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Effect of office screens on the spatial decay of sound pressure level in open-plan offices

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ABSTRACT

Speech privacy is one of the most crucial, yet least satisfying aspects in open-plan offices. Background speech often causes high distraction and dissatisfaction. At medium to large distances speech intelligibility should be minimised to reduce the disturbing impact whereas at short distances intelligibility may remain high to support communication within teams. A holistic acoustical design takes the requirements of the occupants into consideration. Besides the zoning of teams and the application of an appropriate layout, the combined use of sound absorbers, screens and masking can diminish the impact of disturbing speech at medium to large distances. The height of the used screens can have a high impact on the spatial decay of sound pressure level and on the resulting speech privacy at medium distances. As part of this study sound pressure level measurements of 23 offices are clustered into three groups, namely 'no screens', 'half-high screens', and 'room-high screens'. The level differences at medium distances of 5–10 m are significantly different: whilst 'no screens' and 'half-high screens' result in level differences of 15–20 dB, 'room-high screens' yield level differences of 25–35 dB. This implies that only 'room-high screens' can reduce the disturbance by background speech at medium distances sufficiently.

Keywords: Open-plan office, Sound attenuation, Background speech

1. INTRODUCTION

1.1 Effects of Office Noise

Open-plan offices enable an efficient use of limited office space with typical spatial densities of 7 m^2 to 15 m^2 per person (e.g. an average size per workstation of 7 m^2, as reported by Veitch *et al.* (1)). Open offices may simplify communication and may support team collaboration. However, recent findings suggest that face-to-face interaction decreases in open office architectures as compared to traditional office spaces (2).

Particularly, speech privacy is considered to be among the least satisfying aspects of the indoor environmental quality in open-plan offices (3). Background speech that is heard from colleagues' conversations and telephone calls is perceived as the most distracting noise source (4–6).

Background sounds with changing-state features deteriorate the working memory performance which is known as the irrelevant sound effect (7). Spectral fluctuations of background sounds may affect the working memory performance more than level changes, and semantic content may have an additional effect (8). The overall sound pressure level (SPL) of background speech with good intelligibility (e.g. SPLs of 35–57 dB(A)) has no impact on the resulting distraction (9, 10).

The speech transmission index (STI), which is a metric to predict the speech intelligibility, is suggested to predict both subjective noise disturbance and work performance (5, 11–14). According to a model that predicts the effect of the STI on the performance of cognitively demanding tasks, concentration and privacy start to improve at STI values below 0.50 (11, 15). The threshold for improvement may even be at lower values, such as 0.45 (16). Good speech privacy may be achieved at SPI values as low as 0.20 (11, 15).

1.2 Office Acoustics

There are conflicting requirements on speech intelligibility in open-plan offices at short and large distances: whilst the acoustic design may facilitate communication over short distances (1–5 m), the disturbance by background speech and speech intelligibility have to be minimised at medium to large distances (> 5 m). The objective of reducing temporal-spectral variability and intelligibility of irrelevant background speech from adjacent workstations often dominates the acoustical design of open-plan offices. Multiple aspects have to be considered to achieve acceptable speech privacy, such as acoustically absorptive surfaces, effective sound screens, and the use of electronic sound masking (17–19). Furthermore, the architectural design and layout should include sufficient numbers of enclosed meeting rooms and the zoning of working teams.

Appropriate use of sound absorbers and sound screens can reduce the disturbance by background speech from large distances (> 10 m). The use of electronic sound masking and application of a controlled stationary background noise may become necessary to diminish the disturbance by background speech from medium distances of 5–10 m (15, 20).

Experience has shown that the SPL typically attenuates by 10–20 dB at medium distances in open-plan offices with a suspended ceiling and office screens. Therefore, at normal vocal effort of 59–60 dB(A) in 1 m distance the SPL may not attenuate below the background noise SPL (typically 35–55 dB(A) with a maximum range of 37–60 dB(A), as reported by Warnock (21)). However, a negative signal-to-noise ratio (SNR), i.e. the A-weighted SPL of the speech sound is below the A-weighted SPL of the background noise, is usually required to increase the speech privacy and working memory performance (11, 12, 22, 23).

