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Evaluation of the sound field spatial uniformity in offices provided by surface-mounted sound masking systems vs plenum-mounted systems

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ABSTRACT

Sound masking systems are commonly used to improve speech privacy in open-plan offices. In most systems, the masking sound is generated by loudspeakers located within the ceiling plenum and the sound is transmitted through the suspended ceiling material (indirect-sound radiation). Alternatively, some systems use loudspeakers mounted on the surface of the suspended ceiling, facing directly down into the office space (direct-sound radiation). Proponents of surface-mounted loudspeakers state that they can provide a more uniform sound field across the office space. However, no previous studies quantify the difference between plenum-mounted and surface-mounted loudspeakers.

This paper is the first such study to evaluate the sound field spatial uniformity for both indirect and direct masking systems. Firstly, high-resolution sound maps have been created when both systems are consecutively installed in the same office space. Results show that for a typical office design situation, plenum-mounted loudspeakers provide a more spatially-uniform sound field than direct-mounted loudspeakers. Secondly, the in-situ spatial uniformity measurements have been used to calibrate computer simulations of the sound field in the same office space. The effect on spatial uniformity of various parameters, such as the spacing between the loudspeakers, ceiling height, ceiling material and plenum height, is quantified and discussed.

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1 INTRODUCTION

The objective of this study is to evaluate the relative spatial uniformity of the sound fields generated by both plenum-mounted (indirect) and surface-mounted (direct) sound masking systems.

It is commonly understood by the specialists in the application of sound masking that achieving spatial uniformity across the sound field is one of the key parameters for a comfortable and effective masking installation[1]. When defining spatial uniformity, ANSI S12.72-2015[2] presents a method of evaluating whether the sound field in the room is "spatially constant", interpreted as all measurement positions being ± 3 dB from the median, thus permitting a sound level variation of up to 6 dB between measurement points. This could be considered generous given that a 5 dB variation in sound level is commonly understood to be "quite noticeable", where as a 3 dB is change a "barely perceptible" change in loudness (± 1.5 dB from the median). With regards to the spatial uniformity of sound masking specifically, ASTM E 1573-2009[3] presented a method to evaluate the spatial uniformity of a sound masking sound field in open-plan offices where the measurements that are taken across the test space should not vary "significantly" from the mean of these measurements ("significantly" being the ± tolerance typically defined in the system specifications, often ± 2 dB for the A-weighted level). However, a flaw in the 2009 standard was that only a minimum of 5 measurement per test site were required, inadequate sampling to characterize the spatial uniformity of large buildings.

The recently revised version of this standard ASTM E 1573-18[4] also has a minimum of 5 sound level measurements for test spaces under $465m^2$ ($5000ft^2$), but for larger areas the standard stipulates to measure one point every $93m^2$ ($1000ft^2$) with the level at each point being compared to the specified values. The new standard has however removed any prescribed method of evaluating the spatial uniformity of the masking sound field, although it is likely intended that either all or a percentage of the measured positions should match the specified spectrum within specified tolerances that are realistically achievable when sampling any randomly-chosen single position within the room.

Questions remain regarding how these single or average measurements compare to the actual sound field of an office space. Thus, to obtain a true evaluation of the spatial uniformity, a method has been developed to allow a precise determination of the sound level distribution across the open space under investigation. The method is based on measurements of numerous points taken across an office space. A sound map is then generated based on the integration of these measurements using the Kriging interpolation method[4], which then allows the analysis of the spatial uniformity using $0.5m^2$ segmental grid across the open office.

The sound maps generated are then used to verify computer simulations of the resultant sound fields for the same office space. These simulations allow us to evaluate the effect of various parameters on the spatial uniformity of the sound field for both surface-mounted (direct) and plenum-mounted (indirect) sound masking systems.

2 MEASUREMENTS

A surface-mounted (direct-field) masking system and a plenum-mounted sound masking system were installed sequentially in the same open-plan office area. This open office has typical office furnishings, with a 2.5m (8ft) high suspended ceiling at with NRC 0.70 ceiling tiles. There is a commercial carpet, and workstation dividers 1.4m high with a thin absorbent material finish. The height of the plenum is 1m (4ft) and contains ducts for the ventilation. The shape of the open office was a L-shape of 4.3m x 9.5m on the long axis, with an addition 3.0m x 4.5m at one end, for a total of $54m^2$ (540^2ft).

The masking systems were installed as per the manufacturers' recommendations. For the direct system, nine surface-mounted speakers were installed 3.0m (10 ft) apart, facing down into the office. For the plenum system, five speakers were installed 4.6m (15 ft) apart, oriented towards the soffit of the slab. In both cases, the masking sound spectrums were the default spectrums recommended by the manufacturers, with the level adjusted during calibration to provide an average level of 45.0 dBA at a height of 1.5m (5 ft) across the space.

To obtain a measure of the true sound-field spatial uniformity of the office, sound pressure level measurements were made across the office space for both masking systems at locations shown as black dots in Figure 1a, which includes measurements (i) directly under each surface- and plenum-mounted loudspeaker, (ii) at intermediate locations between each loudspeaker, and (iii) between the loudspeakers and the walls. To observe the effect of measurement height variation, the measurements were repeated for two different heights for both systems; (i) centering the measurement at 1.6m (5'4") approximately the typical height of the ear of a standing person, and (ii) centering the measurement at 1.2m (typical height of a seated person). A Class 1 sound level meter and microphone was used for all measurements.

