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Comparison of ceiling absorption placement configurations in a corridor

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ABSTRACT

It is generally acknowledged that speech related noise is a common distractor in many work environments, e.g., open-plan offices. There are many studies and some standards that address these noise related issues, but they generally do not consider sound propagation through corridors. This study investigates how certain spatial arrangements of ceiling absorption affect the spatial decay rate of speech-weighted A-weighted sound pressure levels and speech transmission indices (STI) in a full scale corridor and in a small model tube. Results show that while most of the configurations tested behave similarly, a transverse arrangement of absorptive material has the potential for increased attenuation, especially in the far field, and decreased distraction distance (where STI≤0.5, ISO 3382-3 2012). These findings have relevance for design of corridors, not only in office buildings, but for absorptive treatment of elongated spaces in general.

1 INTRODUCTION

Compared to other parts of a building, generally little to no regard is given to the acoustic properties of corridors. Long corridors represent a distinctive acoustic environment, compared to typical room acoustics. This is due to their length, the presence of close (usually hard) reflecting surfaces, sometimes abrupt bends, and usually a lack of absorptive (or diffusive) treatment (Kang, 2002). Apart from the noise due to impact sources (such as footfalls, heels, etc.), the other sources of noise can include transmission to and from any connecting rooms and whatever sources are at the corridor's ends. While there are studies that examine the acoustics of long corridors, including computational models that can be used to predict the sound transmission, simple treatments, such as the effect of absorption treatment along its length have received limited attention. This study examines the effect that placement of the same amount of absorption in various geometrical configurations in a corridor has on some aspects of the sound field, especially due to speech sounds.

Furthermore, the corridors in open-plan office spaces are considered especially, as it is one of the primary areas where speech-based sound transmission, often at a higher level than usual, can occur (and is generally not preferred), as workers enter or leave the quiet of the office space (Davies, 1973). While many architectural and acoustical elements are taken into account whilst designing open-plan offices, corridors are much less likely to include some of these elements, such as screen partitions, sound absorptive walls or general absorption. The noise transmitted though corridors can be seen to represent another potentially significant source of unwanted noise. The noise transmitted through corridors may compound the detriment of several factors relating to office productivity such as general office noise and speech distraction, which have been reported (Jensen and Arens 2005) as the main sources of indoor environment problems in open-plan offices.

One approach to quantifying the effect of absorptive treatments in corridors of open-plan offices is to estimate the potential distraction using speech transmission index (STI). Hongisto (2005) developed a model capable of predicting the loss of work performance as a function of STI, which was later incorporated in the international standard that characterises the acoustics of open-plan offices (ISO 3382-3 2012). This model has a sigmoid shape with the steepest decrease in task performance for 0.3≤STI≤0.5 (subsequent studies have suggested a refinement of this model, as reviewed by Haapakangas (2017)). Beyond an STI of 0.5, referred to as the distraction distance (r_D in meters), task performance is supposed to increase, which more-or-less means a reduction in the detrimental effect of speech. The work of Venetjoki et al. (2006), Haapakanas et al. (2008) and Haka et al. (2009) provide further evidence that a high STI has a more detrimental effect on work productivity than other surrounding noise sources with the same sound pressure level. Furthermore, distraction distance has recently been shown to be the metric most closely related to subjective impressions of office workers out of all the ISO 3382-3 metrics (Haapakanas et al. 2017), and is used in the present paper.

The other metric used in this paper is the speech-weighted spatial decay rate of sound pressure level (SPL) over distances, as specified in ISO 3382-3 (2012). The idea behind using this metric is that an elongated space such as a corridor is usually formed from reflecting surfaces, where noise reflections along the length will generally provide a poor spatial decay rate of SPL. A clear way of aiding the spatial decay of SPL over distance is to provide some absorption within the space. More equivocally, adding absorption may also reduce STI by reducing speech level, but this may also lower background noise and reverberation time, which would contribute towards the opposite effect on STI. In a corridor, since the area that is accessed by people will generally not be ideal for placing absorptive treatment, the ceiling above head height can be seen as an ideal area to provide some high noise absorption.

With the above in mind, the aim of this paper is to test and evaluate different ceiling absorption spatial configurations in a corridor to determine the performance of these configurations in providing increased spatial decay rates of SPL and in lowering the STI.

