4 kHz)
Number of loudspeakers				
1 speaker	106	106	±8.5	±12
2 speakers	107	107	±3.5	±6
3 speakers	108	111	±2.5	±4
4 speakers	109	116	±2	±2.5
5 speakers	109	108	±1.5	±2.5
6 speakers	112	112	±1.5	±2
7 speakers	106	110	±1	±1.5
Partition heights				
0 m	111	115	±1.5	±2.5
1.1 m	110	107	±1.5	±3
1.4 m	109	104	±2	±2.5
1.7 m	108	112	±2.5	±5
2 m	110	109	±2.5	±6
Ceiling				
NRC 0.3 + no diffuser	106	104	±2.5	±4
NRC 0.3 + 50% diffuser	111	108	±1.5	±4.5
NRC 0.3 + 100% diffuser	107	107	±1	±2
NRC 0.8 + no diffuser	109	104	±2	±2.5
NRC 0.8 + 50% diffuser	106	107	±1.5	±3
NRC 0.8 + 100% diffuser	106	107	±1	±2

In order to compare the $L_{tot,a}$ SPL distribution between the simulation results, Figure. 14 displays the color maps for the current condition, the least, and the most variation of the SMS across the space when changing each design parameter. The maps show a varying ±5 dBA color scale, includes the $L_{tot,a}$ value of the NRC-53 dBA for frequencies between 125 Hz to 4 kHz octave bands. For the condition that the SMS loudspeakers changed from one to seven, the sound distribute much more uniformly across the space. When changing the partition's height, the colormaps of the three conditions are almost similar, except for the positions around the desks with a partition (desks on the right side of the office). By removing the partitions, the sound in that area distributes more uniformly. But, when increasing the partition height to 2 m, the variation of the SPL around the desks with the partitions is more than the other conditions. Comparing the results of the condition that the ceiling absorption and scattering coefficient are changed, the color maps for the condition that the whole ceiling is covered with the sound diffuser with NRC 0.8, presents a more uniform sound field across the office space. Moreover, when the NRC value of the ceiling material is 0.8 the sound distributes more uniformly compare to the condition that the NRC is 0.3. Generally, when comparing all the colormaps, it can be seen that changing the number of the loudspeakers has more effect on the uniformity of the sound field, followed by increasing the scattering coefficient of the whole ceiling and removing the partitions. Moreover, the color maps present that the highest difference in the SPL value was typically observed between the points below the speakers (the yellow points with SPL of 53 dBA) and the points near the walls (the darker points with SPL of 51 dBA or less). This can be the result of the absorption of the walls which is more than the other materials of the office. Therefore, it can be concluded, one of the main factors which affect the variation of the SPL in the space is the absorption coefficient of the surrounding materials. As the SPL uniformity at the seated positions is more important than the other parts of the office, the location of the workstations should be selected in the area where the SPL variation be as low as possible. The points below the speakers are calibrated in a way to match the reference spectrum. By increasing the distance from the calibrated point, the variation of the SPL increases. Therefore, to locate the workstations, the position of the sound masking loudspeakers should be considered. Due to the color maps, in the open-plan office of this research, the SPL variation for the seated positions which are far from the walls is less than the other seated points. Therefore, by relocating the workstations from the sidewalls to the center part of the office (the area below the speakers), although the SPL uniformity of the whole space might not have a significant change, the SPL variation at the seated positions might be improved.



(a) 1 speaker (b) 4 speaker (c) 7 speaker

(d) No partition (e) Partition H=1.4 m (f) Partition H=2m

(g) NRC 0.3 & No diffuser (h) NRC 0.8 & No diffuser (i) NRC 0.8 & 100% diffuser

Figure 14. SPL distributions with physical parameters (loudspeakers, partitions' height and ceiling absorption & scattering properties)

4.3 Effect of parameters on speech intelligibility

In order to assess the effect of the uniformity of the sound field on the speech intelligibility, AI was calculated for each defined condition. If the AI value at the point right below the speaker considered as a target value, the deviation of the AI across the office area was evaluated by using a boxplot. From the calculation, the AI value at the point below the speakers is 0.22. By considering ±0.03 as a margin value, the percentage of the positions which are beyond this range (0.19 to 0.25) was calculated for each condition. In the following sections, the X-axis of the boxplot displays the variation of the defined physical parameters (loudspeakers, partitions' height and ceiling absorption & scattering properties), and the y-axis presents the AI range.

Figure. 15 shows the effect of varying loudspeaker numbers on the AI variation across the office area. A quick glance reveals when the SMS has only one speaker, the AI variation across the office is much more than the other conditions. In this condition, the AI value for only 12.8% of the positions can be between 0.19 and 0.25. By adding one to three speakers to the initial one, the percentage of the office area with the AI value within the defined range is 29.1%, 62.4% and 44.4% respectively. When the SMS has more than four speakers, the AI variation can improve. For the condition with 5 and 6 speakers, the AI value for 87.2% of the positions can be between 0.19 and 0.25, and by adding one more speaker, 94% of the area can achieve this range. Therefore, in order to have ±0.03 AI variation for more than 90% of the office area, beyond ±1 dBA deviation in the SMS should be avoided.

It is good to mention that the AI values which are far from the distribution happened at the points at the right corner of the office which is far from the speakers and surrounded by the wall, window and the desk partition.

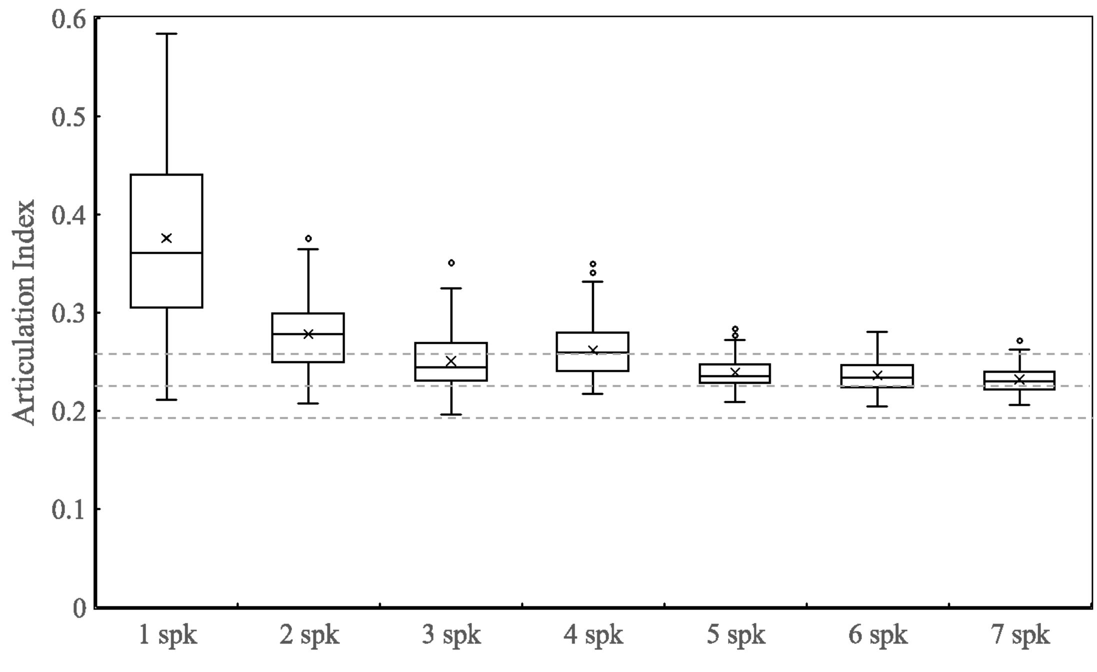


Figure 15. Effect of the number of the speakers on the speech intelligibility. The $L_{tot,a}$ variation of the SMS for 90% of the space for the condition with: (a) 1spk for SMS is ±8.5 dBA, (b) 2spk for SMS is ±3.5 dBA, (c) 3spk for SMS is ±2.5 dBA, (d) 4spk for SMS is ±2 dBA, and (e) 5spk for SMS is ±1.5 dBA, (f) 6spk for SMS is ±1.5 dBA, and (g) 6spk for SMS is ±1 dBA

Table. 7 shows the average, maximum (max) and minimum (min) AI value for changing the number of loudspeakers from 1 to 7. As can be seen, the difference between the max and min AI value for the condition with one speaker is 0.37 which is a wider range in comparison to the other conditions. By adding one more speaker the AI variation become less than 0.2 and when the masking sound has 5 or more speakers the AI variation become less than 0.1.