2.1 Horizontal Sound Map – 1.6 m – Walking Positions

Based on the 30 field measurements, a Kriging interpolation has been performed to generate a measurement-based sound map representing the spatial sound distribution across the open office space. Figure 1a presents the measurement-based sound map at 1.6m for the direct-field sound masking system. The location of the direct-field speakers are highlighted using red circles.

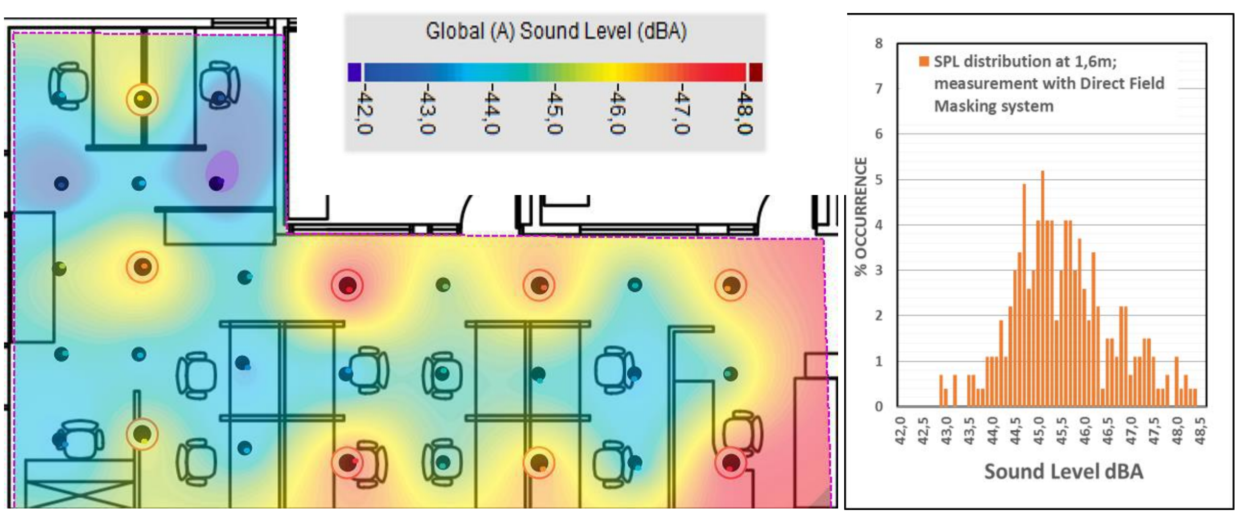


Fig. 1 – a) sound map for the direct masking system at 1.6m (6 dB color scale); b) distribution of the sound level with the standard deviation at 1.1 dB; the L95% is 43.5 dBA and the L5% is 47.9 dBA for a typical difference (L95%-L5%) of 4,4 dB.

As noted, the system was calibrated to 45.0 dBA, so the average SPL across the space is 45.0 dBA but, as can be seen on the sound map with a 6 dB color scale, there are significant variations between the higher levels (measured directly under the loudspeakers) and the lower levels (between loudspeakers). It can also be seen that variations of 2-3 dB occur over a relatively short distance (~1.5m).

Figure 1b provides the statistical distribution of the SPL values using each 0.5m^2 segment of the Kriging-interpolation sound map at 1.6m height. The standard deviation is 1.1 dB. This distribution allows us to determine that the range between the typical low levels ($L_{95\%}$ =43.5 dBA) and the typical high levels ($L_{5\%}$ =47.9 dBA) is 4.4 dB at 1.6m height for the direct-field system.

For the plenum-mounted masking system, the measurements were performed at the same locations. Figure 2a presents the measurement-based sound map at 1.6m height for the plenum masking system, whilst Figure 4b shows the distribution of the SPL values using each 0.5m^2 segment. The standard deviation is 0.7 dB. For the plenum masking system, the typical low sound levels ($L_{95\%}$) are 43.7 dBA and the typical high levels ($L_{5\%}$) are 46.1 dBA. The range between high and low levels is thus 2.4 dBA, which is about the half of the range measured for the direct-field system.

