**Title**

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

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**Abstract**

Many open-plan offices adopt an electronic sound masking system in order to reduce distraction from background noises, primarily intruding speech. Sound masking systems should uniformly generate a masking sound over the entire office area to homogenize the speech privacy whilst minimising occupant perception of the masking sound. This study evaluates the spatial uniformity of the masking sound field in an example open-plan office, where the masking system was set up to represent supposedly optimal installation conditions; 1-speaker zones, individually-calibration of each zone to match the specified curve precisely, and smaller zones than typically specified. Sound level measurements performed as per ASTM E1573-18 were made at each workstation, as well as every 0.6 m across the office, for a total of 117 measurements. Measurement results show that tolerance of ± 0.5 dB for the overall A-weighted level is only achievable at 61% of measurement locations, whilst ± 1 dB is achievable at 99% of locations. For one-third-octave band sound pressure levels between 250 Hz to 4 kHz, ± 2 dB is achieved only 55% of the time, and tolerance of ± 3.5 dB is required to achieve 95% compliance with the specified curve. By using calibrated computer simulations, the study also examined parameters that can influence spatial uniformity in open-plan offices. It was found that the number of sound masking loudspeakers, partition height, and the scattering and absorption coefficient of the ceiling all affect the uniformity of the masking sound. Speech intelligibility was assessed by calculating the Articulation Index (AI) to determine an acceptable tolerance for masking sound variation. Increasing the number of loudspeakers was the most effective way to improve the uniformity of the masking sound. The AI results suggest ±2 dB, when including octave band sound pressure levels, is a minimum required tolerance for a sound masking sound field in an open office to provide AI values within ±0.1 of the targeted value across the office area.

**Keywords**

Open-plan office, Sound-masking system, Spatial uniformity, Speech intelligibility

**Abbreviations**

AI: Articulation Index

HVAC: heating, ventilation, and air conditioning

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

$L_Z$: unweighted octave band sound pressure level

NRC: Noise Reduction Coefficient

SPL: sound pressure level

## 1. Introduction

Open-plan offices have been widely adopted in modern commercial workspace design to encourage communication and collaboration between workers [1]. However, open-plan designs can have a negative impact on employee performance and satisfaction due to disruptive ambient noise, typically unwanted speech comprehension, as well as a lack of speech privacy for their own conversations [2–5]. Since the noise from heating, ventilation, and air conditioning (HVAC) systems is hard to predict and can be highly variable spatially, sound-masking systems have become one of the most common techniques of controlling background sound levels in open-plan offices. A sound-masking system emits an electronic broadband sound with a sound level and spectrum optimized to balance speech privacy with acoustic comfort. The broadband sound 'masks' distracting speech or noise and, in turn, reduces audible distractions and increases the productivity of workers [6,7].

One of the most important factors in designing an efficient sound-masking system is creating a uniform masking sound field across a workspace [8]. The sound masking system should uniformly generate the masking sound over the entire office area by precise system design and calibration. When the masking sound is not uniform throughout the office, uneven sound pressure level (SPL) can be disruptively loud in some areas, while distracting noises and speech are not sufficiently masked in the other areas.

The spatial uniformity of the masking sound can be quantified in terms of the variance of SPLs across a defined space. ASTM E1573-18 [9] provides a method for measuring the masking sound SPLs in open-plan offices but does not address the spatial uniformity of the sound field. ANSI/ASA S12.72 [10] presents a method for assessing whether the sound field from continuous steady sound in a space is "spatially constant," i.e., spatially uniform, which it defines as the measured sound levels at multiple locations in the space not varying by more than ± 3 dB.

Under ASTM E1573-18, A-weighted SPL ($L_{tot,a}$) and unweighted one-third-octave band SPL ($L_z$) values measured at several locations are to be compared with the target spectrum from system specifications rather than achieve a defined range that represents spatial uniformity. The presumption is that specifications will contain the permissible tolerances (deviations) from both the target A-weighted level and the 1/3$^{rd}$ octave spectrum that are realistic considering the variation of an ideal sound field laid down by a sound masking speaker array and the natural influence of office furnishings and architecture on this sound field. ASTM E1573-18 offers no guidance as to the acceptable tolerances from a specification that could represent the achievement of spatial uniformity. Recently, there has been a trend of stipulating tight tolerances (as low as ±0.5 dB) for spatial variation in sound-masking system product specifications, without presenting measurement data showing this level of spatial uniformity from a masking system in real-world office conditions is possible at all workstations, rather than just at prescribed locations (directly under the speaker, or hallway between speakers, for example).

There are a number of factors that can affect the spatial uniformity of the masking sound in a real-world office, including loudspeaker location and directivity, the number of loudspeakers, ceiling types, the height of furnishings including dividing screens, the quantity and location of sound absorptive and diffusive surfaces as well as the existing residual noise from the HVAC equipment [11] or traffic noise ingress. Bradley [12] used acoustic simulation software to evaluate the effects of office design parameters on speech privacy. Among the parameters, ceiling absorption and height and size of the partitions were found to be the most influential in efforts to achieve acceptable levels of speech privacy. In most open-plan offices, loudspeakers are placed in the plenum above the suspended ceiling.

L'Espérance et al. [13] compared the spatial uniformity of the sound fields radiated by a surface-mounted masking system and a plenum-mounted masking system. The study showed that the plenum-mounted masking system could provide more uniform distribution (up to 2 dB) than the other throughout the office space because it radiates masking sound indirectly through the ceiling material. However, the manner in which, and the extent to which, the other variables affect the sound masking field uniformity in real-world open-plan offices has not yet been fully characterized.

To build on previous scholarship and address this gap in the literature, the aim of this study is to evaluate the sound masking field in a real office under idealized conditions (including small speaker spacings and precise calibration) and its effect on speech privacy. The test site was an 18-person, 68.5 $m^2$ open-plan office in Montréal, Canada. The measurement was carried out across the entire accessible office surface, with a resolution grid of 0.6 m × 0.6 m to determine spatial variations of sound-masking levels across the office space. This study also examines the parameters that can influence the spatial uniformity in the open-plan office using a computer-aided simulation. Articulation Index (AI) was utilized to examine speech intelligibility over the open-plan office space to propose an acceptable spatial variation of sound-masking levels.