Table 7. Average, max and min AI value for varying number of loudspeakers from 1 to 7

	1 spk	2 spk	3 spk	4 spk	5 spk	6 spk	7 spk
Average	0.38	0.28	0.25	0.26	0.24	0.24	0.23
Max	0.58	0.38	0.35	0.35	0.28	0.29	0.27
Min	0.21	0.21	0.20	0.22	0.21	0.20	0.21
Max-Min	0.37	0.17	0.15	0.13	0.07	0.08	0.07

Figure. 16 display the effect of varying the partitions height on the speech intelligibility in this open plan office. As can be seen from the graph, when the partition's height changed from 0 to 1.1m, there is not much differences in the AI value. The reason might be due to the height of the mouth and ear of the seated person which is around 1.2m. Therefore, having a partition less than 1.2 m is not an efficient way to reduce the speech intelligibility. For the condition that desk partitions are removed, the AI value for 65.8% of the whole area can be between 0.19 and 0.25 and when the partition height is 1.1 m, 61.5% of the positions can achieve this range. By increasing the partition height to 1.4 m, the percentage of the positions within the defined range reduced to 44.4%. This percentage for the condition when the partition height is 1.7 m and 2 m is 37.6%, and 26.5% respectively. Therefore, changing the partition height can increase the AI deviation across the office area. It is good to mention that when the partitions have 2m height, the extreme values of AI happened at the points around the tables with the partitions.

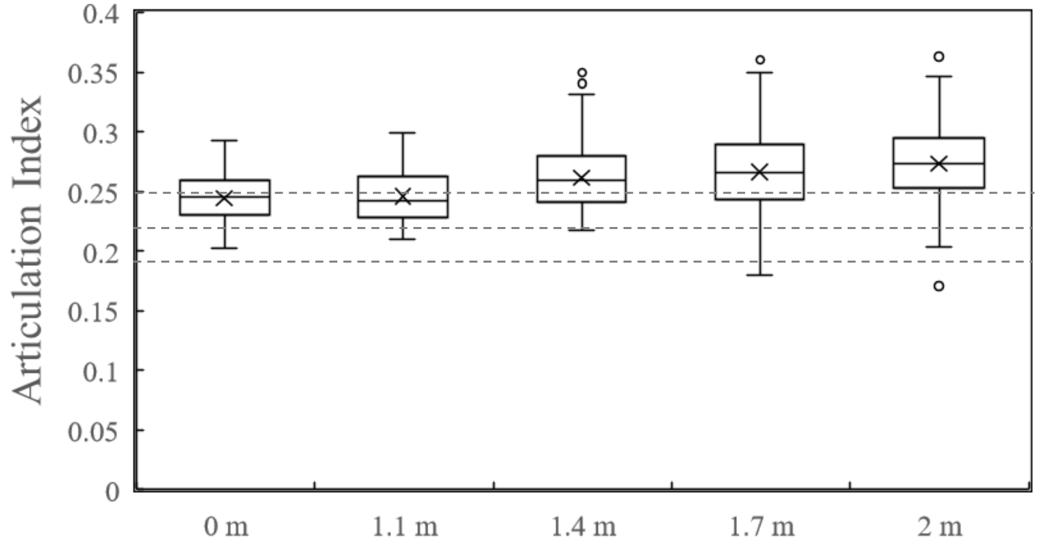


Figure 16. Effect of the partition height on the speech intelligibility. The $L_{tot,a}$ variation of the SMS for 90% of the space for the condition with: (a) No partition is ±1.5 dBA, (b) 1.1m partition height is ±1.5 dBA, (c) 1.4m partition height is ±2 dBA, (d) 1.7m partition height is ±2.5 dBA, and (e) 2m partition height is ±2.5 dBA

Table. 8 show the Average, max and min AI values for varying the partition height from 0 m to 2m. As can be seen, the average value for all the conditions are changed between 0.24 to 0.27 which is not a wide range. On the other hand, the difference between the max and min value of the AI varied from 0.09 for partition less than 1.1 m, to 0.2 for 2 m partition.

Table 8. Average, max and min AI value for varying the partition height from 0m to 2m

	0 m	1.1 m	1.4 m	1.7 m	2 m
Average	0.24	0.25	0.26	0.27	0.27
Max	0.29	0.30	0.35	0.36	0.37
Min	0.20	0.21	0.22	0.18	0.17
Max-Min	0.09	0.09	0.13	0.18	0.20

Figure. 17 displays the effect of varying the scattering and absorption coefficient of the ceiling on the speech intelligibility. As the graph shows, for the condition that the NRC of the ceiling is 0.3, when the ceiling has no diffuser, 53% of the office area can be between 0.19 and 0.25. This percentage when 50% of the ceiling has diffuser is 62.4%, and when the whole ceiling covered by the diffuser is 80.3%. When changing the NRC of the ceiling material to 0.8, the for the condition that the ceiling has no diffuser, only 44.4% of the positions can be within the defined AI range. By adding the diffuser to the 50% of the ceiling the percentage of the positions with the AI value between 0.19 and 0.25 is 60%, and when the whole ceiling is covered by the diffuser, 99% of the positions can be within the defined range.