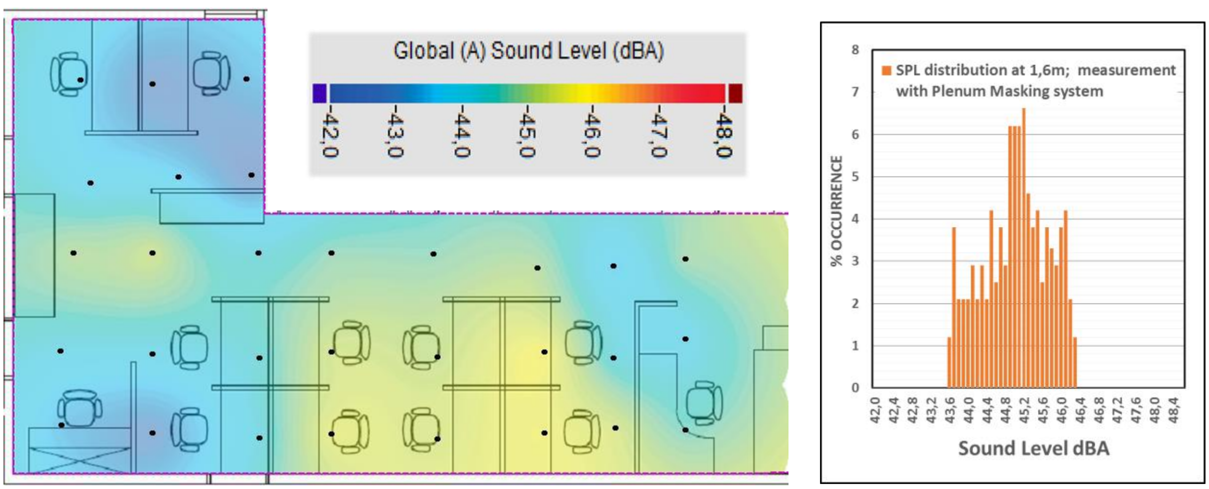
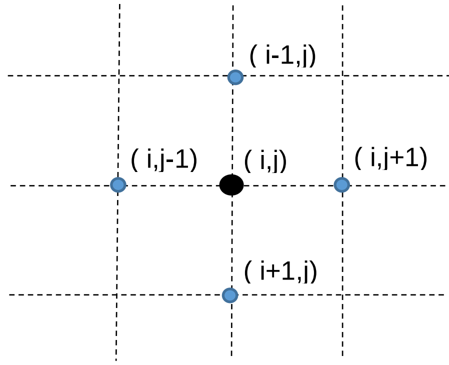


Fig. 2 – a) sound map for the plenum masking system at 1.6m (6 dB color scale); b) distribution of the sound level with the standard deviation at 0.7 dB; the L95% is 43.7 dBA and the L5% is 46.1 dBA for a typical overall variation ($L_{95\%}$-$L_{5\%}$) of 2.4 dB.

When comparing Figures 1a and 2a, it can be seen that significant variations in the sound field under the direct-field system can occur over shorter distances than under the plenum system. To evaluate this spatial variation further, the sound level variation between each point of the segmental grid and the four adjacent segment points, ($Var(i, j)$, has been evaluated. The mean sound level variation between adjacent segment points across the entire space, $\overline{Var}$, has been calculated as follows:

$$\mathrm{Var}(i,j) = \big(|Lp(i,j)-Lp(i-1,j)| + |Lp(i,j)-Lp(i+1,j)| + |Lp(i,j)-Lp(i,j-1)| + |(Lp(i,j)-Lp(i,j+1)| \big)/4$$

$$\overline{Var} = \sum_{i,j}^{n,m} \mathrm{Var}(i,j)$$



(1)

When considering a grid of 1m^2, the $\overline{Var}$ is calculated to be 1.2 dB and 0.5 dB for the direct-field and plenum masking systems respectively. This means that, for this office, the typical SPL variation every meter is 1.2 dB for the case of the direct field system and 0.5 dB for a plenum masking system. In essence, for a person walking through the open space SPL variations may be more perceptible under a direct-field system than for a plenum system.

2.2 Horizontal Sound Map – 1.2 m – Seated Positions

Figure 3a and Figure 3b present the measurement-based sound maps and statistical distribution respectively at 1.2m (4') above the floor (the typical ear height of a seated person) for the direct-field masking system. For the direct-field system, the standard deviation using all 0.5m^2 segments is 1.0 dB, and the range between the typical low levels (L95%=43.4 dBA) and typical high levels (L5%=46.4 dBA) is 3 dB.

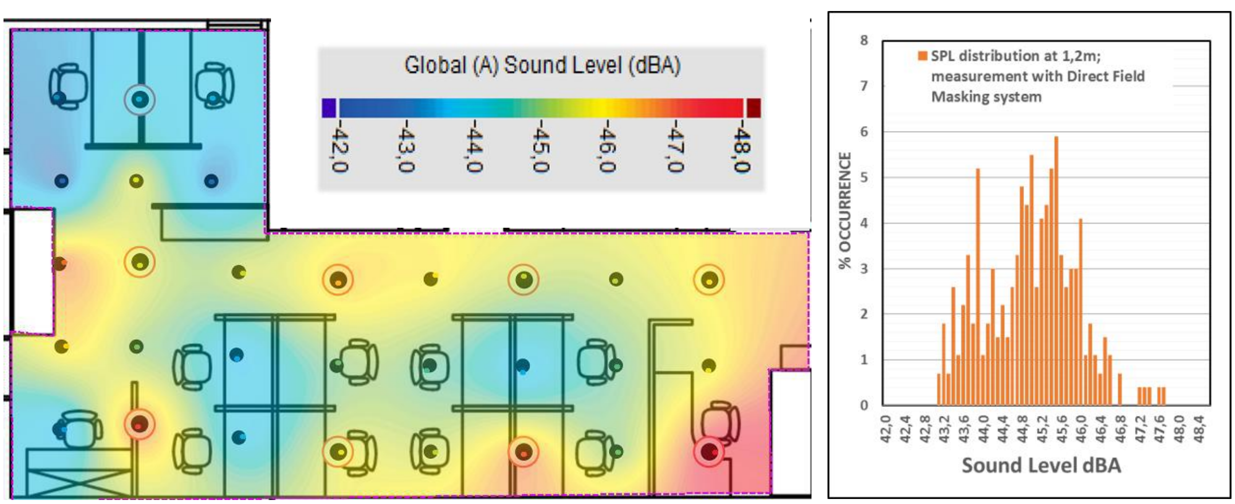


Fig. 3 – a) sound map at 1.2 m for the direct masking system; b) distribution of the sound level with the standard deviation at 1.0 dB and the difference between the typical low levels (L95%=43.4 dBA) and the typical high levels (L5%=46.4 dBA) is 3 dB.