## 2. Methodology

The acoustic measurements were carried out in order to investigate the spatial uniformity of the masking sound. A room acoustic simulation was implemented with the obtained data to investigate how three physical parameters (the number of sound-masking speakers, the partition height, and the ceiling's scattering and absorption properties) affect the spatial uniformity of the masking sound.

### 2.1. Test Site and Installation of the Sound Masking System

The measurement was carried out in an open-plan office located in Montréal, Canada. The L-shaped open-plan office studied has a floor area of approximately 68.5 m$^2$ with a height of 2.7 m. Figure 1 illustrates a schematic plan of the office.

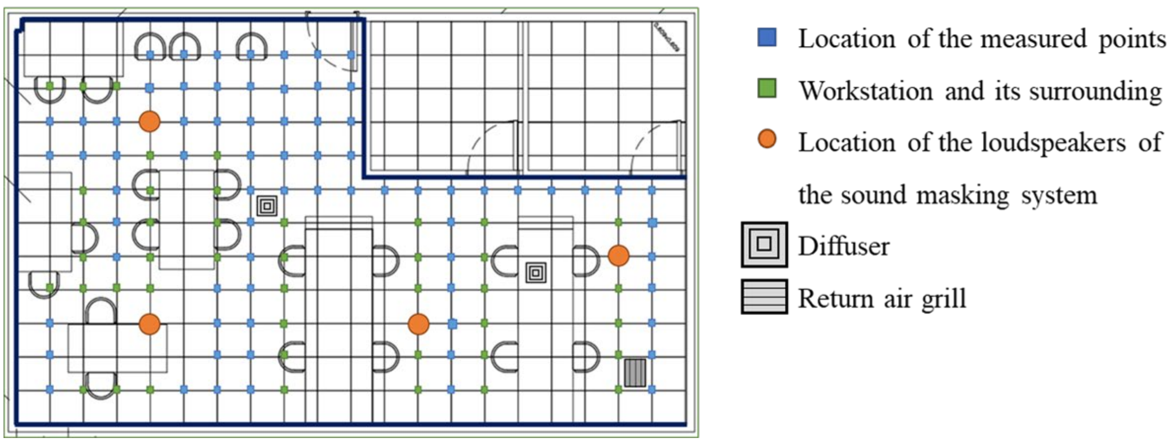



*Figure 1. The layout of the open-plan office, including the location of the loudspeakers, measured points, air diffusers, and air return grille*

The masking system consisted of four loudspeakers suspended facing upwards within the ceiling plenum above the suspended glass-fibre ceiling. The system design incorporated a higher concentration of loudspeakers than would typically be found in a room of this size, and 1-speaker per zone (i.e., an independent spectrum and level emanating from each speaker) that would not normally be specified for such a relatively small area. The intention was to have as near a perfect sound masking field as could be generated. The location of both plenum ventilation obstructions and return-air grills (which should be distant from the loudspeakers to avoid elevated sound levels below them) prevented a precisely equidistant speaker layout; this would also be the case in a real-world office. The system was calibrated for the CNRC optimized masking spectrum [12] but set to a higher than normal $L_{tot,a}$ of 53 dB to minimize the influence on the ambient sound level of the building's HVAC system, which could not be disabled during the measurement session. The calibration data is presented in Table 1.

*Table 1. Calibration results at the points below the loudspeakers (spk) and the differences between the target value (following CNRC-53 spectrum) and the measured values*

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

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| $L_{tot,a}$ | 53.36 | 52.94 | 53.18 | 52.78 | 52.68 | 0.7 | 0.3 | 0.5 | 0.1 |

In order to calibrate each loudspeaker, a fixed-point calibration method was used. Each loudspeaker was calibrated to have the targeted spectrum SPL at the location directly below the loudspeaker and the height of 1.2 m above the floor. The calibration was repeated three times, and the difference between the reference spectrum and the SPLs below the four loudspeakers was found to be less than 1 dB for all one-third octave band SPLs.

### 2.2. Measurement Method

One hundred-seventeen locations were measured in order to evaluate the spatial uniformity of the masking sound levels across the office. The distance between the measured points was found to be 0.6 m, except the locations where furniture with the potential to cause significant reflections was within 1 m of the measurement position [9]. A class-1 Mezzo Precision sound level meter (SLM) was used for the measurement and calibrated before and after the measurement, with no significant change in microphone sensitivity. A broad set of data, including the equivalent, maximum, minimum, and statistical SPLs, was obtained. The measurement procedure followed the stipulations of ASTM E1573-18 [14].

Prior to the spatial uniformity measurement, the background noise level of the office was measured. The sound masking system was then activated and, the sound power level outputs of the loudspeakers were calibrated accordingly to match the optimal CNRC masking spectrum [12]. Figure 2 presents the average SPL of the background noise and masking sound. 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 HVAC system cannot be turned off during the measurement, the SPL with masking loudspeaker was raised to overall $L_{tot,a}$ of 53 dB 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 $L_{tot,a}$ of the sound masking system in open plan offices is between 42 to 48 dB [15]. Some locations near the air diffuser and return grill still failed to achieve the minimum 10 dB difference due to the HVAC noise. Totally, 40 points were influenced by the background noise; therefore, only 77 positions are considered for analysis. Figure 2 presents the average SPLs of the background noise (ambient) and the masking sound level.

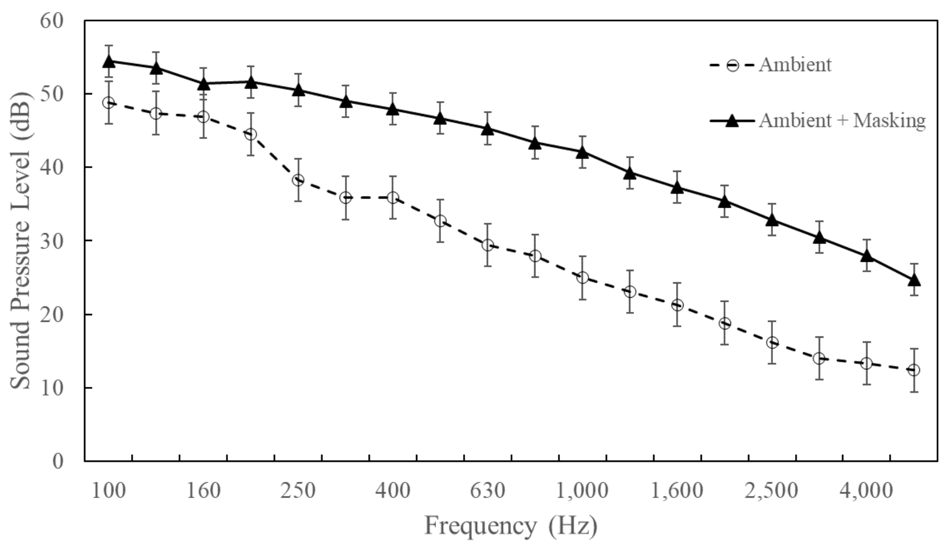



*Figure 2. Average SPL of the whole space without masking sound (ambient) and with masking sound (ambient + masking)*