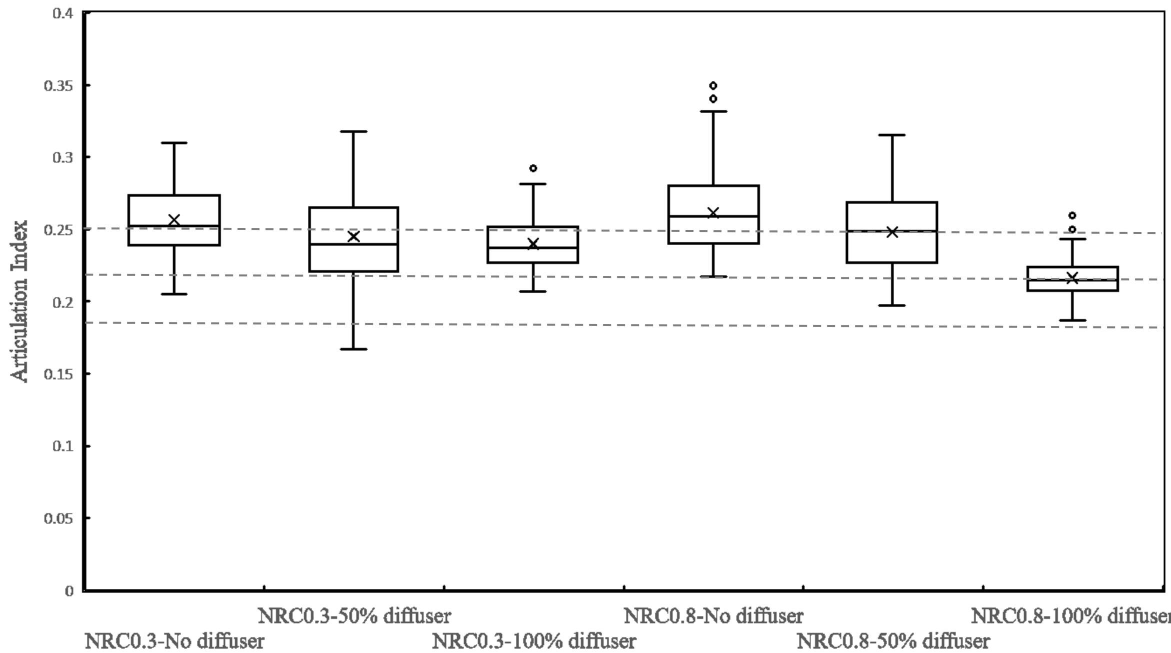


Figure 17. Effects of the scattering coefficient on the speech intelligibility. The $L_{tot,a}$ variation of the SMS for 90% of the space for the condition with: (a) NRC 0.3-no diffuser is ±2.5 dBA, (b) NRC 0.3-50% diffuser is ±1.5 dBA, (c) NRC 0.3-100% diffuser is ±1 dBA, (d) NRC 0.8-no diffuser is ±2 dBA, (e) NRC 0.8-50% diffuser is ±1.5 dBA, and (f) NRC 0.8-100% diffuser is ±1 dBA.

Table. 9 display the Average, max and min AI value for varying the ceiling absorption and scattering coefficient. As the results display, absorption coefficient of the ceiling material just has a slight influence on the AI variation across the space. But when changing the ceiling scattering coefficient, the difference between the max and min value of the AI can change from 0.15 to 0.07.

Table 9. Average, max and min AI value for varying the absorption and scattering coefficient of the ceiling material

	NRC0.3-No diffuser	NRC0.3-50% diffuser	NRC0.3-100% diffuser	NRC0.8-No diffuser	NRC0.8-50% diffuser	NRC0.8-100% diffuser
Average	0.26	0.25	0.24	0.26	0.25	0.22
Max	0.31	0.32	0.29	0.35	0.32	0.26
Min	0.21	0.17	0.21	0.22	0.20	0.19
Max-Min	0.10	0.15	0.09	0.13	0.12	0.07

4.4. Discussion

From the measurement, it was found that the variation of the SPL throughout the office space for the overall A-weighted SPL was within ±1.5 dBA while considering the SPL in each 1/3rd-octave band, the variation was not less than ± 4.5 dB. The simulation results for the current condition present a ±2 dBA tolerance for the overall A-weighted and ±3.5 dB range of SPL variation in the octave bands from 125 Hz to 4 kHz. In order to assess the parameters that can influence the spatial uniformity of the sound masking system, three scenarios were defined as follow: 1. changing the number of the SMS loudspeaker, 2. changing the partitions' height, 3. changing the absorption and scattering coefficient of the ceiling.

Among these parameters, changing the number of the SMS loudspeakers had the most influence on the uniformity of the sound field, followed by changing the absorption and scattering coefficient of the ceiling and the partitions height. However, even when the SMS had seven loudspeakers, although there were improvements in the results, the SPL variation for more than 90% of the space for the frequencies from 125 Hz to 4 kHz, fall into the ±1.5dB range through the octave bands and ±1dBA for the overall A-weighted SPL. It is good to mention that, in reality, most of the open-plan offices are much complicated than this model and so many other factors influenced the uniformity of the masking sound across the office space. Therefore, achieving a tight range for the SPL uniformity of the sound masking system could not be realistic in most of the open-plan offices. In this regard, more research should be done to find the necessity of defining tight tolerances and the effect of SPL variation of the masking sound on the speech privacy in open-plan offices. For instance, by walking through the space it can be found that if the listeners are able to find the location of the speakers, or if they are able to find a non-uniformity of the sound field in the space. Then, a proper solution can be conducted for those specific locations.

From the results of the simulation, the color maps present that the highest difference in the SPL value was typically observed between the points below the speakers (the yellow points with SPL of 53 dBA) and the points near the walls (the dark blue points with SPL of 51 dBA or less). This can be the result of the absorption of the walls which is, due to the Table. 2, more than the other materials of the office. Therefore, it can be concluded, one of the main factors which affect the variation of the SPL in the space is the absorption coefficient of the surrounding materials.

As the SPL uniformity at the seated positions is more important than the other parts of the office, the location of the workstations should be selected in the area where the SPL variation be as low as possible. The points below the speakers are calibrated in a way to match the reference spectrum. By increasing the distance from the calibrated point, the variation of the SPL increases. Therefore, to locate the workstations, the position of the sound masking loudspeakers should be considered. Due to the color maps, in the open-plan office of this research, the SPL variation for the seated positions which are far from the walls is less than the other seated points. Therefore, by relocating the workstations from the sidewalls to the center part of the office (the area below the speakers), although the SPL uniformity of the whole space might not have a significant change, the SPL variation at the seated positions might be improved.

By examining the speech intelligibility over the open-plan office, the acceptable spatial variation of the masking sound levels was achieved. The results indicate that when there is a higher variation in the sound field, the AI range change more. Therefore, it can be concluded a tight tolerance of the $L_{tot,a}$ SMS ensure that the AI value in the whole space remain almost constant and as a result the masking effect can be efficient across the office area. Generally, from the results of this study, it can be concluded that in order to have more than 60% of the positions within ±0.03 AI range, the variation of the sound field across the office area should be less than ±1.5 dBA, and to have more than 80% of the office area within ±0.03 deviation for the AI value, beyond ±1 dBA deviation in the SMS should be avoided. However, it is good to mention that, in reality, most of the open plan offices are much complicated than this model and so many other factors influenced the uniformity of the masking sound across the office space. Therefore, achieving a tight range for the SPL uniformity of the sound masking system could not be realistic in most of the open plan offices. In this regard, more research should be done to find the necessity of defining tight tolerances and the effect of SPL variation of the masking sound on the speech privacy in open-plan offices.

4.5. Summary

To evaluate the SPL uniformity of the masking sound, the results of the measurement and simulation for the overall A-weighted and unweighted SPL distribution for the frequencies from 125 Hz to 4 kHz were analyzed in this chapter. As the results display, when considering the overall A-weighted SPL, the maximum difference between the SPL of the positions is less than ±1.5 dBA in all conditions. However, when considering the SPL throughout the octave band frequencies, the results show a wider range of variation than the overall A-weighted SPL. There is ±3.5 dB variation in SPL across the office space for all the defined conditions. Moreover, the results indicate that when there is a higher variation in the sound field, the AI range change more. Therefore, a proper understanding of the variation in the sound field is clearly required when specifying spatial uniformity tolerances that sound masking systems should achieve.