Figure 5 presents the results for the plenum system.

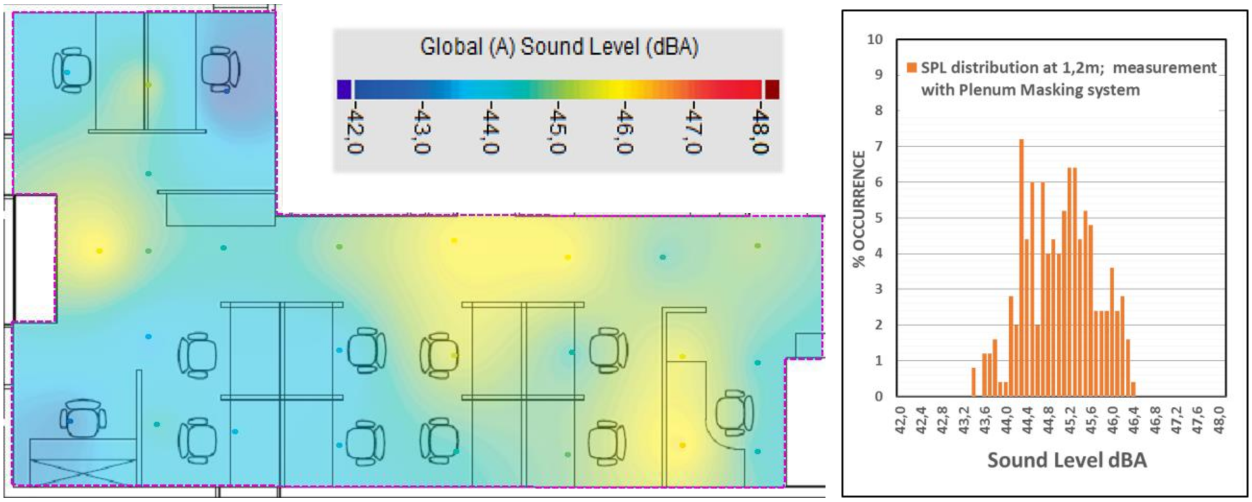


Fig. 5 – a) sound map for the plenum masking system at 1.2m; b) distribution of the sound level with the standard deviation at 0.7dB and the difference between the typical low levels (L95%= 43.9 dBA) and the typical high levels (L5%=46.1 dBA) is 2,2 dB.

For the plenum system, the standard deviation using all 0.5m^2 segments is 0.7dB, and the range between the typical low levels (L95%=43.9 dBA) and the typical high levels (L5%=46.1 dBA) is 2.2 dB. In summary, for a seated position, the plenum-sound masking system provides greater spatial uniformity than the direct-field system (2.2 dB range vs 3 dB range).

Using Equation. 1, the mean variation, $\overline{Var}$ of 1m^2 segments at 1.2m high is 0.9 dB and 0.5 dB for the direct-field and the plenum masking systems respectively. This result means that the spatial variation in the sound level between two seated positions spaced 1m apart is 0.9 dB using the direct field system, and 0.5 dB using the plenum masking system. Essentially, the mean variation, $\overline{Var}$, reduces with height for the direct-field system, but remains constant between heights for the diffuse plenum system. This consistency can also be seen in the vertical sound maps in the following section.

2.3 Vertical Sound Maps

Figure 6 presents the vertical-plane sound maps of a) the direct-field masking system and b) the plenum masking system. The sound maps have been obtained by measurement of the sound pressure level using the *I-track* acoustical imaging system[6,7]. Each map has been measured in a plane where the loudspeakers were installed. The dB scale in each of the maps is the same 12 dB range from 43 to 55 dBA. In the case of the direct-field system, sound levels can be seen to significantly increase as the measurement point moves closer to the emitter, as the sound field is dominated by the direct sound coming from the loudspeaker. As the distance increases relative to the emitter towards the seated position, the contribution of other nearby emitters and of the reverberant field becomes more significant than the direct field and the overall sound field become more homogeneous.