After calibrating the loudspeakers, the SPLs were measured at 117 locations over the open-plan office. At each location, the SPL was measured while sweeping the SLM for 10 seconds around a circle of 1 m radius centered on the location. The SLM's microphone was positioned at 45 degrees above the horizontal plane. The height of the microphone, meanwhile, was set at 1.2 m, which is the typical 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. Once the measurement had been completed, in order to gain an understanding of how the masking sounds were distributed across the office space, noise maps were generated using RAP-ONE II room acoustic modelling software developed by Soft dB. The program can generate experimental sound maps from measured data using the Kriging interpolation [16].

### 2.2. Acoustic Simulation

The simulation was carried out using commercial acoustic simulation software, CATT Acoustic v9.1e [17], chosen due to its ability to include scattering coefficients and speaker directivity. The program utilizes a combination of an image source method and ray-tracing to accurately simulate the acoustic property of the space. Figure 3 illustrates the 3D geometric model of the office, including layout, the location of the loudspeaker, and the workstations, with the geometry of the open-plan office simplified based on a cut-off dimension of 50 cm for computational efficiency.

*Table 2 Absorption coefficients of the materials used in the open-plan office simulation model*

| Element | Material | Absorption coefficient (%) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 125Hz | 250Hz | 500Hz | 1kHz | 2kHz | 4kHz |
| 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 |
| Windows (interior) | double glazing, 2-3 mm glass, 10 mm gap | 10 | 7 | 5 | 3 | 2 | 2 |
| Windows (exterior) | 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 (double-sided) | 10 | 35 | 50 | 55 | 70 | 70 |

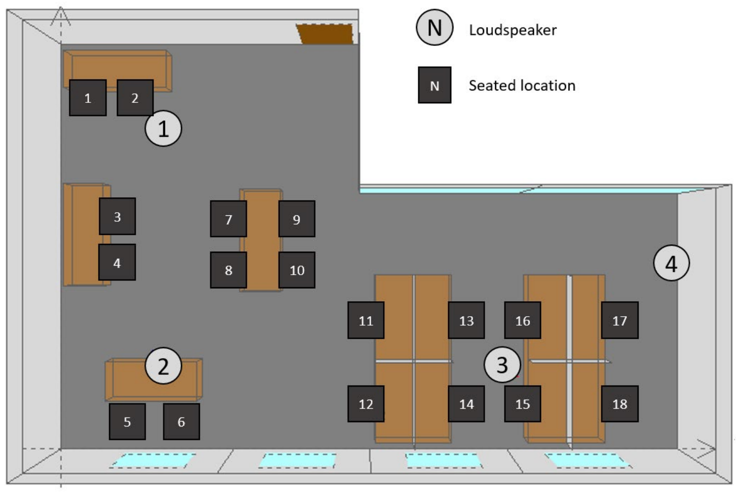



*Figure 3. The three-dimensional model of the open-plan office layout and the locations of the sources and workstations*

For each surface, a sound absorption coefficient was defined based on the actual material as described in the Physikalisch-Technische Bundesanstalt (PTB) database [18]. Table 2 presents the material and absorption coefficient information used in the simulation model. A frequency-independent scattering coefficient of 10% was used for the large and flat surfaces, including the walls, floor, structural ceiling, and suspended ceiling. The directivity, orientation, and dimensions of the speakers in the simulation matched exactly those of the loudspeaker actually used in the experiment.

The ceiling plenum where the loudspeakers were placed consisted of unpainted concrete and 16mm Armstrong acoustic ceiling tiles. The loudspeaker was suspended 0.8 meter below the plenum ceiling and aimed upward to a concrete deck. The height of the plenum was 0.9 m. The transmission coefficient for the ceiling material was assigned according to the manufacturer's specification. The average of the coefficients from 125 Hz to 500 Hz octave bands was 0.35. No transmission was specified for the partition. The absorption coefficients

The sound power levels of the speakers in the CATT model were defined in the same manner as the calibration procedure during the measurement, having the sound spectrum at the location directly below the speaker follows the reference spectrum of octave bands ranging from 125 Hz to 4 kHz. The differences between the SPL at the location directly below the speakers and the reference spectrum were less than 0.5 dB across all the defined octave bands. After calibrating the loudspeakers, the SPLs at the 117 locations as designated in the measurement were simulated.

Three physical parameters were investigated to gain insight as to the manner in which and the degree to which they influence the spatial uniformity of the masking sound field. First, the number of loudspeakers was adjusted from one to five. The locations of the loudspeakers in each condition were selected in such a way as to cover the greatest possible proportion of the space. The effect of partition height on spatial uniformity was also analyzed. Five different heights (0 m, 1.1 m, 1.4 m, 1.7 m, and 2 m) were used for the acoustic simulation. Lastly, the absorption and scattering characteristics of the ceiling surface were manipulated in order to study the effect on the masking sound field of altering these parameters. In this regard, a more uniform masking sound field was expected when a more diffusive ceiling panel was used. The five different ceiling combinations of scattering and absorption conditions were configured as follows: (1) Noise Reduction Coefficient (NRC) 0.3 absorption tiles and 0% RPG diffusive ceiling panels, (2) NRC 0.3 absorption tiles and

RPG diffusive panels with 50% coverage of the ceiling, (3) NRC 0.8 absorption tiles and 0% RPG diffusive ceiling panels, (4) NRC 0.8 absorption tiles and RPG diffusive panels with 50% coverage of the ceiling, and (5) RPG diffusive panels with 100% coverage of the ceiling.