5. Chapter five. Conclusion

5.1. Summary

Uniformity of the sound masking system has a vital role in the occupant's comfort and performance. However, due to the furniture, office layout and distribution of sound absorbers providing a uniform sound field in open-plan offices can be a challenge. ASTM E 1573-18 provides a method to evaluate the uniformity of the sound masking system, but, the maximum tolerance to achieve an acceptable SPL uniformity is not determined by this standard. This research is aimed to find out the achievable tolerance of the SPL variation of the sound masking system across the open-plan office. In this regard, after measuring the variation of the sound field across the workspace, three parameters that could have an effect on the uniformity of the sound masking system was evaluated by using the simulation. As a result, the percentage of the positions that can achieve a specific tolerance of the SPL variation for each factor was found. Moreover, by examining the speech intelligibility over the open-plan office, the acceptable spatial variation of the masking sound levels was achieved. Form the results of this study, it can be concluded that in order to have more than 60% of the positions within ±0.03 AI range, the variation of the sound field across the office area should be less than ±1.5 dBA, and to have more than 80% of the office area within ±0.03 deviation for the AI value, beyond ±1 dBA deviation in the SMS should be avoided.

5.2. Limitations

Although the measurement method was reliable and the simulation was almost precise, it is good to mention that each method has its limitations. In the measurement, the loudspeakers were not perfectly calibrated and there was up to 1 dB variation between the measured points right below the speakers. Moreover, as the measurement was done manually, it might not be conducted exactly in the same way for all the 117 positions. However, measurement seems to be the more accurate method compared to the simulation. In the simulation, the main source of uncertainty would be the details in the model, kind of materials and their absorption or diffusion coefficients.

When comparing the result of the measurement and simulation, it can be found that the results are not the same. The main reason for the deviation of the simulation results from the measurement might be the limitation of the CATT Acoustic software. CATT acoustic is based on the geometrical acoustic and the wave phase calculations are excluded. The limitation of this method is that the simulation results are only valid for the frequencies which are above the Schroeder frequency. In order to calculate the Schroeder frequency, reverberation time and the volume of the office were measured. From the measurement, the reverberation time for the open-plan office of this research is 0.3s and the volume of the office is $185.2m^3$. Therefore, Schroeder frequency is 80.49 Hz. Although for this office, the Schroeder frequency is lower than 250 Hz and the area of the big surfaces (e.g. floor, ceiling, and walls) are larger than the wavelength of the sound wave at 250 Hz frequency, due to the parallel surfaces, the reverberation time will likely be more than the value that a diffuse field method can predict. Therefore, in the simulation, Schroeder frequency would be more than the real value. Another reason for the difference between the measurement and simulation results is that the scattering coefficient of the big flat surfaces in the simulated model was defined as 0.1 in all the octave bands. However, in reality, some parts of the office might have a different scattering coefficient.

5.3. Future Research

The ASTM E1573-18 method [20], suggested that one measurement for every 93 m^2 can be enough to assess the uniformity of the sound masking system. On the other hand, the results of this study indicate that, the SPL variation was over small distances. It can be concluded from this research that a single point in this room cannot present the SPL variation throughout the whole office space. In this regard, continuing research should investigate the number of the required measured positions for evaluating the uniformity of sound masking systems in open-plan offices.

In addition, more studies are required to find out the tolerance limit and necessity of defining the tight tolerance for the SPL variation throughout the office space. In this regard, the subjective perception of the SPL uniformity of the masking systems should be investigated.

Furthermore, the results of this research show that the most variation throughout the workspace is between the points right below the speakers which are perfectly calibrated and the parts that are far from the speakers that cannot be covered in the speaker zone. Therefore, more research is required to identify the radius that each loudspeaker can be able to cover within a certain tolerance.

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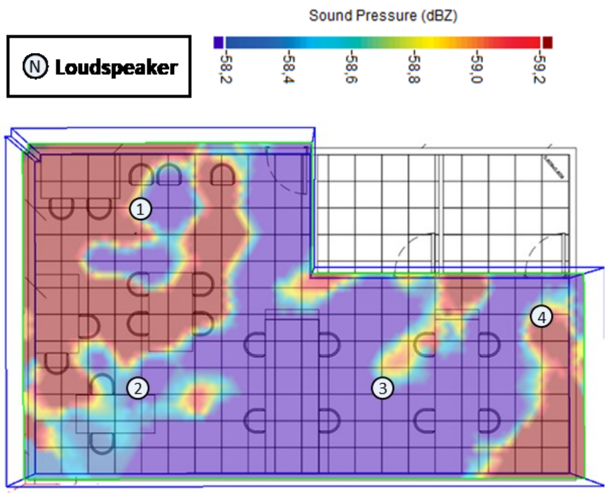
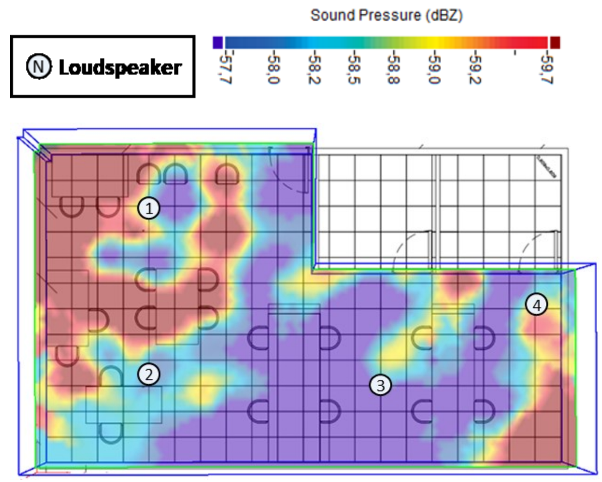
Appendix

A. Result of the measurement

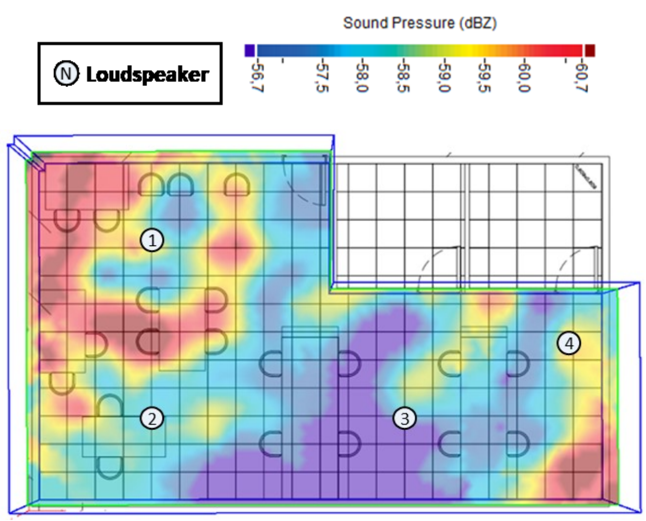
Sound pressure level distribution for 125 Hz to 4 kHz octave band frequencies