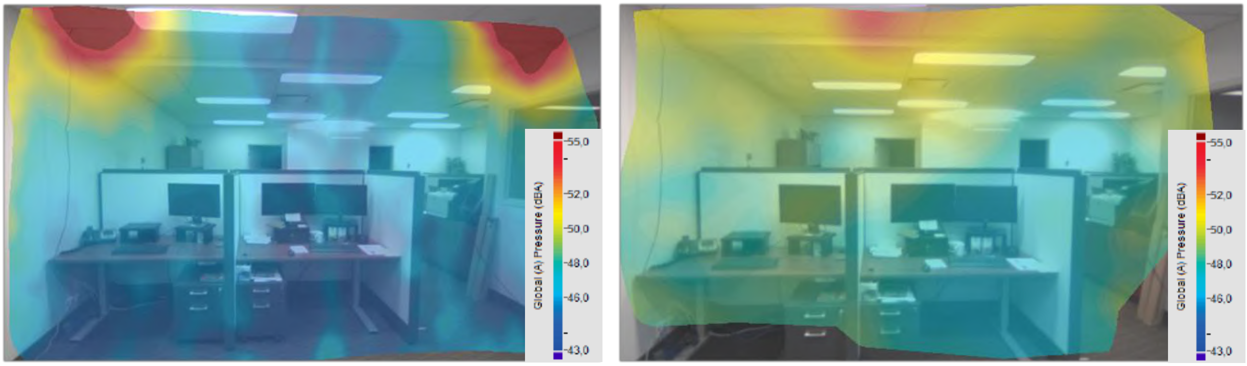


Fig. 6 – Measured vertical sound maps (12 dB scale) for a) the direct-field masking system (left) and b) the plenum masking system (right). In the case of the direct-field masking system, the two loudspeakers can be seen as "hot spots" in the measurement plane (3m apart). For the plenum system, the loudspeaker located in the plenum above of the measurement plane.

3 THEORETICAL SIMULATIONS

In order to evaluate the effect on the sound field of changing the room parameters, computer-generated acoustic simulations of the office have been created to analyze the sound field of the direct-field masking system and the plenum masking system. The simulations were created with the *RAP-ONE II* software[8]. This Room Acoustic Prediction software considers the geometry of the room, the acoustic absorption of the surfaces (floors, ceiling, walls and barriers) and the sound transmission loss of the surfaces (such as the suspended ceiling and the partitions between desks). In the following figures, the plenum- or surface-mounted speaker locations are represented by red dots.

3.1 Computer Simulation of the Direct-Field Masking System

Figure 7 presents the simulated sound maps for the direct-field sound masking system. Figure 7a presents the horizontal sound map at 1.6m (6 dB color scale) and Figure 7b presents the vertical sound map simulated in the plane of two direct emitters (plane *AA'*). Note that a different 12 dB color scale from 43 dBA to 55 dBA is used for the vertical map, as was the case with for the measured sound pressure level results in Figure 6b.

By comparing the measurement-based and simulated horizontal sound maps (Figure 1 and Figure 7a respectively) and the measured and simulated vertical sound maps (Figure 6a and Figure 7b), we can see that the simulations are representative and generally confirm the effective sound distribution occurring with a direct-field masking system.

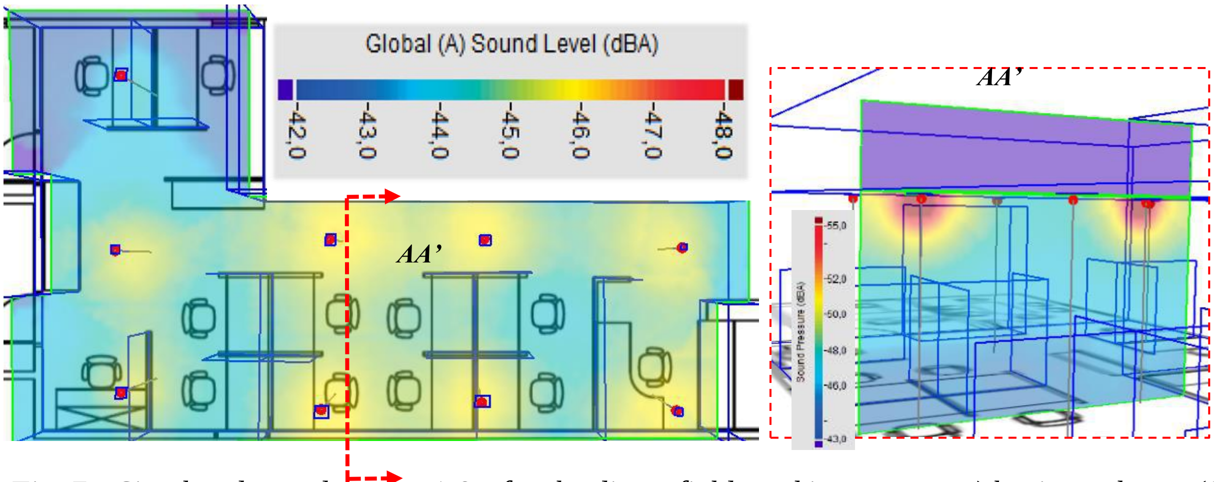


Fig. 7 – Simulated sound map at 1.6m for the direct-field masking system: a) horizontal map (6 dB scale) and b) vertical sound map (12 dB scale) including the plenum. The simulations are validated by the measured results for the same room.

3.2 Computer Simulation of the Plenum Masking System

Figure 8a presents the simulated horizontal sound map at 1.6m for the plenum masking system (6 dB color scale) and the Figure 8b presents the vertical sound map in the plane of a plenum loudspeaker, plane *BB'*(12 dB scale). As in Section 3.1, the simulated results compare well with the measured horizontal and vertical sound maps of the plenum system in Figure 2a and Figure 6b respectively.