2 METHOD

Two sets of measurements were made, one in a model corridor tube (with the shape of a corridor; Figure 1) and one in a full scale corridor (Figure 2). Both these measurements included ceiling absorption in five different configurations:

- Empty: no added absorptive material
- Horizontal: flat absorptive panels forming a uniform layer along one of the surfaces
- Transverse: vertically oriented absorptive panels placed at equal intervals perpendicular to the length, along one of the surfaces
- Diagonal: vertically oriented absorptive panels placed at equal intervals at about 45 degrees with respect to the length, along one of the surfaces
- Long (refers to longitudinal): vertically oriented absorptive panels placed to form two straight uniform vertical lines at equal distances to the side walls, parallel to the corridor walls

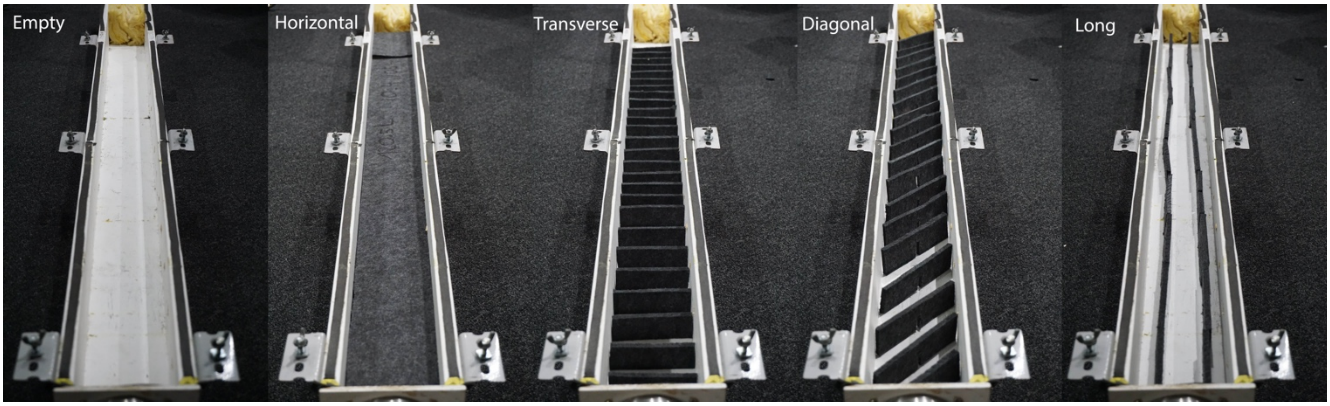

Figure 1: Photographs of the five absorption configurations (Empty, Horizontal, Transverse, Diagonal and Long), as arranged in the model tube corridor.

The absorptive materials used for the configurations above were tested in an impedance tube to determine their normal incidence absorption coefficients (Figure 3). The corridor material's single number ratings are $\alpha_w = 0.95$ and NRC = 0.68. Single number ratings are not given for the tube material due to its arbitrary scaling.

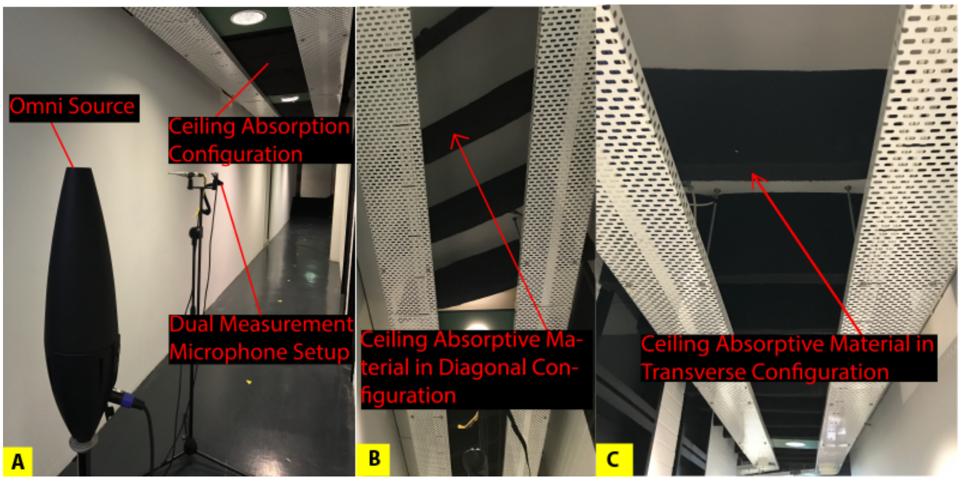

Figure 2: The corridor setup showing one of the sound source and microphone measurement placements, with the cable tray holding the absorptive material in the horizontal (A), diagonal (B) and transverse (C) configurations.