(a) ±0.5 dB tolerance

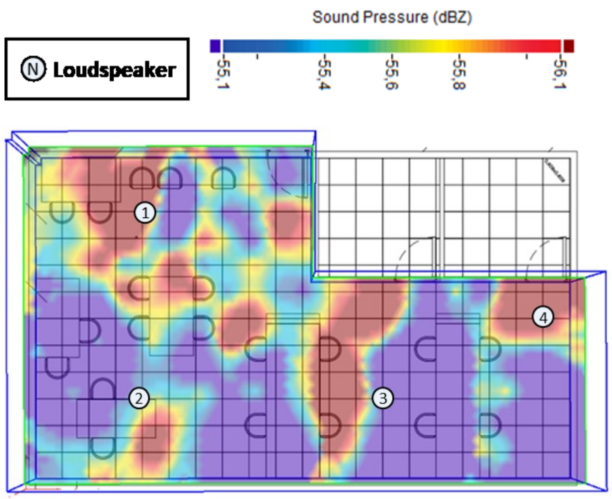


(b) ±1 dB tolerance

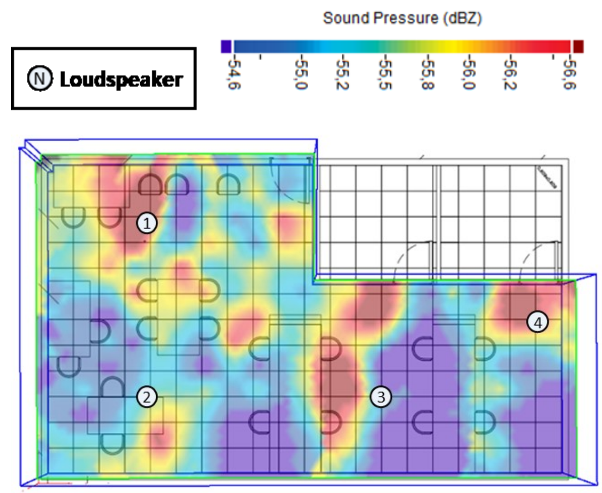


(c) ±2 dB tolerance

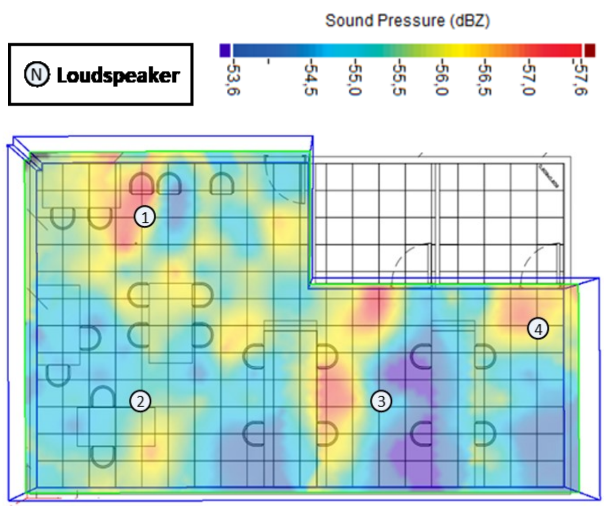
Figure 18. Sound pressure level distribution for 125 Hz using (a) 1 dB, (b) 2 dB and (c) 4 dB ranges



(a) ±0.5 dB tolerance

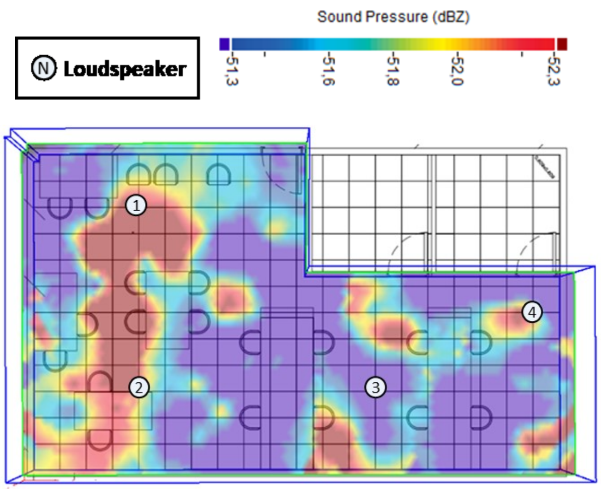


(b) ±1 dB tolerance

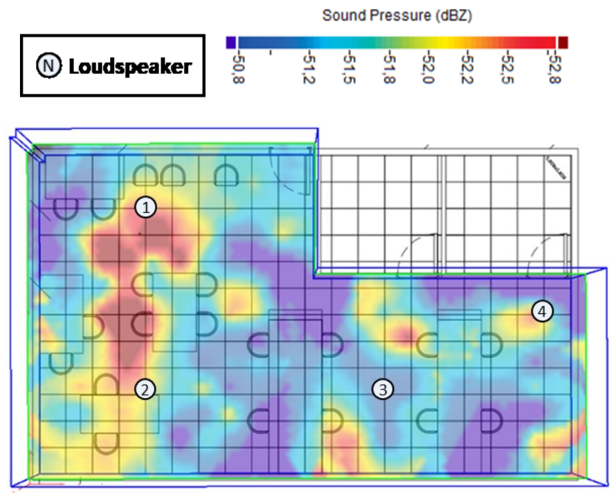


(c) ±2 dB tolerance

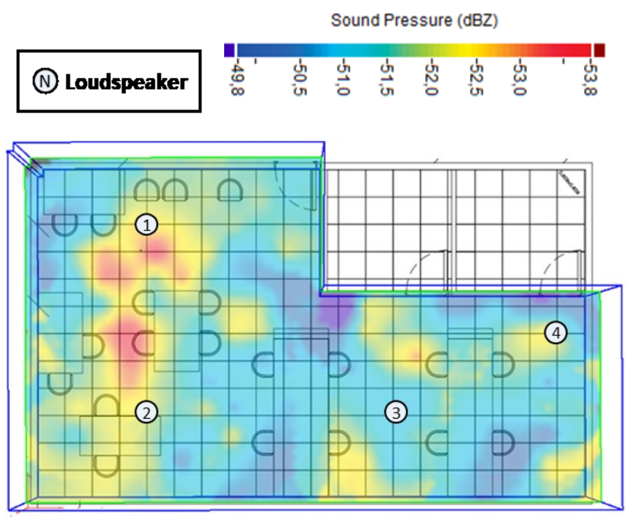
Figure 19. Sound pressure level distribution for 250 Hz using (a) 1 dB, (b) 2 dB and (c) 4 dB ranges