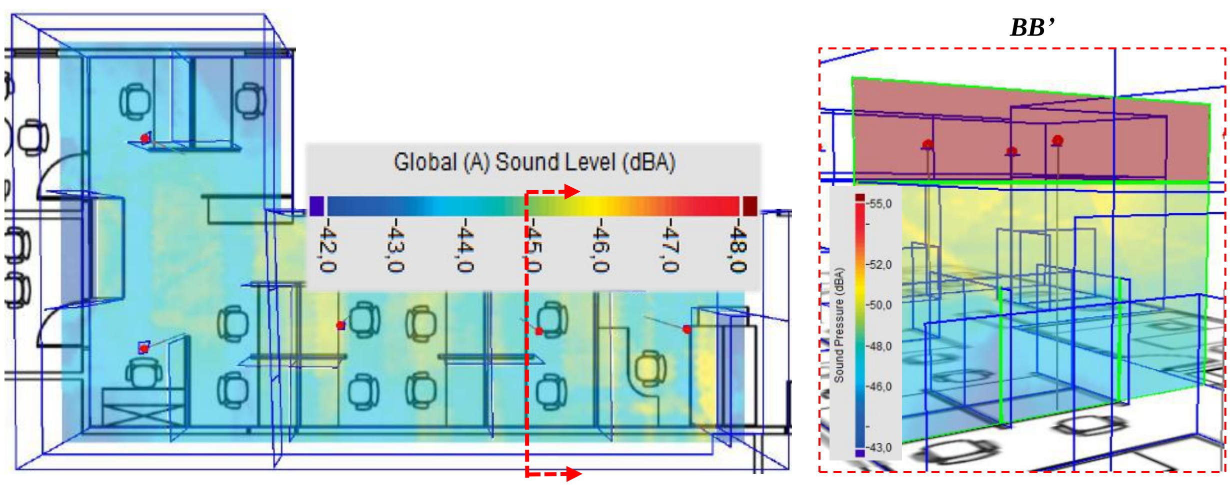


Fig. 8 – Simulated sound map at 1.6m for the plenum masking system: a) horizontal map at 1.6m (6 dB scale) and b) vertical sound map at Section BB' including the plenum (12 dB scale).

The comparison of these simulated sound maps with the measurement-based sound maps demonstrates that the simulations closely represent the sound masking fields for both direct-field and plenum masking systems based on the existing room configuration.

3.3 Effect of Room Parameter Variation

It is then useful to use the simulations to evaluate the effect of changing parameters on the variation of the sound masking sound field, such as (i) the effect of return-air ventilation grills inserted into in the suspended ceiling, and (ii) the effect of obstructions in the plenum such as ventilation ducts.

3.3.1 Effect of Ventilation Grills

In the open space under study, the plenum includes a ventilation grill of 300mm x 600mm, located in the right-bottom corner of the schematic. During measurements, this opening did not appear to cause any significant increase in sound field of the plenum masking system in this area, since sound levels on the measurement-based plenum-system sound maps (Figure 2 and Figure 4) do not appear significantly higher in this area relative to adjacent areas. Figure 9 presents the simulated sound map at 2.2m, which is 0.3m (1ft) below the suspended ceiling and the grill opening.

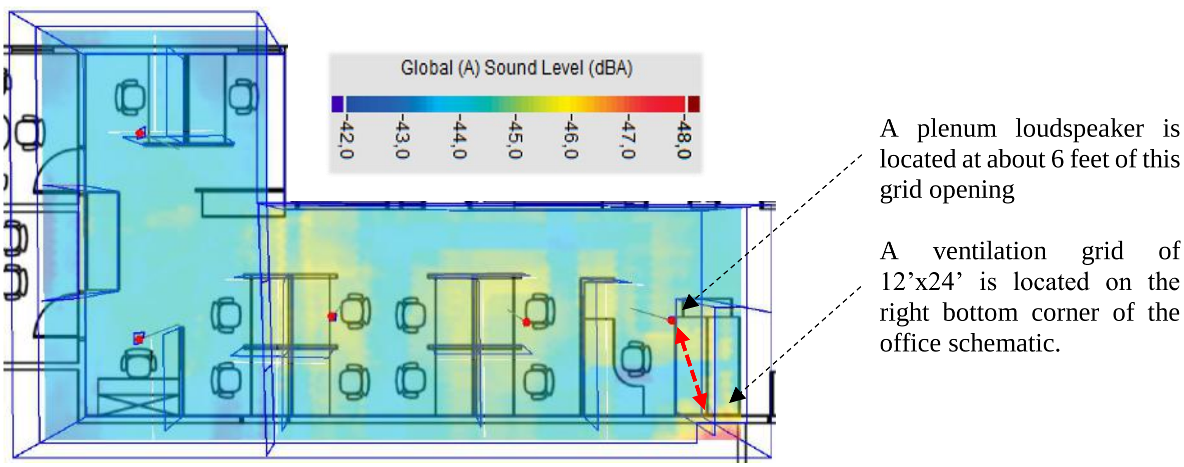


Fig. 9 – Theoretical sound map at 2.2m height for plenum sound masking system (6 dB scale). The sound field below the grill opening (on the right bottom of the schematic) is higher by 1-2 dB.

For the 2.2m sound field, the simulated sound level is highest near the grill opening (in this case 1-2 dB higher relative to adjacent measurement positions). As for the measurement-based sound map in Figure 2, this variation from adjacent positions effectively disappears from the sound field at 1.6m, where variations in the sound field are more likely to be related to the presence of reflective surfaces.