In the defined conditions, the scattering coefficient of the ceiling was changed based on an actual acoustic diffuser (Waveform Harmonix-K) [19]. To assess the effect of the ceiling absorption coefficient on the sound field, a 0.8 NRC value of the acoustic ceiling tile (ACT) and a 0.3 NRC value of Waveform Harmonix-K were considered for this scenario. For the condition in which 50% of the ceiling is covered by the diffuser, the diffuser was located at the center of the ceiling. For the acoustic simulation, only the defined parameter for room side was modified, while the other conditions remained the same (including the coefficients for plenum side), and the sound power of the loudspeaker was calibrated before the simulation.

In order to evaluate the effect of the uniformity of the sound field on speech intelligibility in an open-plan office, the AI was calculated. AI is a metric to predict speech intelligibility using the difference between one-third octave band SPLs of standard speech and given background noise spectra. The CNRC-48 curve ($L_{tot,a}$=48 dB) was used for the background noise spectrum in this study. The calculation procedure is standardized in ASTM E1130-90 [20]. In our simulation, the normal speech spectrum of a male was used for the AI calculation, where a speech source was assumed to be located at an adjacent workstation. $L_{tot,a}$ of the reference male speech spectrum and the spectrum used at a given receiver were 59.5 dB and 54.3 dB, respectively. Hence, the constant level of the speech spectrum and varying levels of background noise due to spatial variations were assumed for the AI calculation.

## 3. Results and Discussion

### 3.1. Spatial Uniformity

Table 3 presents the percentage of the 77 measured locations that fall within the corresponding tolerance class (with increments of 0.5 dB). The tolerance was determined based on the incremental range (plus and minus) from the reference spectrum and corresponding overall A-weighted SPL of 53 dB.

*Table 3. Percentages of measured locations, where the SPLs are within specified tolerances (in dB) relative to the targeted sound levels as determined using (1) overall A-weighted SPL ($L_{tot,a}$) only and (2) unweighted one-third octave band SPLs ($L_z$) ranging from 250 Hz to 4 kHz, and where the total number of measured locations is 77.*

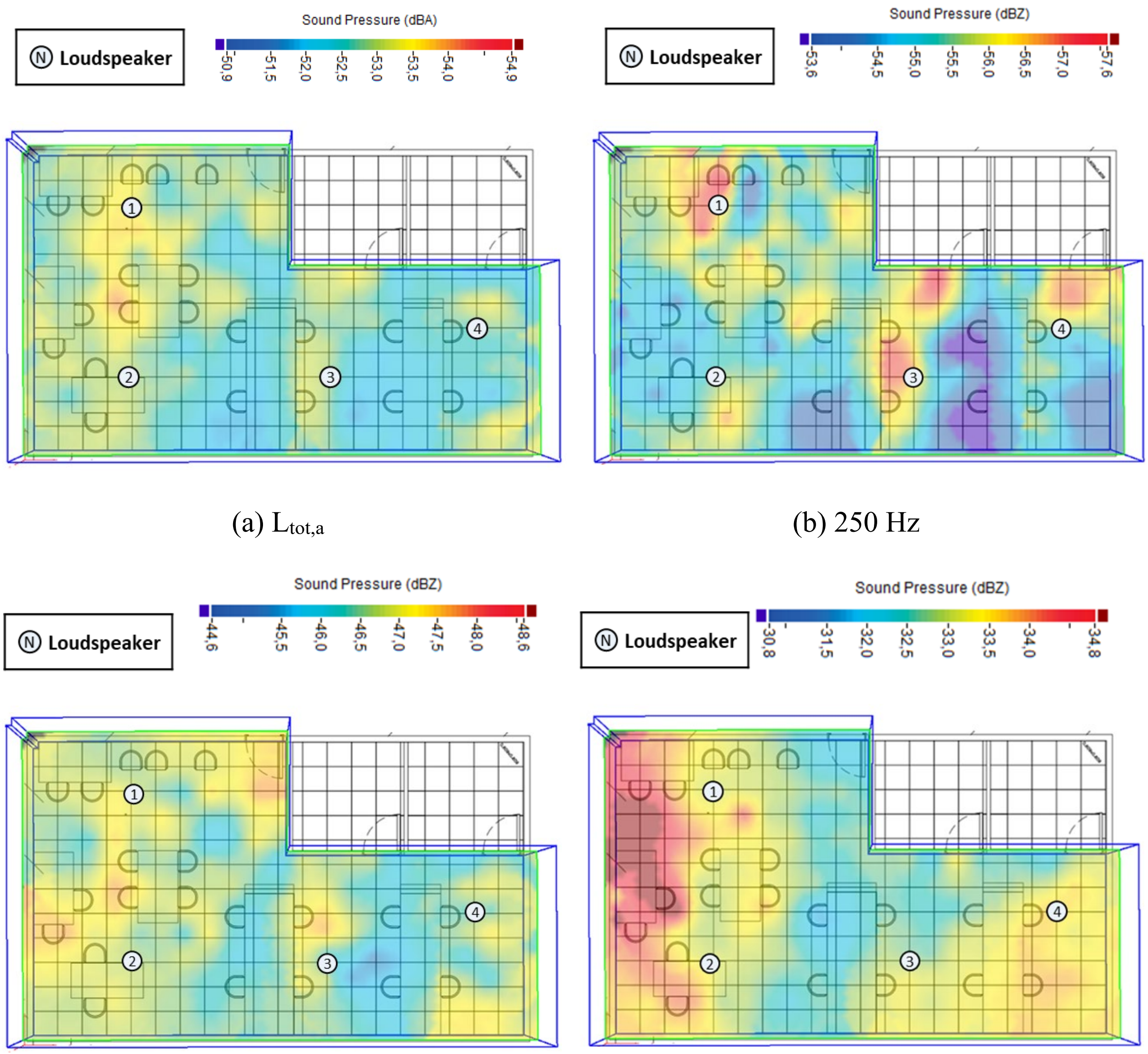
| Tolerance (dB) | ±0.5 | ±1 | ±1.5 | ±2 | ±2.5 | ±3 | ±3.5 | ±4 | ±4.5 |
|---|---|---|---|---|---|---|---|---|---|
| $L_{tot,a}$ | 61% | 99% | 100% | | | | | | |
| $L_z$ (250 – 4 kHz) | 0% | 4% | 22% | 55% | 69% | 87% | 95% | 99% | 100% |

For $L_{tot,a}$, 61% and 99% of the positions were found to be within ±0.5 and ±1 dB, respectively, and all locations were found to fall within the tolerance range of ±1.5 dB. This is generally in accordance with industry perception of the tolerances considered realistically achievable for sound masking systems. The average $L_{tot,a}$ was 51.91 dB, with a standard deviation of 0.51 dB.