Room acoustical set values mainly follow the goal of assessing the impact of background speech. The international measurement standard ISO 3382-3 (24) suggests the use of reverberation time, SPL measurements and parameters that are based on the STI. The Finnish standard guideline RIL 243-3-2008 (25) classifies target values into four classes. The values are based on the measurement parameters – spatial decay rate of speech $D_{2,S}$, A-weighted SPL of speech at a distance of 4 m $L_{p,A,S,4m}$, and distraction distance r_D. The Finnish room acoustic regulations from 2018 name target values of reverberation times below 0.6 s and STI values below 0.5 in open-plan offices (26). The French standard NF S31-199 (27) recommends spatial decay rates $D_{2,S}$ of more than 7–9 dB and reverberation times below 0.6 s (the target values depend on the work type, namely telephone work, collaborative work, low-level or non-collaborative work, and public receptions). The German standard guideline VDI 2569 (28) classifies the recommendations for maximum reverberation times and sound propagation into three groups. While target values of $D_{2,S}$ and $L_{p,A,S,4m}$ are provided, target values for STI measurements are neglected, and hence the effect of sound masking is not considered (29).

Offices with suspended ceilings and effective screens between adjacent workstations may meet the requirements of the highest level of sound attenuation ($D_{2,S} \geq 8$ dB, $L_{p,A,S,4m} \leq 47$ dB). ISO 3382-3 (24) names values of $D_{2,S} \geq 7$ dB, $L_{p,A,S,4m} \leq 48$ dB, and $r_D \leq 5$ m as an example of target values for good acoustic conditions. However, such values are rarely achieved in the field (14, 15, 30).

Room-high sound screens are one possibility to meet the requirement of minimising the disturbance by background speech at medium to large distances (31, 32). Offices with room-high sound screens between adjacent workstations, as shown in Figure 1, may reach values as high as $D_{2,S} \geq 14$ dB $L_{p,A,S,4m} \leq 42$ dB, and $r_D \leq 5$ m (33, 34).

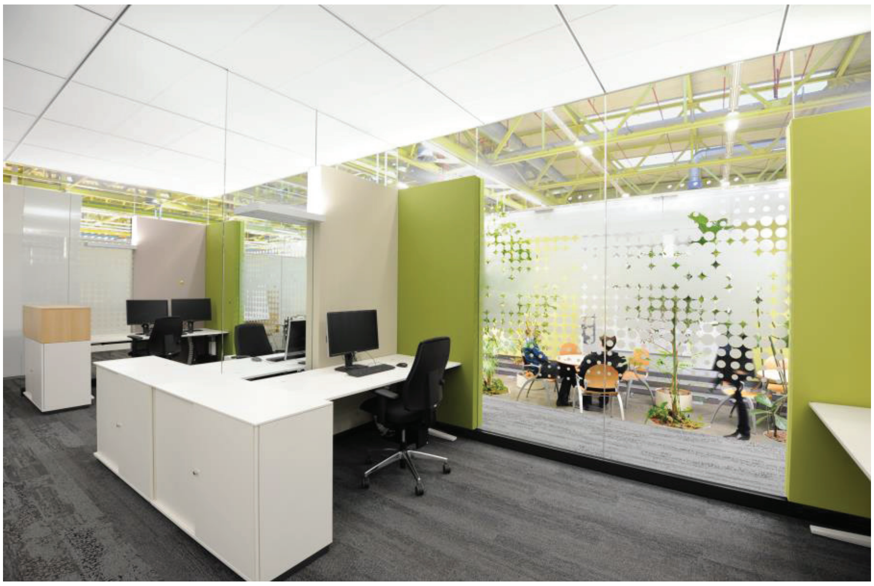

Figure 1 – Open office with room-high sound screens between adjacent workstations

Since the spatial decay rate of speech $D_{2,S}$ does not consider the absolute attenuation of SPL in the near field and the distraction distance r_D only denotes the distance at which STI values of 0.5 are measured, the results of all values should be considered in combination to assess the acoustical quality (cf. Ref. 14). Moreover, the STI measurements consider the background noise SPL in unoccupied conditions which may not be representative for the acoustic conditions during working hours. Hence, absolute A-weighted SPL measurements (in occupied and unoccupied conditions) may be more meaningful when only one measurement parameter is to be compared.