Obviously, if the grill were to be located closer to the loudspeaker, the sound level directly below the opening would increase. As an example, Figure 10 presents the simulated sound field at 1.6m-high with a 300mm x 600mm ventilation grill located only 0.3m (1ft) from the plenum loudspeaker. At 1.6m height under the grill, the sound levels are approximately 2 dB higher than adjacent measurement points. Thus, in comparison with the sound maps in Figures 2 and 8, a relocation of the grill opening and/or the plenum loudspeaker a couple feet away from each other eliminates this relative increase.

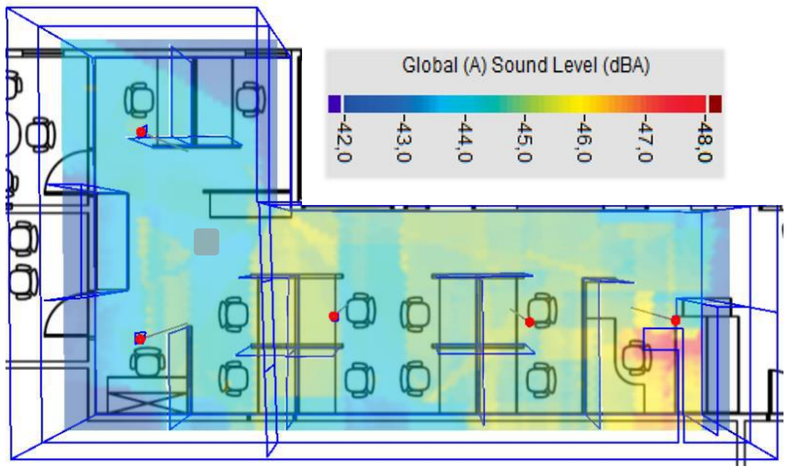


Fig. 10 – Theoretical sound map (6 dB scale) for plenum sound masking system with a ventilation grid at 1 ft next to a plenum loudspeaker: b) sound map at 1.6m height.

Nevertheless, when comparing Figure 10 with Figures 1 and 7, clearly potential variation in the sound field due to the presence of ventilation grills is less dramatic than the relative variation in sound levels seen at 1.6 m below and between surface-mounted loudspeakers.

3.3.2 Effect of Obstacles in the Plenum

It is sometimes thought that ventilation ducts and other obstructions in the plenum can affect the uniformity of the sound field laid down in the office below. In the open office considered in this study, many ventilation ducts surrounding loudspeaker number #3 (towards the center of the open space). There is even a solid gypsum division in the plenum, a remnant of a wall dividing the open plan in the past. Figure 11 provides the schematic of the duct location around the plenum loudspeaker #3, and a composite photograph of this area.

Despite these obstructions, as the measurement-based plenum-system sound map of Figure 2 shows, in this area the spatial uniformity of the sound field is consistent with the other parts of the office, and still clearly more uniform than the direct-field masking system (Figure 1).

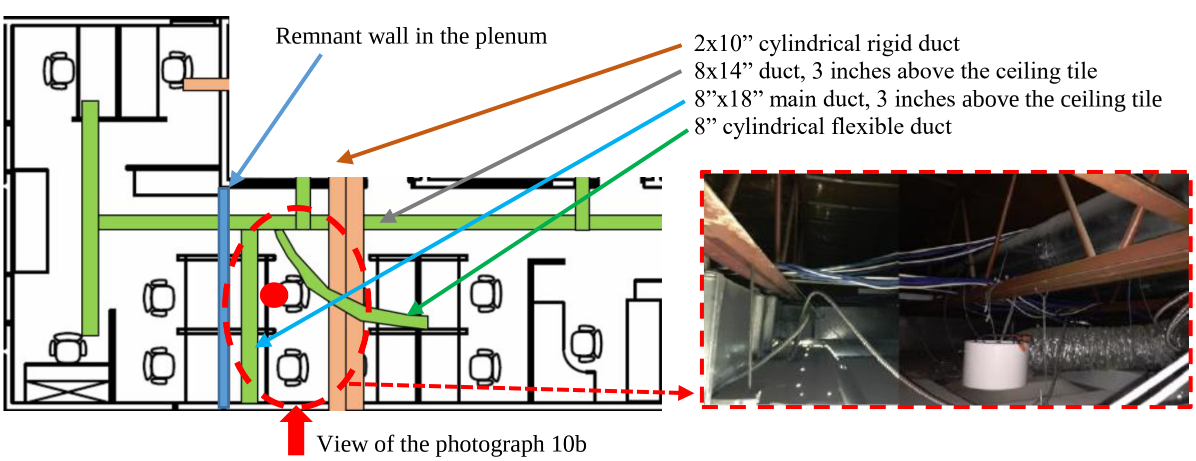


Fig. 11 – a) schematic of the duct location around plenum loudspeaker #3 (as a red circle), and b) photograph of this area.

Figure 12 presents *RAP-ONE II*-generated theoretical sound maps of the sound field above and below the suspended ceiling created by loudspeaker #3 only, which is located between ventilation ducts. The multiple ventilation ducts appear as transparent blue boxes in the images. The two images show that even if there are many ducts that create obstructions to sound propagation, since the plenum is a relatively reverberant area (the surface of the ducts and concreate slab above the ducts are all reflective), the sound field below the suspended ceiling is quite uniform.