When looking at the tolerances from the reference spectrum for the one-third octave band SPLs, none of the measured points were found to fall within ±0.5 dB in each and every one-third octave band, while all locations fell within ±4.5 dB in each and every one-third-octave band. 95% were within ±3.5 dB, and 87% were within ±3 dB. Generally, industry perception is that one-third octave band spectra should be within ±2 dB from the reference spectrum; it can be seen, however, that even under this effectively idealised installation scenario of one speaker per zone with smaller zonal densities, ±2 dB in each and every one-third-octave band between 250 Hz and 4 kHz is only achieved in 55% of measurement locations.

Figure 4 illustrates the sound level distribution maps of $L_{tot,a}$, and of the 250 Hz, 1 kHz, and 4 kHz one-third octave band $L_Z$ measured at a height of 1.2 m from the floor, where the ±2 dB color scale is used for the color maps. In the figure, the purple (low end) and dark-red (high end) colored locations are outwith the ±2 dB range that is centered on the reference value for each band. Loudspeaker positions are indicated with a numbered circle.

As can be seen in Figure 4, the spatial dispersion of sound levels in the 1 kHz one-third octave band shows a more uniform distribution of the masking sound over the office space in comparison to the other frequency bands. The standard deviation of SPLs at 1 kHz one-third octave band was found to be 0.57 dB, which is the second smallest following the standard deviation of 0.50 dB at 1.6 kHz one-third octave band among the one-third octave bands analyzed. Lower levels than the reference value were found between loudspeakers in the color map of the 250 Hz one-third octave band SPL. The standard deviation of the SPLs at the 250 Hz one-third octave band was found to be 1.49 dB, the largest among the one-third octave bands. The results show that the ±4.5 dB tolerance range obtained by including the one-third octave band SPLs from 250 Hz to 4 kHz was heavily influenced by the SPL variations in the lower frequencies. In general, this follows expectations of larger variations of the sound levels relative to the reference spectrum in the lower frequencies than in the higher frequencies. An unexpected result at this point is the higher levels (relative to the reference value) near the left and right wall surfaces in the color map of the 4 kHz one-third octave band SPL.




(a) $L_{tot,a}$

(b) 250 Hz

(c) 1 kHz

(d) 4 kHz

*Figure 4. SPL distribution maps at 1.2 m height for (a) overall A-weighted SPL ($L_{tot,a}$), (b) 250 Hz, (c) 1 kHz, and (d) 4 kHz one-third octave band SPLs ($L_z$). The locations of the four plenum-mounted loudspeakers are marked with numbers, where the purple (low end) and dark-red (high end) colored locations denote areas that are outside the ±2 dB range. The middle values indicate SPL values of the target CNRC-53 spectrum.*

### 3.2. Room acoustic simulation results

The simulated SPL distributions in the office with the same configuration as the measurement was compared in order to validate acoustic simulation results. The tolerance range which all locations were found to fall within was ±1.5 dB for $L_{tot,a}$, which was the same range as the measurement result. The tolerance ranges of all octave-band SPLs from 250 Hz to 4 kHz using simulation and measurement were ±3.5 dB and ±4.5 dB, respectively. The SPL distribution trends in the color maps in Figure 4 and Figure 5 show similar patterns also.

However, the simulation results in Figure 5 show more clear SPL attenuation depending on the distance from a loudspeaker than the measurement results in Figure 4. The discrepancy between the simulation and measurement results, especially for the octave-band SPL results, was due to the lack of HVAC noise variation across the locations and outdoor noise transmission in the simulation process. Even though the discrepancies of results were found, the findings from the acoustic simulation will still be helpful to understand the effect of physical parameters on spatial uniformity by sound masking systems.

Table 4 presents the variations of the $L_{tot,a}$ and octave-band $L_Z$ corresponding to three varying physical parameters; (i) the number of speakers, (ii) desk partition height, and (iii) ceiling absorption and scattering coefficients were adjusted to predict the SPLs in the same locations of the measurement. The tolerance ranges were determined taking into account approximately 90% of the locations (105 locations out of 117), with a small number of outlier locations having been excluded to eliminate their effect on the results.

*Table 4. Tolerance ranges (in dB) from the targeted sound levels determined based on 90% of locations using (1) overall A-weighted SPL ($L_{tot,a}$) only and (2) unweighted one-third octave*

*band SPLs ($L_z$) with varying physical parameters (number of loudspeakers, partition height, ceiling absorption and scattering). Conditions appearing in bold text in the figure are indicative of a configuration identical with the measurement (base condition).*

| | Tolerance | |
|---|---|---|
| | $L_{tot,a}$ (dB) | $L_z$ (250 – 4 kHz) (dB) |
| Number of loudspeakers | | |
| 1 speaker | ±7 | ±9 |
| 2 speakers | ±4.2 | ±5.2 |
| 3 speakers | ±3.1 | ±4.5 |
| **4 speakers** | **±1.6** | **±2.2** |
| 5 speakers | ±1.5 | ±2.2 |
| Partition heights | | |
| 0 m | ±1.3 | ±2.4 |
| 1.1 m | ±1.3 | ±2.1 |
| **1.4 m** | **±1.6** | **±2.2** |
| 1.7 m | ±1.3 | ±2.3 |
| 2 m | ±1.7 | ±2.5 |
| Ceiling | | |
| NRC 0.3 + no diffuser | ±1.3 | ±1.9 |
| NRC 0.3 + 50% diffuser | ±1.1 | ±2.1 |
| NRC 0.3 + 100% diffuser | ±0.7 | ±2.1 |
| **NRC 0.8 + no diffuser** | **±1.6** | **±2.2** |
| NRC 0.8 + 50% diffuser | ±0.7 | ±2.3 |