1.3 Aim of This Study

This study analyses SPL measurements of 23 offices. The measurement data is clustered into three groups, namely ‘no screens’, ‘half-high screens’, and ‘room-high screens’ (see Figure 2). The absolute SPL values and resulting sound attenuation at different distances are compared and visualised. The significance of SPL measurements at different distances and the effect of different office screen heights on the SPL at these differences are discussed. For this reason three distance ranges are defined: small distances (1–5 m), medium distances (5–10 m), and large distances (> 10 m).

Figure 2 – Illustration of room-high I-shaped sound screens (left) and T-shaped sound screens (right)

2. METHODS AND MATERIALS

2.1 Measurement Data

The analysed data consists of 23 field measurements performed in German, Austrian and Swiss open-plan offices during 2011 and 2018. SPL is measured with a sound level meter NTi XL2 (NTi Audio AG, Schaan, Liechtenstein) and NTi M2210 class 1 certified 1/2 in pressure microphone at a height of 1.2 m. The loudspeakers Genelec 8040A (Genelec Oy, Iisalmi, Finland), Blaupunkt Velocity 2GO (Blaupunkt Europe GmbH, Schönefeld, Germany) or NTi DO12-S are used as sound source. Pseudo random pink noise is used as measurement signal. Table 1 summarises the properties of the open-plan offices in which the measurements are done.

2.2 Design and Procedure

The SPL is measured at workplaces in the analysed offices. These measurements are subtracted from the SPL measurement at 1 m distance (measured in an open area in the same office) which provides an SPL difference at a distance x from the source. All data points (SPL, x) are clustered into the following three groups:

- ‘no screens’: no office screens on the measurement paths.
- ‘half-high screens’: half-high barriers (office screens, cabinets, etc. with approx. 1.3–2.0 m height) on the measurement paths.
- ‘room-high screens’: screens from floor to ceiling (combination of glazing and acoustic panels with approx. 2–3 m width) on the measurement paths.

In a first step, all data points are depicted in a semi-log plot with the SPL difference over log2(x). The same data is shown in a limited distance range of 2–16 m, as suggested by ISO 3382-3 (24) to determine the spatial decay rate of speech $D_{2,S}$. The resulting level differences are compared to the determined spatial decay rates of speech $D_{2,S}$.

In a second step, the data points between 1 m and 10 m distance are shown in a graph with the SPL difference over the distance x between source and receiver. These data points are analysed separately because the screen height not only has a significant effect on the resulting SPL differences, but also on the speech privacy (at medium distances of 5–10 m).