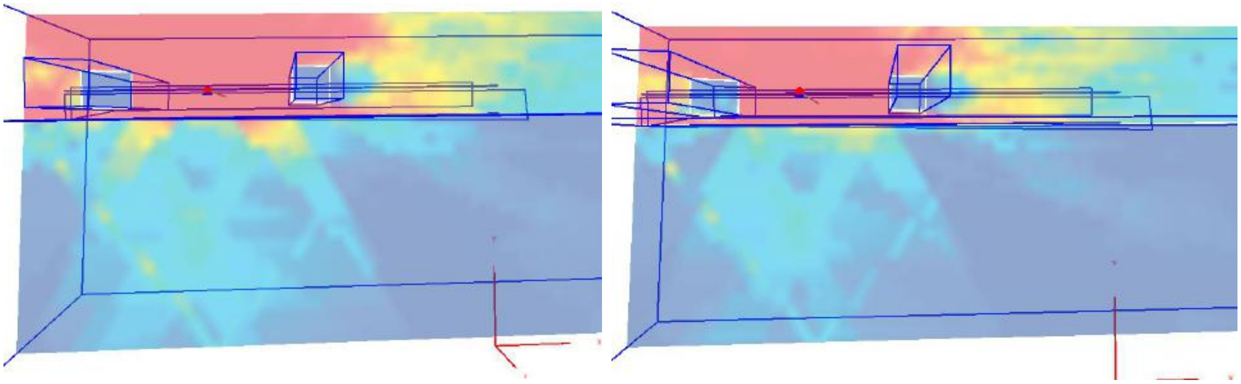


Fig. 12 – theoretical vertical sound map generated by the plenum loudspeaker #3 alone and located between the two ventilation ducts (12 dB scale): a) vertical sound map in the plane of the loudspeaker and b) map in the vertical plane 1.5 m away from the loudspeaker (i.e. towards the base of the schematic in Figure 11).

Naturally, if a duct is located just above the suspended ceiling, this forms an obstruction and less sound will be able to pass through the acoustical tiles directly below this duct relative to adjacent acoustical tiles. However, the variations of the plenum-speaker sound field immediately below the suspended ceiling will still be significantly less than the variation of the sound field created by a direct-field masking system, as can be demonstrated by comparing Figure 12 with Figures 6 and 7.

4 CONCLUSIONS

The spatial uniformities of the sound fields created by a surface-mounted direct-field masking system and a plenum-mounted masking system in a standard $54m^2$ open office have been studied in detail by both measurement and simulation. High-resolution Kriging-interpolation maps of the sound fields from each system have been created from field measurements at heights of 1.2m and 1.6m. Computer simulations of the sound fields resultant from both masking systems have been validated by the measurements and suitably represent the likely variations seen in the measurements of spatial uniformity.

In comparing the spatial uniformities of the two types of sound masking systems, the results show that there is greater variation in the sound field at walking height (1.6m) when using a surface-mounted direct-field sound masking system ($L_{95\%}$-$L_{5\%}$ = 4.4 dB range), relative to a plenum-based sound masking system ($L_{95\%}$-$L_{5\%}$ = 2.4 dB range). It has been demonstrated that the mean sound level variation ($\overline{Var}$) between two adjacent positions 1m apart at walking height (1.6m) is 1.2 dB and 0.5 dB for the direct-field system and plenum-based masking systems respectively. This difference reduces at seated height (1.2m) between surface-mounted ($L_{95\%}$-$L_{5\%}$ = 3.0 dB range) and plenum-mounted ($L_{95\%}$-$L_{5\%}$ = 2.2 dB range).

With regards to whether each system achieves subjective spatial uniformity to the occupant, under ANSI S12.72 criteria (maximum ±3 dB from the median of a minimum of 4 measurements at 1.5m), then using the 1.6m measurements as a proxy, both direct and plenum-mounted systems would likely be deemed spatially constant. For a user walking through the space served by a diffuse plenum-mounted masking system, an $L_{95\%}$-$L_{5\%}$ range of 2.4 dB means the change in sound level would likely not be perceptible. However, for a user walking through the space under the direct-field surface-mounted system with an $L_{95\%}$-$L_{5\%}$ range of 4.4 dB and a mean variation ($\overline{Var}$) between any 2 points 1m apart of 1.2 dB, the change in sound level may likely be perceptible and quite noticeable depending on the speed of walking.

Using simulations, this study has demonstrated that the presence of an open return-air ventilation grill in the suspended ceiling is effectively negligible if the loudspeaker is more than 1 m from the ventilation grill. It was also demonstrated that should the loudspeaker be located closer to the grill, then the effect would be similar to that provided by a surface-mounted speaker (i.e. a 1-2 dB increase in sound level directly under the grill or surface speaker). Finally, it was demonstrated by simulation that any variation in sound field caused by the obstructions will still be less than the variations in the horizontal and vertical sound field resulting from a surface-mounted system.

This study has also demonstrated that both furniture and architectural conditions can induce natural variations in a sound field. It has been shown that, at seated height, an L_{MAX}-L_{MIN} = 3 dB range in the A-weighted sound pressure level (or ±1.5 dB from the mean) may typically occur even for a diffuse and well-calibrated masking system. This variation has nothing to do with the number of loudspeakers; variations in the SPL are shown to occur over relatively small distances served by a single speaker due to proximity to reflective or absorbent surfaces. This has implications for the current ASTM E1573-18 method, which uses a single location within this space to evaluate the conformity of the masking sound. Obviously, it is clear that a single position within this room does not represent the potential sound field variation or spatial uniformity across the space.

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