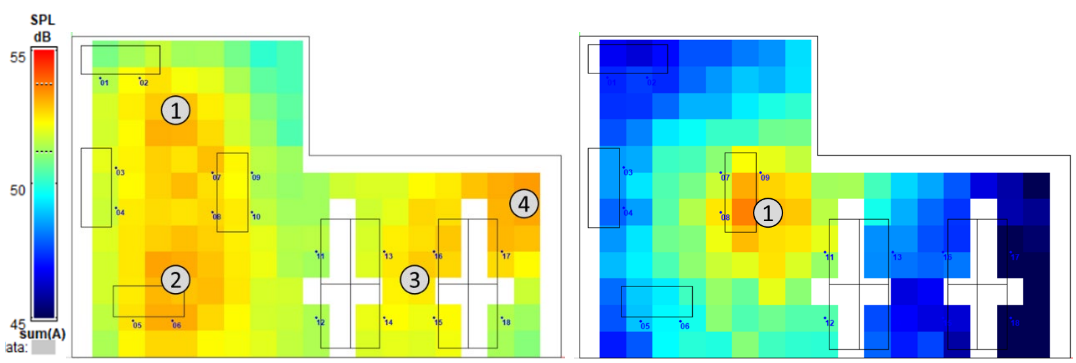
As expected, the use of a higher number of loudspeakers evenly distributed over the office space produces a more uniform field of masking sound. There is a significant improvement in performance (i.e., reduced deviation from specified level by almost half) when shifting from 3 speakers to 4 speakers. The minimum SPL variation of the locations examined here (representing 90% of the 117 locations under investigation overall in the study) was found to fall within ±2.2 dB when utilizing 4 loudspeakers. Beyond 4 speakers, the improvement in performance was marginal; there is effectively no difference between 4 and 5 speakers. The range was improved by 13.6 (±6.8) dB from the SPL distributions with a loudspeaker installed. The margin of improvement decreased, though, when increasing the number of loudspeakers.

In terms of the partition height, lowering the partition was found to improve the uniformity of the sound masking slightly. However, in general, partition height would appear to be a minor influence on the achieved tolerance when using 4 loudspeakers. The change in the tolerance range was only 0.8 (±0.4) dB between the extremes of no barriers and 2 m high barriers. This may be a consequence of only half the room having barriers, to begin with, and a single loudspeaker being present between each barrier so as not to form an obstruction to the sound field emitted from the area above the workstations.

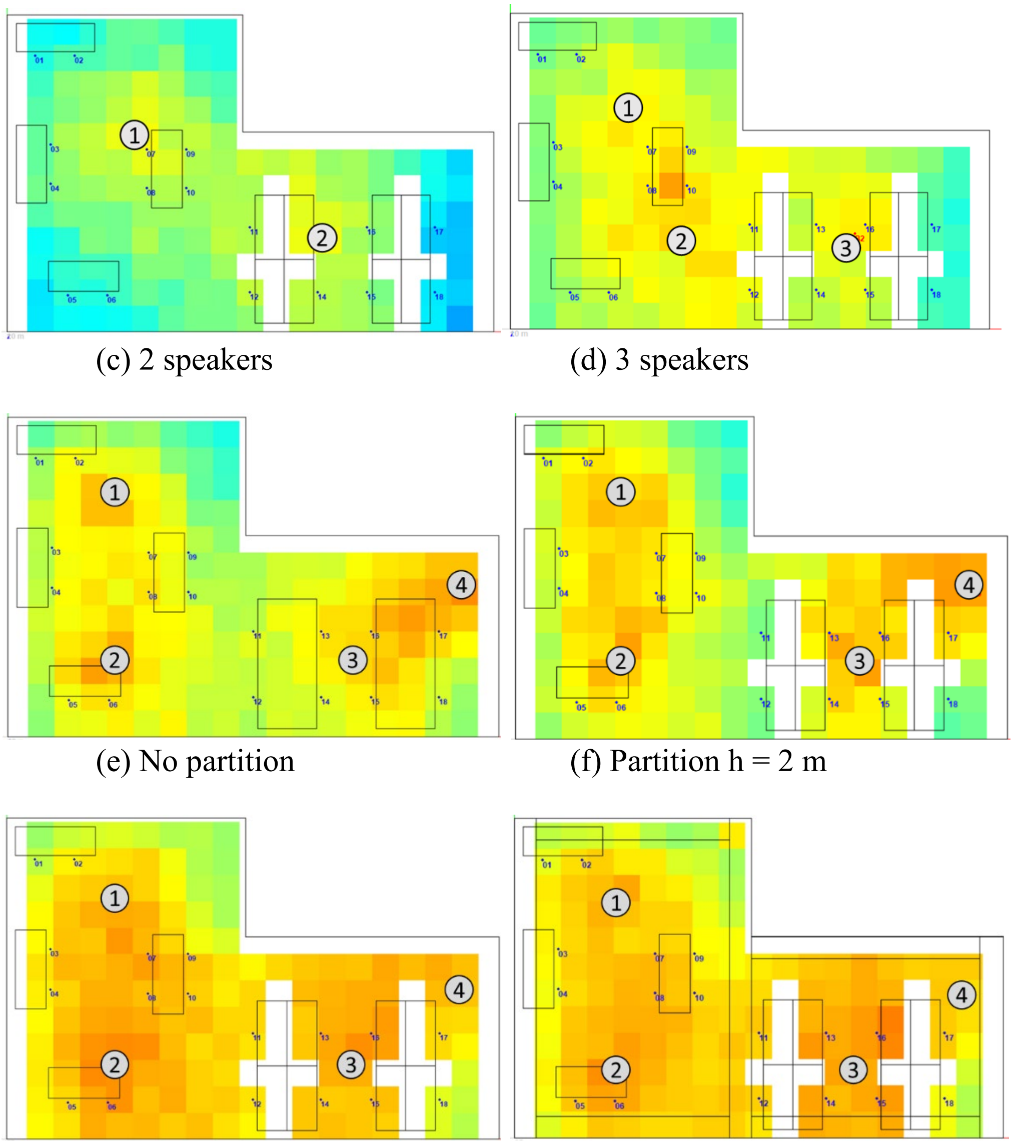
The use of a more absorptive ceiling (NRC 0.8) did not show a significant improvement in performance (i.e., decrease in tolerance) than the less absorptive ceiling (NRC 0.3). The less absorptive ceiling tile is shown to have a 0.3 dB lower tolerance than the more absorptive tile. This minor change is not unexpected given the sound field at 1.2 m is likely dominated by a combination of the direct sound energy radiated from the ceiling and the localised absorption conditions of the workstation rather than the absorptive condition of the ceiling, which would otherwise form at least a 2$^{nd}$ order reflective surface. For the same ceiling absorption conditions, meanwhile, adding more diffusive ceiling panels resulted in an improvement of 1.8 (±0.9) dB for the $L_{tot,a}$ and 0.4 (±0.2) dB for the octave-band $L_Z$.