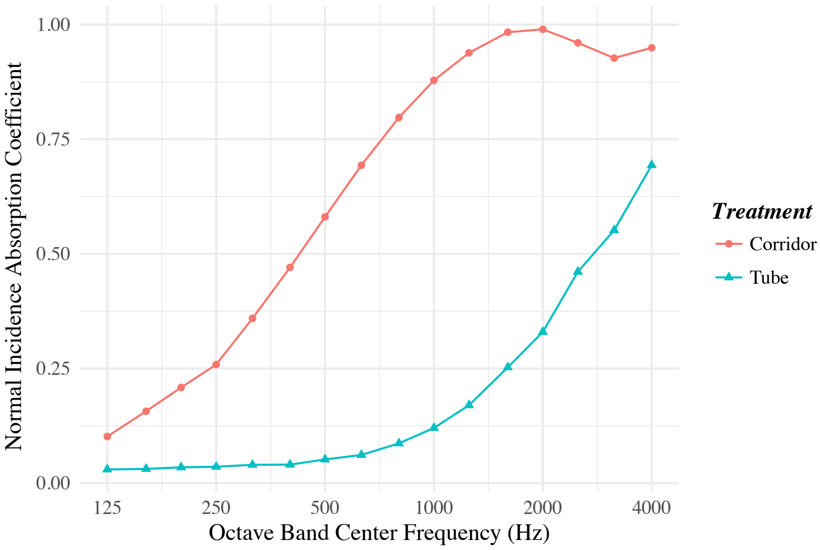

Figure 3: Normal incidence absorption coefficients of the materials used in the corridor and the tube.

2.1 Testing

2.1.1 Model Tube: Apparatus and measurement details

The model tube used for these measurements (L:1.5 m × H:0.1 m × W:0.1 m) is made of varnished heavy timber. The sound source was a Gallo Acoustics (San Antonio, TX, USA) loudspeaker with a 76.2 mm driver, which covered almost the entire aperture of one end of the tube. The other end of the tube was made fairly anechoic by filling it with 0.3 m of fibre glass wool. The material used to provide absorption was 0.005 m thick synthetic felt. It was cut and shaped to fit along the length of the tube whilst maintaining the different configurations. The material itself was chosen for its ease of access (during the measurement period) rather than its performance.

Around 40% of the model tube cross-section consisted of absorptive material; placed at 0.035 m intervals within the tube for the transverse and diagonal configurations, with a constant height of 0.04 m for all configurations.

The test signal used was an exponential sinusoidal sweep ranging from 90 Hz to 16 kHz. It was generated and recorded using a Matlab based signal processing suite, AARAE (Cabrera et al. 2014), at a sampling frequency of 48 kHz. This signal was amplified (B&K Audio Power Amplifier type 2716-C; Nærum, Denmark) and routed to the speaker through a RME Babyface (Haimhausen, Germany) unit that interfaced with a computer. This signal was preamplified, digitised and recorded (using RME Babyface) at fourteen positions that were along one side of the length at every 0.1 m, with an Earthworks M30 omnidirectional microphone (Milford, USA). During the measurements, the microphone was placed just off the centre of the tube at each measuring position to avoid the odd-order mode pressure null at the tube's centre. Each position was measured individually for each of the five configurations stated above (Figure 1).

2.1.2 Corridor: Apparatus and measurement details

The corridor used for this measurement (L:14 m × H:2.75 m × W:1.5 m) includes several wooden doors with door frames along its length, and the two open ends of the corridor (Figure 2). For testing purposes, both ends of the corridor were treated with absorptive polyester wool panels. Fourteen measuring positions were defined, at 1 m increments along the length. The same five configurations as used in the tube (Figure 1) were tested in the corridor ceiling, with the surface area of material being held constant. The material used was 0.075 m thick polyester wool panels. This material was cut to fit between the suspended cable trays and the ceiling, with a height of 0.4 m. Both the transverse and diagonal accounted for a 0.4 m gap between each element. This gap size was specified as to keep the surface area a constant. Absorptive material accounted for approximatively 14.5% of the corridor cross-section area.