(a) ±0.5 dB tolerance

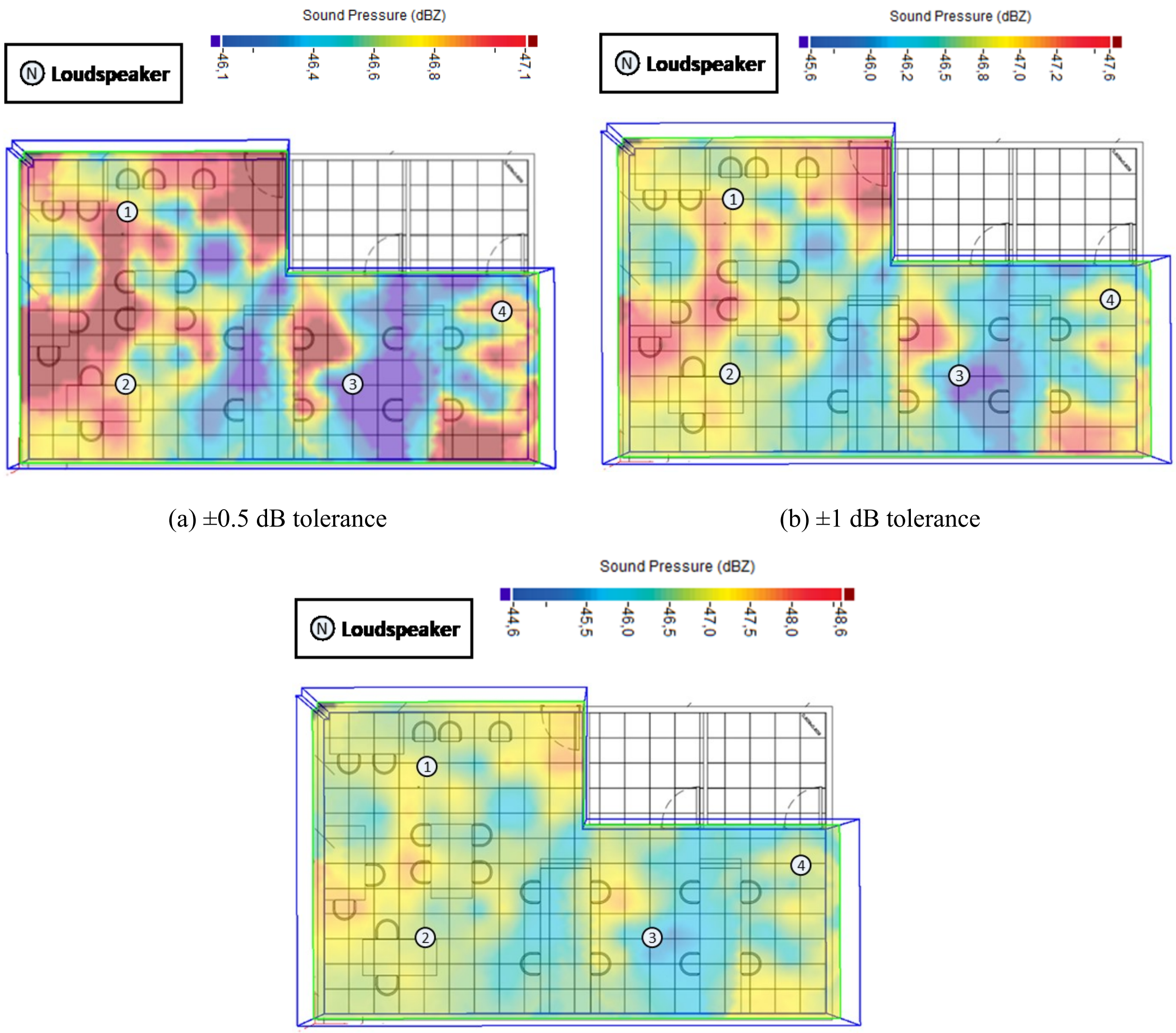


(b) ±1 dB tolerance



(c) ±2 dB tolerance

Figure 20. Sound pressure level distribution for 500 Hz using (a) 1 dB, (b) 2 dB and (c) 4 dB ranges

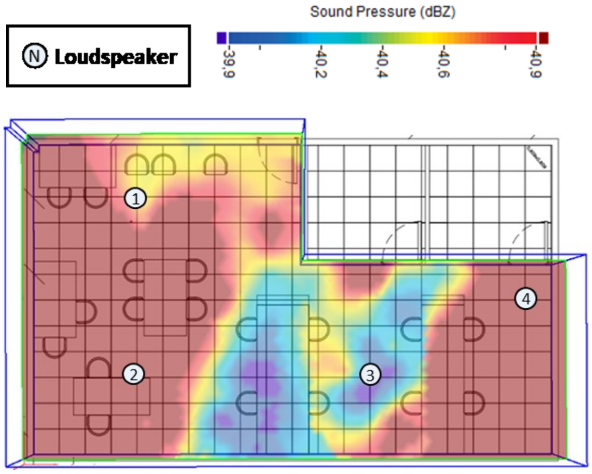


(a) ±0.5 dB tolerance

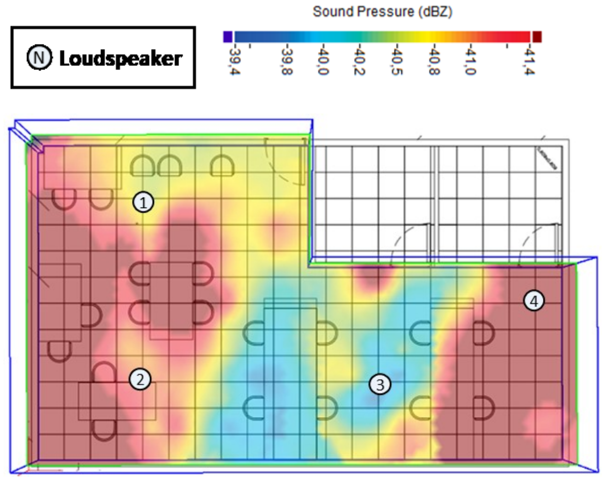
(b) ±1 dB tolerance

(c) ±2 dB tolerance

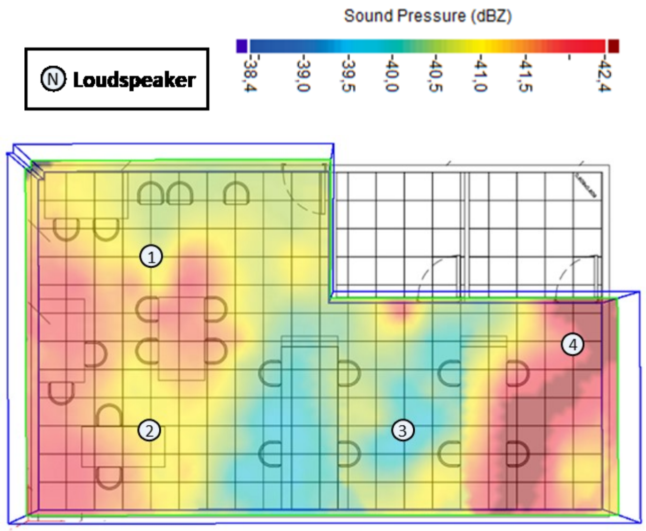
Figure 21. Sound pressure level distribution for 1000 Hz using (a) 1 dB, (b) 2 dB and (c) 4 dB ranges