Figure 5 presents the $L_{tot,a}$ distribution maps showing the base condition, the minimum, and maximum variation of the masking sound across the space corresponding to the altering of each design parameter, where the color maps show that the highest deviation in the SPL is typically observed in the middle areas between the loudspeakers and near the sidewalls.

When varying the number of loudspeakers, adding more loudspeakers showed improvement of the uniformity, especially in the locations between loudspeakers. When utilizing ceiling diffusers, as in Figure 6(g) and 6(h), the color maps show more uniform SPL distribution over the space, which is in agreement with the results outlined in Table 4. Moreover, the SPLs near sidewalls and between loudspeakers generally improved. When varying the partition height, it can be seen that the color maps of the three conditions look similar, with the exception of the positions around the desks with a partition. In the presence of a partition, a sudden decrease of SPLs can generally be observed behind the partitions, and this trend is more pronounced with the 2 m partition. By lowering or removing the partitions, the masking sound in that area distributes more uniformly. The color maps show more SPL variation for the seated positions close to the wall surface. It can be inferred from these observations that relocation of the workstations away from the sidewalls would minimize the SPL variation at the seated positions.




(a) Base condition (b) 1 speaker



(c) 2 speakers (d) 3 speakers

(e) No partition (f) Partition h = 2 m

(g) NRC 0.3 & 100% diffuser (h) NRC 0.8 & 50% diffuser

*Figure 5. Overall A-weighted SPL (Ltot,a) distributions with modification of physical parameters (number of loudspeakers, partition height, ceiling absorption and scattering properties), where the base conditions are the use of 4 loudspeakers, 1.4 m partition, and acoustic ceiling tiles with NRC value of 0.8 and no diffuser.*

In order to assess the effect of the uniformity of the masking sound on speech intelligibility, AI values were calculated for each simulation between each workstation and the nearest adjacent workstation. An AI value of 0.22, calculated using the masking noise spectrum (CNRC-48) at the location right below the speaker, was set as the target value representing the non-distracting speech privacy condition. The deviation of the AI values over the entire office space was then analyzed. If a change in AI value exceeds the just-noticeable difference (JND), as the term suggests, an employee is likely to notice the change in sound-masking performance. As the JND of AI has not yet been determined, this study assumes a JND of 0.10, approximately equivalent to a JND in the speech-to-noise ratio of 3 dB [21][22].

Figure 6 shows the effect of loudspeaker numbers and corresponding spatial deviation of SPLs on the AI variation across the office area, where the tolerance ranges for each condition are ±9 dB, ±5.2 dB, ±4.5 dB, ±2.2 dB, respectively, with an increasing number of loudspeakers. Considering 0.10 (±0.05) as an acceptable range, the percentage of the positions beyond this range (i.e., 0.17 to 0.27) was calculated for each condition. As shown in Figure 7, approximately 82% (96 out of 117) positions were found to have AI values higher than 0.27, with 0.59 being the maximum AI value reached when a loudspeaker was utilized only. When adding more loudspeakers, the percentage outside the JND range was found to decrease significantly. Specifically, 53% and 31% of the positions were found to be outside the defined range for the masking sound conditions when 2 loudspeakers and 3 loudspeakers, respectively, are used. When using 4 loudspeakers, only 13% of the positions were found to have AI values higher than 0.27. By using 5 loudspeakers, there was a slight improvement by 5% (6 positions) of the positions. The results imply that a spatial variation of approximately 3.2 dB (±1.6 dB, and ±2.2 dB in each one-third-octave band) in masking sound fields is likely to be unnoticeable and, in turn, acceptable. However, this does conflict with the achievable tolerances seen in the field measurements where 90% of cases were achieved using 4 speakers for ±1.0 dB for $L_{tot,}$a and ±3.5 dB in each one-third-octave band.

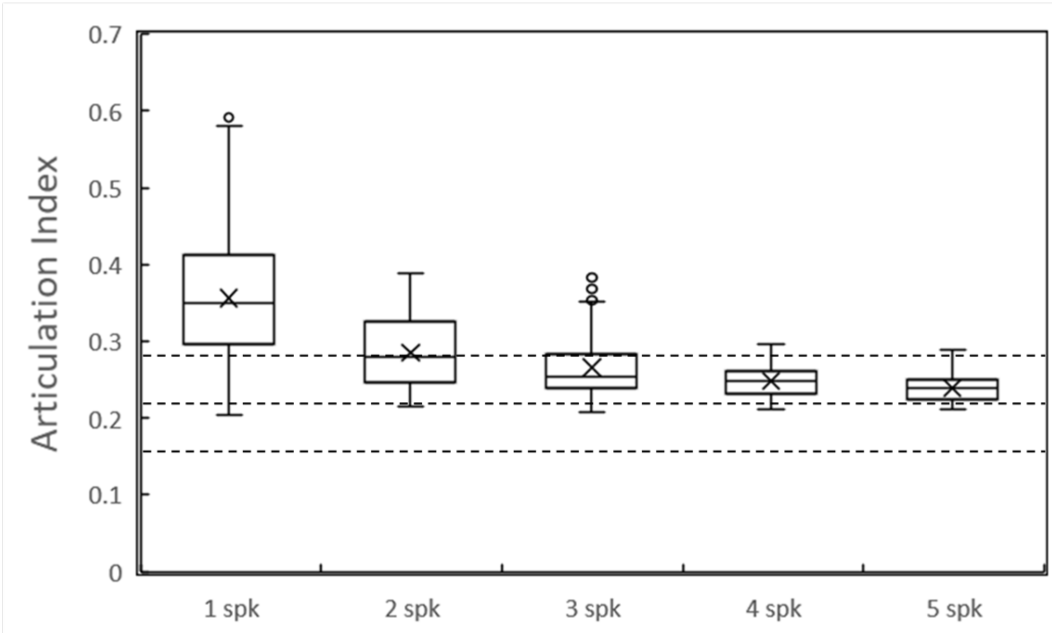



*Figure 6. AI variations over the office space with a number of sound-masking loudspeakers. The tolerance ranges for each condition are ±9 dB, ±5.2 dB, ±4.5 dB, and ±2.2 dB, respectively, with increasing number of loudspeakers. The cross mark in boxplots indicates an average AI value and the circles indicate the outliers (beyond 1.5 times the interquartile range above the upper quartile value). The dotted lines indicate the targeted AI value of 0.22 with ±0.05 range.*