In order to avoid strong influences of room modes on measured pressure, two microphones were used, one centred to the corridor width and another one 0.2 m to the side and the results were averaged (Davies, 1973). The microphones used were omnidirectional measurement microphones (Earthworks M30). The source used was an omnidirectional loudspeaker (B&K OmniSource Sound Source Type 4295). The signal emitted from the source was an exponential sinusoidal sweep spanning 16-16000 Hz. The rest of the apparatus and the signal chain was the same as described in section 2.1.1. To comply with the method described in ISO 3382-3 (2012), the corridor was measured in both directions for each configuration, where the source would be located at either end of the corridor for each set.

2.2 Data Analysis

For both the model tube and the corridor recordings, the relevant acoustical parameters were derived from impulse responses (IR; causal part trimmed at one second) for each source-receiver-material configuration within AARAE (Cabrera et al. 2014) and further processing was done within Microsoft Excel and Matlab.

For the model tube measurements, octave-band sound levels (in dB) were derived. While the tube was readily available, its dimensions did not scale to a usable multiple of the corridor in all its dimensions. An approximate working scaling factor of 1:10 was used to infer from the data of 1-16 kHz octave-bands. For each band, the sound levels were converted to level attenuations, with reference to the averaged level of the five treatments at the closest microphone position (0.1 m) from the loudspeaker. These level attenuations, which were expected to vary for the five absorption configurations, were intended to not only provide a proof-of-concept before a full-scale measurement, but also a reference for future comparisons in highly-controlled spaces.

For the real corridor measurements, the data was converted to *speech-weighted* values using the method outlined in ISO 3382-3 and analysed further for the five absorption configurations as follows:

<u>*Case 1*</u>: As 125–8000 Hz octave-band sound pressure levels (SPL; in decibels).
<u>*Case 2*</u>: As spatial decay-rate of A-weighted speech SPLs, per distance doubling ($D_{2,S}$). Instead of $D_{2,S}$ for the entire 2-13 m range of the measurement positions, 'near' and 'far' ranges corresponding to 2-8 m ($nearD_{2,S}$) and

8-13 m (*far*$D_{2,S}$) are considered here. This allowed comparisons of the effect of the absorption configurations within *near* and *far* ranges from the source, which may have some relevance for deciding on the absorption distribution along the length of a long corridor.
Case 3: As distraction distances (r_D in m). Speech transmission indices (STI) for deriving r_D were calculated using AARAE (Cabrera et al. 2014a,b). To comply with the ISO 3382-3 (2012) STI determination, auditory masking, hearing threshold and gender specific differences were not included.

To avoid confounding issues, values for background noise in indirect STI measurements calculations were held constant, based on a Room Criterion Mark II of RC35 (ANSI/ASA S12.2 2008).

For each of the cases above, separate statistical analyses were performed in the software R (R Core Team, 2013). Since the performance of the five absorption configurations was measured by the same twelve measurement locations in the corridor (1 m measurements omitted from further analysis), this represents a repeated-measure design, where the parameters derived per measurement location are correlated. These parameters, or response variables, were different for each case: octave band L_{eq} in case 1, L_{Aeq} in case 2, $D_{2,S}$ for case 3; speech-weighted values in each case. Mixed-effects models (one per case) were used to fit these response variables (fixed-effects in the mixed model) as a function of the different absorption configurations. The dependency of each configuration's measured values on the measurement microphones' location in the corridor was modelled as a random-effect (measurement location within configuration) in each mixed model. The mixed-effects models were created using the *lme* function from the *nlme* package (Pinheiro et al. 2014), using the maximum-likelihood method for estimating the parameters in the analysis. *Post-hoc* analysis was done using the function *glht* from the package *multcomp* (Hothorn et al 2013), with the means per configurations compared using Tukey's contrasts method.

3 RESULTS AND DISCUSSION

Figure 4 shows the tube results for two example octave-bands, where a difference between the empty and the other absorption configurations can be noticed; in particular, there are more pronounced level decays for the *transverse* and *diagonal* configurations. The 1 kHz band and part of the 2 kHz band are below the frequency at which the cross-tube modes occur (1.7 kHz), and so they emphasise the effect on sound that is mostly travelling along the pipe's length. However, at higher frequencies there is much less difference between the configurations' effects. This exaggerated distinction was expected, partly due to the simplicity and more controlled nature of the tube measurement method (compared to a real corridor). Nonetheless these results were seen to serve their purpose of encouraging further investigation of the different configurations in a full corridor.