Table 1 – Properties of the open-plan offices

No.	Office screens	Ceiling	Spatial decay $D_{2,S}$, dB	Reverberation time, s	Speaker
1	room-high screens	treated	8.2–12.4	0.29	Velocity 2GO
2	no screens	treated	6.5	(0.26)	Velocity 2GO
3	room-high screens	treated	12.8	(0.26)	Velocity 2GO
4	room-high screens	treated	6.9–7.0	0.25	Velocity 2GO
5	room-high screens	treated	6.6–11.6	(0.30)	Velocity 2GO
6	no screens	treated	3.7	0.46	–
7	room-high screens	treated	12.5	0.42	8040A
8	room-high screens	treated	11.5–12.7	0.34	8040A
9	room-high screens	treated	6.1–6.3	0.20	Velocity 2GO
10	room-high screens	treated	10.7–12.5	0.30	Velocity 2GO
11	room-high screens	treated	7.8–11.8	–	8040A
12	room-high screens	treated	11.8	0.32	DO12-S
13	no screens	concrete	4.5–7.1	0.46	8040A
14	no screens	treated	7	0.48	8040A
15	half-high screens	treated	5.7–6.8	–	Velocity 2GO
16	room-high screens	treated	10.3	0.29	DO12-S
17	half-high screens	treated	7.7	0.61	Velocity 2GO
18	room-high screens	treated	8.5–17.3	0.23	DO12-S
19	half-high screens	treated	6.4	0.37	DO12-S
20	room-high screens	treated	12.7	0.27	DO12-S
21	room-high screens	concrete	10.4–13.0	0.32	Velocity 2GO
22	half-high screens	treated	5.8–8.3	0.40	8040A
23	half-high screens	treated	3.9–5.4	0.57	8040A

3. RESULTS

Figure 3 depicts the determined SPL differences. Measurement points in offices with ‘no screens’ and ‘half-high screens’ result in similar SPL differences at same distances whilst the regression line of the measurements with ‘half-high screens’ is slightly steeper. Three of the four analysed offices with ‘no screens’ have highly absorptive acoustic ceilings (suspended ceiling with mineral fibre boards or ceiling sails) whereas most of the offices with ‘half-high screens’ have less absorptive ceilings (concrete partly covered with ceiling sails or acoustic baffles). The effect of ceiling absorption on speech privacy may be as large as the effect of screen height (17). The small differences between ‘no screens’ and ‘half-high screens’ may be explained by the small screen height (approx. 1.3–2.0 m) and variation due to the relatively small number of data points (26 measurements with ‘no screens’ and 43 measurements with ‘half-high screens’ as compared to 121 measurements with ‘room-high screens’).

Figure 4 shows the determined SPL differences in a limited distance range of 2–16 m. The regression line of the measurements with ‘room-high screens’ is much steeper than the other two regression lines. The positions of the regression lines of ‘no screens’ and ‘half-high screens’ are comparable while the regression line of ‘room-high screens’ is shifted to larger SPL differences. Offices with ‘room-high screens’ result in much larger SPL differences than offices with ‘no screens’ or ‘half-high screens’.

Figure 5 depicts the SPL differences over the distance on a linear axis. The SPL differences in offices with room-high screens in the near field at small distances (1–5 m) vary highly (between 0 dB and –34 dB). These variations are caused by deviating measurement positions behind the first sound screen and in front of the first sound screen (line of sight to the speaker, i.e. no screen between speaker and receiver). Different screen shapes and widths, different numbers of screens (screen between every second or every fourth workplace), and different sound reduction indices of the screens due to different air tightness (some screens are not mounted joint-tight) may also contribute to variability.

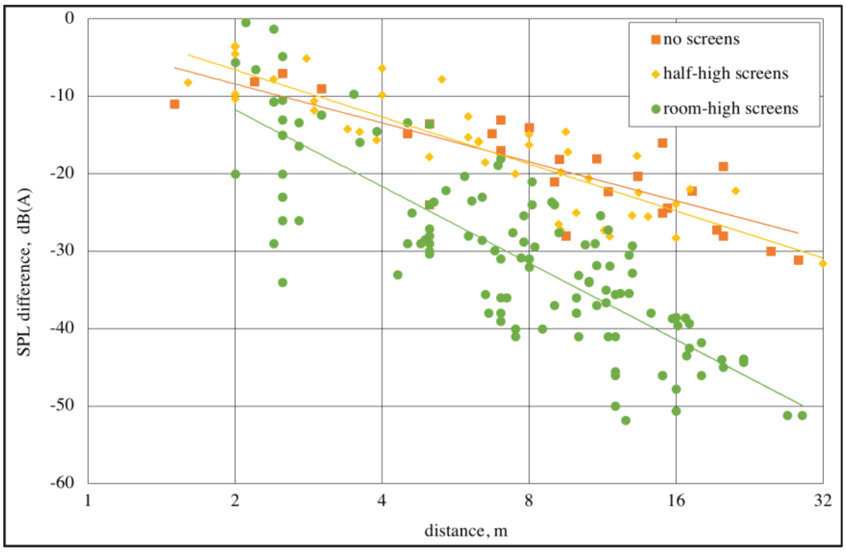

Figure 3 – Measured SPL differences over log2(distance)