## 4. Conclusion

This study investigated the spatial uniformity of an overdesigned, 1-speaker per zone sound-masking systems within a reduced spatial density of loudspeakers, specifically with respect to the effect of three key office design parameters (number of loudspeakers, partition height, ceiling acoustic characteristics) on the spatial uniformity across a typical open-plan office. This was achieved by using a combination of measured and simulated data. Sound maps were created with a measurement grid of 0.6 m × 0.6 m to visualize the spatial variations of the masking sound levels across the office space. Moreover, acceptable spatial variation of masking sound levels was determined by examining Articulation Index across the open-plan office. The sound maps show the SPLs can change over relatively short distances, particularly at locations between loudspeakers and near walls or partitions. It has been found that to achieve greater than 90% conformity to a specified reference sound level at each of the 77 measurement locations across the office, a tolerance of ± 1.0 dB is required for the A-weighted sound level, and ±3.5 dB is required for the one-third-octave sound level between 250 Hz to 4000 Hz. Among the design parameters investigated, the number of loudspeakers was found to have the most significant effect on spatial uniformity. The calculated AI results suggest a 4 dB tolerance range of masking sounds in order for occupants not to perceive the masking performance difference across the office area.

As a possible avenue of future work, it is recommended that other speech intelligibility metrics such as Speech Intelligibility Index or Speech Transmission Index be used to augment the findings of the present study, which only utilized AI. This study also relied on measurement and simulation data to suggest the acceptable deviation of masking sound levels. Validation with subjective testing is thus needed.

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## References

[1] Duffy F. Office design and organizations: 1. Theoretical basis. Environment and Planning B: Planning and Design 1974;1:105–18. https://doi.org/10.1068/b010105.

[2] Frontczak M, Schiavon S, Goins J, Arens E, Zhang H, Wargocki P. Quantitative relationships between occupant satisfaction and satisfaction aspects of indoor environmental quality and building design. Indoor Air 2012;22:119–31. https://doi.org/10.1111/j.1600-0668.2011.00745.x.

[3] Kaarlela-Tuomaala A, Helenius R, Keskinen E, Hongisto V. Effects of acoustic environment on work in private office rooms and open-plan offices – longitudinal study

during relocation. Ergonomics 2009;52:1423-1444. https://doi.org/10.1080/00140130903154579.

[4] Jensen KL, Arens E, Zagreus L. Acoustical quality in office workstations, as assessed by occupant surveys. Indoor Air 2005.

[5] Sundstrom E, Town JP, Rice RW, Osborn DP, Brill M. Office Noise, Satisfaction, and Performance. Environment and Behavior 1994;26:195–222. https://doi.org/10.1177/001391659402600204.

[6] Vassie K, Richardson M. Effect of self-adjustable masking noise on open-plan office worker's concentration, task performance and attitudes. Applied Acoustics 2017;119:119–27. https://doi.org/10.1016/j.apacoust.2016.12.011.

[7] Virjonen P, Keränen J, Helenius R, Hakala J, Hongisto O V. Speech privacy between neighboring workstations in an open office - A laboratory study. Acta Acustica United with Acustica 2007;93:771–82.

[8] Pierrette M, Parizet E, Chevret P, Chatillon J. Noise effect on comfort in open-space offices: development of an assessment. Ergonomics 2015;58:96–106.

[9] E 1573-93. Standard test method for evaluating masking sound in open offices using A-weighted and one-third octave band sound pressure levels. vol. 93. 1998.

[10] ANSI/ASA. ANSI/ASA S12.72 American National Standard Procedure for Measuring the Ambient Noise Level in a Room. Acoustical Society of America (ASA); 2015.

[11] Chanaud R. Sound masking done right: simple solutions for complex problems, Magnum: 2008.

[12] Bradley JS. THE ACOUSTICAL DESIGN OF CONVENTIONAL OPEN PLAN OFFICES. Canadian Acoustics 2003;31:23–31.

[13] L'Espérance A, Boudreault L, Demers N, Mackenzie R. Evaluation of the sound field spatial uniformity in offices provided by surface-mounted sound masking systems vs plenum-mounted systems. Inter-Noise, Chicago, Illinois: 2018.

[14] ASTM E1573 - 18. ASTM E1573-18: Standard Test Method for Objective Measurement of Speech Privacy in Open Offices Using Articulation Index 1. 1994.

[15] Veitch, J., Bradley, J., Legault, L., Norcross, S., and Svec J. Masking speech in open-plan offices with Filtered Pink Noise noise: noise level and spectral composition effects on acoustic satisfaction. Ottawa, Canada: 2002.

[16] Matheron G. Kriging or polynomial interpolation procedures. CIMM Transactions 1967;70:240–4.

[17] CATT-Acoustic n.d. https://www.catt.se/ (accessed June 17, 2020).

[18] PTB (Physikalisch-Technische Bundesanstalt). The room acoustic absorption coefficient database 2012. www.ingenieriaacusticafacil.com.

[19] RPG Acoustical Systems LLC. Waveform Harmonix-K 2016. https://www.rpgacoustic.com/documents/2016/08/harmonix-k_brochure.pdf/.

[20] ASTM. ASTM E1130-90 Standard Test Method for Objective Measurement of Speech Privacy in Open Offices Using Articulation Index. n.d.

[21] Killion K Mead C. The noise problem: There's hope. Hear Inst 1985;36:26–32.

[22] McShefferty D, Whitmer WM, Akeroyd MA. The Just-Noticeable Difference in Speech-to-Noise Ratio. Trends Hear 2015;19. https://doi.org/10.1177/2331216515572316.