(a) ±0.5 dB tolerance

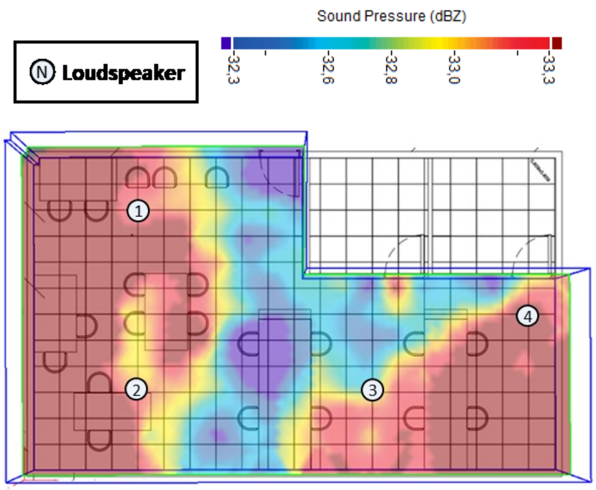


(b) ±1 dB tolerance

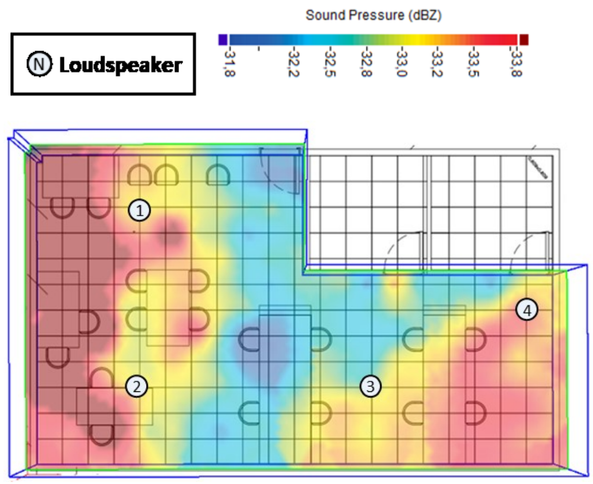


(c) ±2 dB tolerance

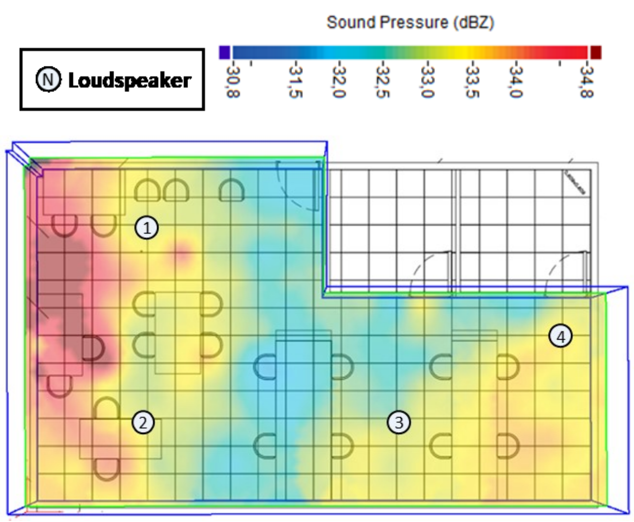
Figure 22. Sound pressure level distribution for 2000 Hz using (a) 1 dB, (b) 2 dB and (c) 4 dB ranges



(a) ±0.5 dB tolerance



(b) ±1 dB tolerance

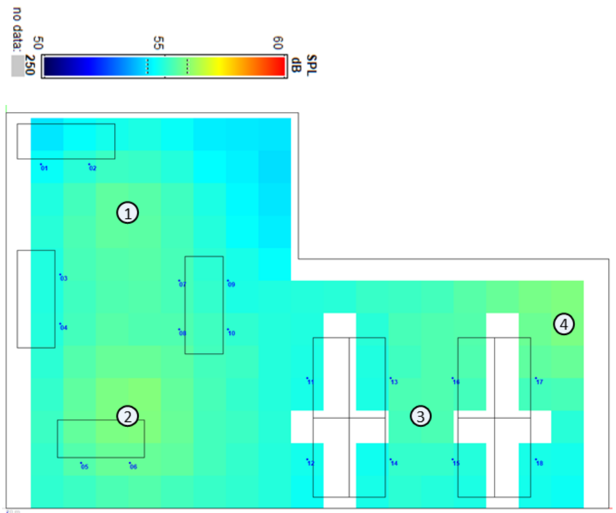


(c) ±2 dB tolerance

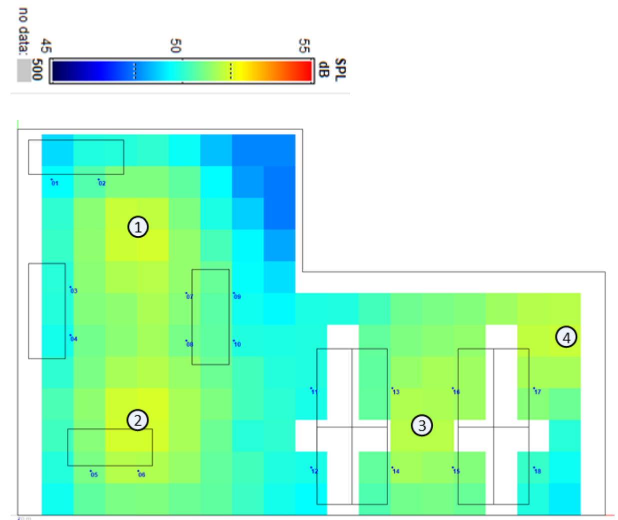
Figure 23. Sound pressure level distribution for 4000 Hz using (a) 1 dB, (b) 2 dB and (c) 4 dB ranges

B. Result of the simulation for the current condition

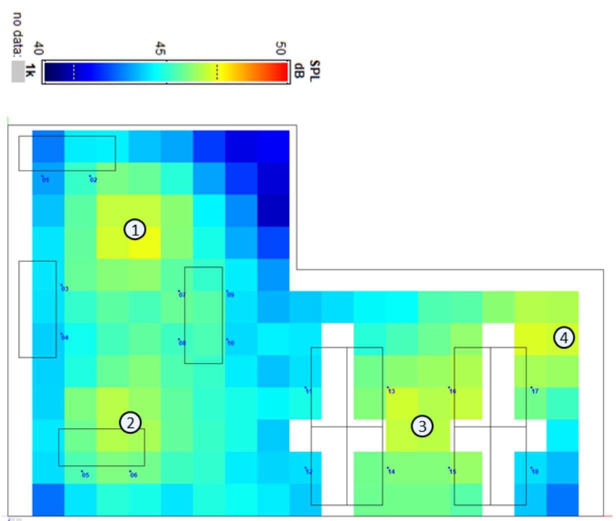
Sound pressure level distribution of the current condition for 125 Hz to 4 kHz octave band frequencies



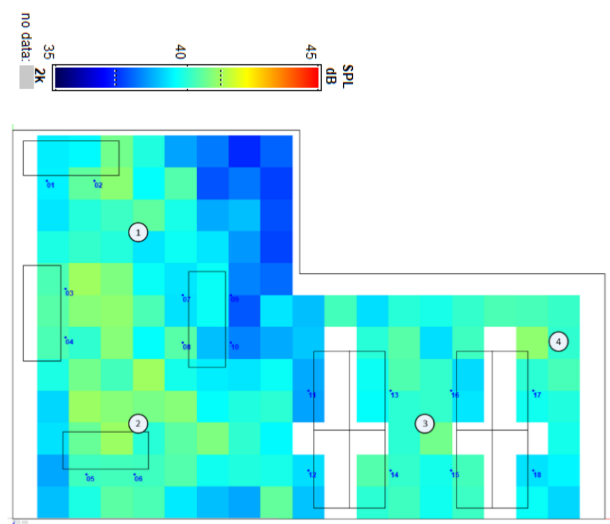
(a) Simulation results at 250 Hz



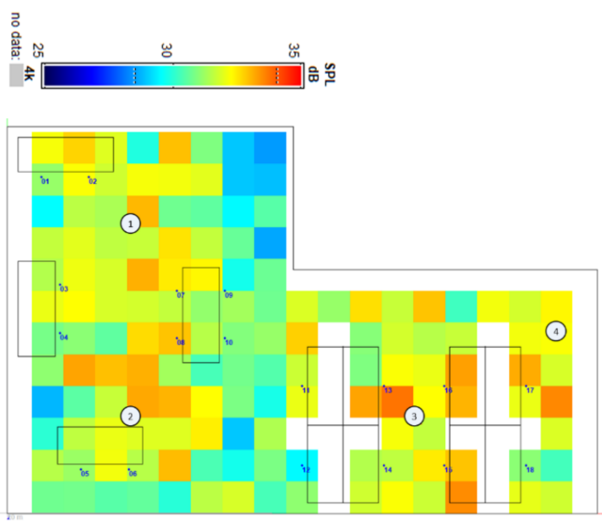
(b) Simulation results at 500 Hz (±2.5 dB tolerance)