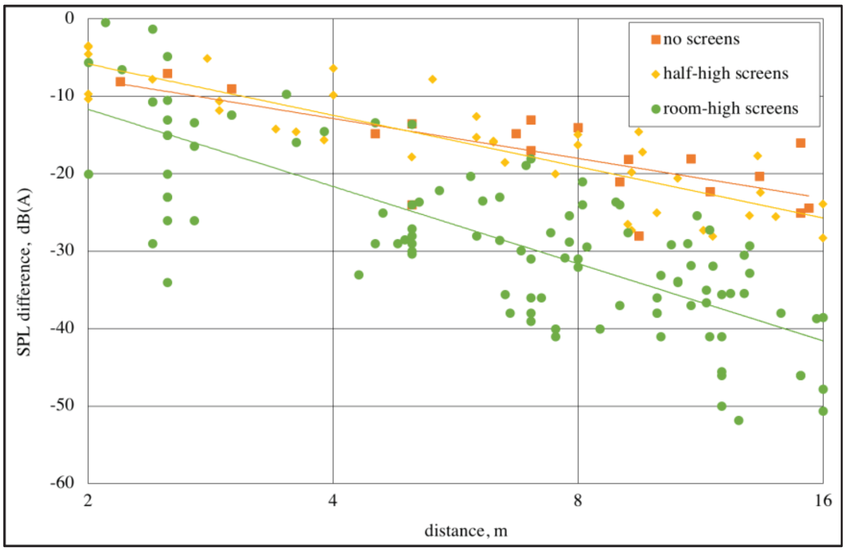

Figure 4 – Measured SPL differences over log2(distance), limited to distances from 2–16 m

The SPL differences at medium distances (5–10 m) with ‘no screens’ and ‘half high-screens’ are similar and on an average between –15 dB at 5 m and –20 dB at 10 m. Offices with ‘room-high screens’ result on an average in SPL differences of –25 dB at 5 m and –35 dB at 10 m. The absolute SPL differences at these distances range from approx. 13–28 dB, 8–27 dB, and 14–41 dB for measurements with ‘no screens’, ‘half-high screens’, and ‘room-high screens’, respectively (9, 16, and 43 data points).

The spatial decay rate of speech $D_{2,S}$ was on an average at 6 dB (4.5–7.1 dB) on measurement paths with ‘no screens’, at 6 dB (3.9–8.3 dB) on measurement paths with ‘half-high screens’, and at 11 dB (6.1–17.3 dB) on measurement paths with ‘room-high screens’.