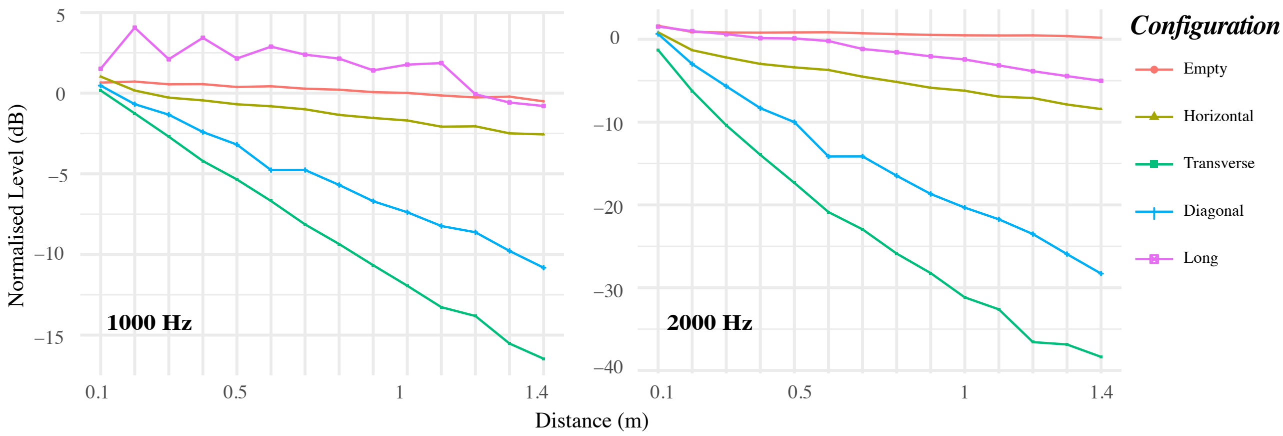

Figure 4: The normalized levels (section 2.2) for the five absorption configurations in the 1000 Hz and 2000 Hz octave-bands.