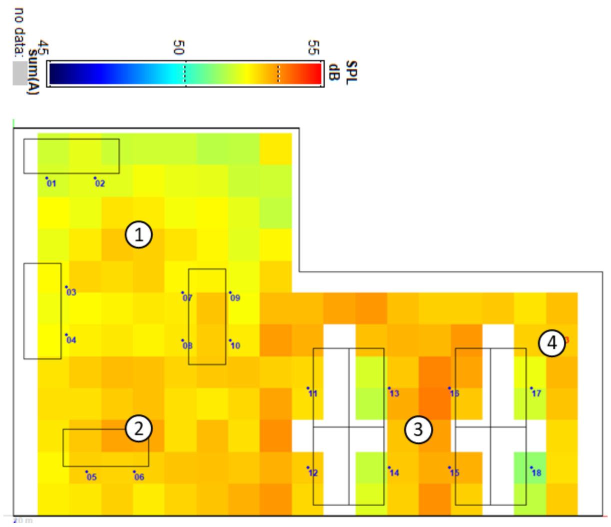
(c) Simulation results at 1k Hz (±2.5 dB tolerance)



(d) Simulation results at 2k Hz



(e) Simulation results at 4k Hz



(f) Simulation results in dBA from 125Hz - 4k Hz

Figure 24. sound pressure level distribution for the present condition using a 1/1 octave band frequencies from 125 Hz to 4 kHz and the overall A-weighted SPL

C. Calculation of the Schroeder frequency

The formula to calculate the Schroeder frequency is defined in the below equation [28]:

$$f_s = 2000\sqrt{\frac{T_{60}}{V}}$$

f_s (Hz): Schroeder frequency

T_{60} (s): Reverberation time

V (m^3): Volume of the room

From the information provided by the SoftdB office, the Reverberation time for this office is 0.3s and from the measurement the volume of this office is 185.2 m^3. Therefore, the Schroeder frequency of the office is achieved from the below equation:

$$f_s = 2000\sqrt{\frac{0.3}{185.2}} = 80.49\ Hz$$

D. Sample calculation for the percent of the measured positions within a certain tolerance for the 1/3rd-octave band SPL from 100 Hz to 5 kHz frequencies

1. Importing the SPL at frequencies from 100 Hz to 5 kHz for each measured position

Table 10. SPL of the positions for the frequencies from 100 Hz to 5 kHz

Frequency	100	125	160	200	…	2000	2500	4000	5000
NRC-53 dBA	54.9	53.9	52.7	51.9	…	35.4	32.9	30.4	27.4
Position	Lzeq 1/3rd octave bands								
1	57.3	55.4	53.6	53.7	…	36.3	32.9	32.2	28.9
2	58.3	55	52.5	52.5	…	37.9	34.1	32.2	31
3	53.2	57.6	52.5	53.2	…	36.3	34.6	32.7	29.8
…	…	…	…	…	…	…	…	…	…
117	52.7	53.1	51.8	55.6	…	35.5	32.7	30.1	28.2

2. Finding the difference between the SPL of the measured point and NRC-53 at each 1/3rd-octave band frequency

Table 11. Difference between the SPL of the measured points and NRC-53 dBA

Frequency	100	125	160	200	…	2000	2500	4000	5000
Position	difference between LZeq 1/3Oct and NRC 53 dB								
1	2.4	1.5	0.9	1.8	…	0.9	0	1.8	1.5
2	3.4	1.1	-0.2	0.6	…	2.5	1.2	1.8	3.6
3	-1.7	3.7	-0.2	1.3	…	0.9	1.7	2.3	2.4
…	…	…	…	…	…	…	…	…	…
117	-2.2	-0.8	-0.9	3.7	…	0.1	-0.2	-0.3	0.8

3. Finding the maximum difference between the SPL of the measured points and NRC 53 dB for each position, through all the defined frequencies.

Table 12. Maximum differences between the SPL of the measured points and NRC-53 dBA

Maximume difference between LZeq 1/3Oct and NRC 53 dB for each point from 100 Hz to 5k Hz	
1	2.80
2	3.60
3	3.70
…	…
117	3.70

4. Finding the number of positions within a certain tolerance, using this formula in Excel:

=SUMPRODUCT(-(ABS(selecting all the maximum differences values)<=(tolerance range(e.g. 0.5))))

Table 13. Number of positions within a certain tolerance

tolerance	number of positions
±0.5 dB	0
±1 dB	0
±1.5 dB	3
…	…
Until all the measured points are within this tolerance	117 (number of the measured positions)

5. Finding the percent of the positions within a certain tolerance, using this formula in Excel:

=(number of the positions within the specified tolerance)/(number of all the measured positions)*100

Table 14. Percent of the positions within a certain tolerance

tolerance	Percent of positions
±0.5 dB	0
±1 dB	0
±1.5 dB	3%
…	…
Until all the measured points are within this tolerance	100%

E. Sample calculation for the percent of the measured positions within a certain tolerance for the overall A-weighted SPL for the frequencies from 100 Hz to 5 kHz

1. Applying the A-weighted corrections for each measured SPL at each frequency from 100 Hz to 5 kHz

Table 15. A-weighted SPL at each frequency from 100 Hz to 5 kHz

A-Weighting correction	-19.5	-16.6	-13.7	-11.2		1.5	1.5	1.4	1.0
frequency	100	125	160	200	…	2000	2500	4000	5000
Position	LAeq 1/3rd octave bands								
1	37.9	38.8	39.9	42.5	…	37.8	34.4	33.6	29.9
2	38.9	38.4	38.8	41.3	…	39.4	35.6	33.6	32.0
3	33.8	41.0	38.8	42.0	…	37.8	36.1	34.1	30.8
…	…	…	…	…	…	…	…	…	…
117	33.3	36.5	38.1	44.4	…	37.0	34.2	31.5	29.2

2. Calculating the overall A-weighted SPL for each position, using this formula in Excel:

=10*(LOG(((10^(A-weighted SPL at 100 Hz/10)) +(10^(A-weighted SPL at 125 Hz /10))+(10^(A-weighted SPL at 160 Hz /10))+ … +(10^(A-weighted SPL at 5000 Hz /10)))))

Table 16. overall A-weighted SPL for each position

Position	Overall A-weighted SPL
1	52.55
2	52.86
3	52.65
…	…
117	51.88

3. Finding the difference between LAeq and NRC 53 dBA at each position

Table 17. difference between LAeq and NRC-53 dBA at each position

Position	Overall A-weighted SPL	NRC-53	difference between LAeq and NRC 53 dBA
1	52.55	52.68	-0.13
2	52.86	52.68	0.18
3	52.65	52.68	-0.04
…	…		
117	51.88	52.68	-0.81

4. Finding the number of positions within a certain tolerance, using this formula in Excel:

=SUMPRODUCT(--(ABS(selecting all the difference values between LAeq and NRC 53 dBA)<=(tolerance range(e.g. 0.5))))

Table 18. number of positions within a certain tolerance

tolerance	number of positions
±0.5 dB	78
…	…
Until all the measured points are within this tolerance	117 (number of the measured positions)

5. Finding the percent of the positions within a certain tolerance, using this formula in Excel:

=(number of the positions within the specified tolerance)/(number of all the measured positions)*100

Table 19. percent of the positions within a certain tolerance

tolerance	Percent of positions
±0.5 dB	67%
…	…
Until all the measured points are within this tolerance	100%