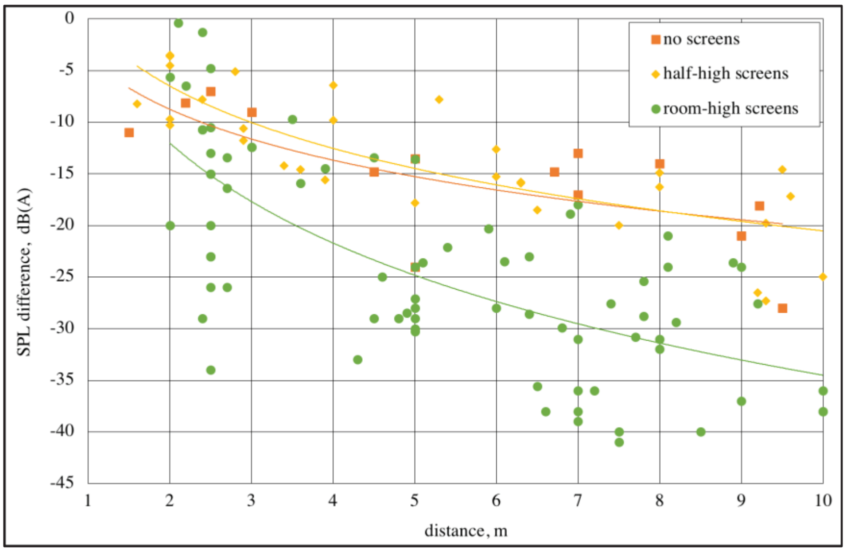

Figure 5 – Measured SPL differences over distance, limited to distances from 1–10 m

4. DISCUSSION

The determined SPL differences at medium distances of 5–10 m are significantly different: whilst the first two groups ('no screens' and 'half-high screens') result in SPL differences of approx. 15–20 dB, offices with 'room-high screens' yield level differences of approx. 25–35 dB. This implies that only offices with 'room-high screens' can reduce the disturbance by background speech at medium distances sufficiently.

The spatial decay rates that were determined on measurement paths were notably higher for 'room-high screens' than 'half-high screens' and 'no screens'. The results also imply that spatial decay rates in offices with room-high sound screens may depend highly on the position of the first measurement point (first measurement position at 2 m distance behind the first sound screen or in front of the first sound screen with no screen between speaker and receiver).

Absolute SPL measurements, such as A-weighted SPLs of speech at distances of 4 m $L_{p,A,S,4m}$, 8 m $L_{p,A,S,8m}$, and 16 m $L_{p,A,S,16m}$ (or at respective workstations), are expected to be more meaningful in such cases. While speech from 4 m distance may still be intelligible and disturbing in open-plan offices with low background noise SPLs of 30–40 dB (mean SPL difference over 20 dB for 'room-high screens'), acceptable levels of speech privacy are expected at distances of 8 m from the speech source (mean SPL difference over 30 dB for 'room-high screens'). This may allow small teams (approx. 4 workers) to collaborate whilst they are not distracted by other office occupants.

5. FINAL REMARKS

The German guideline VDI 2569 (28) recommends the combined assessment of $D_{2,S}$ and $L_{p,A,S,4m}$ measurements to characterise the sound propagation in open-plan offices. In practice, $D_{2,S}$ is often taken into account whilst $L_{p,A,S,4m}$ does not receive as much attention as $D_{2,S}$. Combined considerations of $D_{2,S}$ and $L_{p,A,S,4m}$ may have a similar meaning as absolute SPL measurements at workstations. However, $D_{2,S}$ is often understood as a metric of mean sound attenuation, but it only describes the behaviour between certain distances (measurements at 2–16 m according to ISO 3382-3 (24)). Furthermore, the determined values vary highly depending on the selected measurement paths and locations. When the closest measurement point is separated from the speaker by a sound screen, the resulting values of $D_{2,S}$ are lower as compared to a measurement with the first measurement point not being separated from the speaker by a sound screen. Particularly in offices with room-high screens the values may vary highly. $D_{2,S}$ also depends greatly on the measurement path and cannot predict the spatial decay at short distances. Moreover, Haapakangas *et al.* (14) show that there is no correlation between $D_{2,S}$ and the percentage that are highly disturbed by speech or by noise in general.

Established measurement procedures in open-plan offices, such as the consideration of $D_{2,S}$ and $L_{p,A,S,4m}$ values may be misleading and insufficient to characterise offices with room-high sound screens. The screen height and screen shape may have a high effect on the SPL differences and not on the rate of spatial decay per distance doubling, as illustrated in Figure 3 and Figure 4. The reduction to two single values may indicate a measurement accuracy and reproducibility which does not necessarily exist (e.g. Refs. 35, 36). It is highly recommended to consider additional parameters besides reverberation time, $D_{2,S}$ and $L_{p,A,S,4m}$ in the acoustical design of offices (cf. Ref. 30), such as STI and SPL values at multiples locations (e.g. Ref. 37).

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