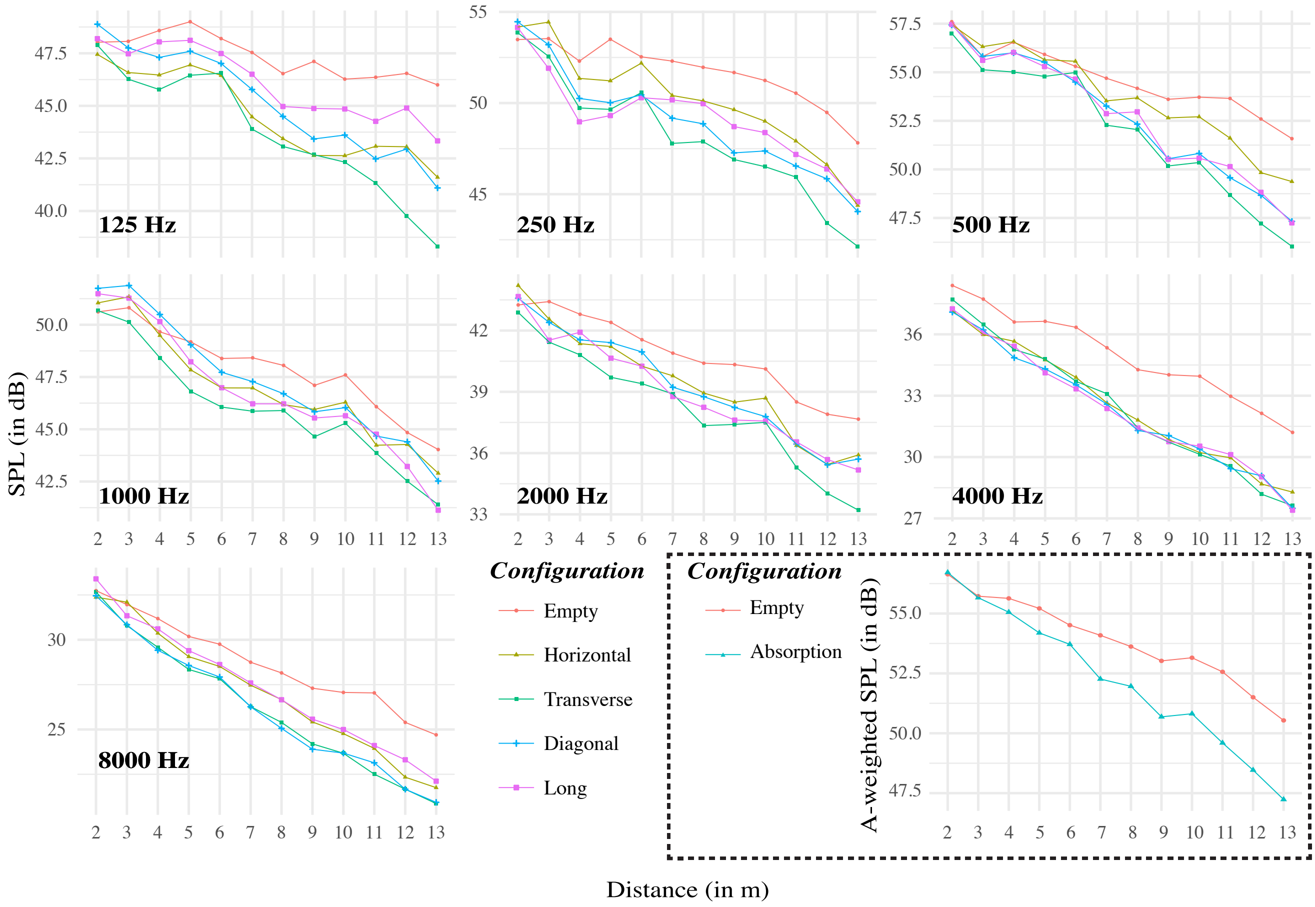

Figure 5: Speech-weighted octave-band sound pressure levels and A-weighted sound pressure levels (in the dashed subplot) for the corridor measurements. Note that the SPL scale for each subplot is different and the absorption configuration is different for the A-weighted subplot.

Figure 5 shows the speech-weighted and octave-band SPLs for the five absorption configurations. The mixed model analyses for case 1 (section 2.2) in each octave-band showed similar trends for the most part, so for brevity only significant results are reported here. Overall, the absorption configuration used had a significant effect on the speech-weighted SPL (this result is for the 500 Hz band, but other bands had similar statistics), $\chi^2(4) = 50.8$, $p<.01$. *Post-hoc* tests are presented in two parts. Overall, the speech-weighted levels were significantly higher in the empty configuration than the other absorption configurations, which can be expected as the adding absorption in any configuration should lead to lowering of sound levels (also seen in the dashed subplot in Figure 5). As far as the differences between the absorption configurations other than the empty one is concerned (i.e., horizontal, transverse, diagonal, long and transverse), Table 1 shows the cases where significance was reached in individual *post-hoc* tests for the octave-bands. Over the octave-bands (except 4000 Hz), the *transverse* configuration (shown in bold in Table 1) showed significantly lower levels more than any other configuration.

To aid comparison of the configurations in the corridor, reverberation times in octave bands are shown in Table 2. While a clear difference exists between the empty configuration and any configuration with absorptive material, a clear distinction cannot be made between the differences in reverberation times for configurations with absorptive material (Table 2).

From Table 3, presenting the results from the ISO 3382-3 methods (modified slightly here), it can be seen that for the close distance range (2-8 m), the spatial decays of A-weighted speech (*near*$D_{2,S}$) of all the configurations are similar. The averaged decay rate for the four absorption configurations is 2.4 dB, and with no absorption has a 1.4 dB decay rate (i.e. ~ 1 dB lower). However, the range of decay rates is more pronounced if the far range

(8-13 m) is considered, with the transverse configuration exhibiting ~ 1.5 dB higher values (not considering empty configuration). No further statistics was used here due to the limited sample size, but the results presented thus far suggest that the performance of the transverse configuration is potentially worth considering in future comparisons.

Table 1: *Post-hoc* comparison of speech-weighted sound pressure levels that reached significance (at least $p<.05$) per absorption configuration other than empty, per octave-band. Columns 3-5 show the estimated differences of the comparison, the associated standard error (*SE*) and *z*-value, respectively.

Comparisons	**Octave Band Center Frequency (Hz)**	**Difference**	***SE***	***z*-value**	***p***
Long vs. Horizontal	125	1.5	0.3	4.4	<.01
Diagonal vs. **Transverse**	125	1.5	0.3	4.1	<.01
Long vs. **Transverse**	125	2.4	0.3	7.0	<.01
Diagonal vs. Horizontal	250	-1.2	0.3	-3.4	<.01
Long vs. **Transverse**	250	1.1	0.3	3.2	<.05
Diagonal vs. Horizontal	500	-1.1	0.3	-3.5	<.01
Long vs. Horizontal	500	-1.1	0.3	-3.4	<.01
Diagonal vs. **Transverse**	1000	1.4	0.2	6.8	<.01
Horizontal vs. **Transverse**	1000	1.0	0.2	4.8	<.01
Long vs. **Transverse**	1000	0.8	0.2	3.7	<.01
Long vs. Diagonal	1000	-0.6	0.2	-3.0	<.05
Diagonal vs. **Transverse**	2000	1.1	0.2	5.8	<.01
Long vs. **Transverse**	2000	0.8	0.2	4.1	<.01
Horizontal vs. **Transverse**	8000	0.9	0.2	4.2	<.01
Long vs. **Transverse**	8000	1.2	0.2	5.4	<.01
Long vs. Diagonal	8000	1.2	0.2	5.3	<.01

Table 2: Octave band reverberation times (T20 in seconds) of the five corridor configurations

	Octave Band Center Frequency (Hz)						
Configuration	125	250	500	1000	2000	4000	8000
Empty	1.1	1.2	0.9	0.8	0.8	0.7	0.8
Horizontal	1.1	0.6	0.5	0.6	0.6	0.5	0.6
Transverse	0.9	0.6	0.7	0.6	0.5	0.5	0.4
Diagonal	0.8	0.6	0.5	0.6	0.5	0.5	0.4
Long	0.9	0.6	0.5	0.6	0.5	0.5	0.4

The distraction distance (r_D) values (Table 3), where lower values are preferred, demonstrate that a transverse configuration provides a lower distraction distance by about 4 m compared to an empty configuration. Other configurations only provided a little improvement in comparison – by about 1 m for the horizontal configuration and by approximatively 2 m for diagonal and longitudinal configurations. However, the results for distraction distances here should be interpreted within the context of the corridor measurement scenario, which is different to the more typical use of distraction distance in ISO 3382-3 (2012). The latter is used to characterise cognitive performance increase for workstations with STI≤0.5 from the speech source. Whereas in the case of the corridor measurement, the aim in using distraction distances is mainly to compare the spatial decay of STI for the five absorption configurations (Table 3). In other words, no cognitive performance characterisation is intended with the distraction distance values from the current corridor measurement. In this regard, although the results show a decrease in the distraction distances for the four absorption configurations compared to the empty one, it should be borne in mind that adding absorption will have affected the STI in two opposite ways: reducing the speech level reduces STI, while reducing reverberation time increases STI.

Table 3: For the five absorption configurations, the first row shows the spatial decay-rate of A-weighted speech SPLs, per distance doubling, $D_{2,S}$, for the *near* (2-8 m; in light orange), *far* (8-13 m; in light green) and the full (2-13 m; in yellow) ranges in the corridor. The second row shows the distraction distances, r_D

	Empty			Horizontal			Transverse			Diagonal			Long		
$D_{2,S}$ (dB)	1.4	4.1	2.0	2.2	5.9	3.0	2.4	7.4	3.6	2.5	5.9	3.5	2.5	6.6	3.5
r_D (m)	17.8			16.6			13.9			15.7			16.2		

4 CONCLUSIONS

In general, the current study presents preliminary findings that placement of absorptive treatment in the ceiling of corridors in certain geometrical configurations can function better acoustically than others. More specifically, absorptive material in a transverse configuration provided an overall greater decrease in A-weighted speech levels in the far field, and a lower distraction distance (ISO 3382-3 2012), when compared to other absorption configurations. From a geometrical acoustics perspective, this finding makes sense if we consider ray paths, which are likely to be maximally intercepted by the transverse configuration. Overall, the benefits of such findings could have an impact on the design parameters within office layouts, as to where and how corridors are built and how absorption is distributed. However, in order to reach that stage, further studies are required to investigate the effect of various geometries on speech attenuation in corridors. These geometries could be evaluated within acoustic software and in real corridors to determine their acoustic performance.

The findings of this paper can also be useful in treating the acoustics of long spaces in general, where rapid attenuation of sound level and speech intelligibility is crucial; examples being hospital corridors, educational establishments, etc. An analysis into the design and acoustic properties of such spaces could aid a further understanding of acoustically efficient corridors.

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