PREDICTION OF SPEECH TRANSMISSION INDEX IN OPEN-PLAN OFFICES

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1. INTRODUCTION

According to questionnaire studies, speech is the most annoying sound source in open-plan offices [1]. The most distracting speech comes from the nearest workstations. Therefore, speech privacy between workstations should be as high as possible, that is, the speech transmission index, *STI*, should be low. This presupposes that the speech is properly attenuated, e.g. using absorbents, screens, and masked by using sufficient but not annoying background noise. Also the mutual distances and orientations of the workers are important.

There are practically no regulations regarding the acoustical design of open-plan offices in Finland. Conventionally, HVAC designers aim at 35 dBA regarding HVAC noise and architects choose the absorption materials mainly by their visual properties. Office screens are seldom higher than 130 cm. As a result, workers complain about the speech disturbance, both from close and distant workstations. The acoustical reasons for the complaints are insufficient speech attenuation and speech masking. In single rooms, speech noise is not the most disturbing noise source because the speech levels are, inherently, lower and one can reduce the noise by closing the door, whenever needed. Continuous distraction due to speech leads to reduced work performance and productivity of work. Therefore, the need for better acoustical design is evident.

At the moment, there are no simple models, which could help the architects in room acoustical design of open-plan offices. The aim of this study is to present a simple and validated model that can predict the *STI* between two nearby workstations and facilitate the all-inclusive design of open-plan offices.

2. METHODS

2.1. The model

Speech intelligibility was described using the Modulation Transfer Function method, which gives the *STI*, or the rapid speech transmission index, *RASTI*. The value of *STI* can be within 0 and 1. High value of *STI* means high speech intelligibility and vice versa. E.g. in classrooms, high *STI* is desired, but between workstations in open-plan offices we choose an opposite scale. We should aim at low *STI* value, that is, high speech privacy.

The prediction of *STI* presupposes that the signal-to-noise ratio of speech and the early part of the local reverberation time at the listener's location are known. The speech level propagating different paths and masking noise level from different sources are calculated using conventional room acoustical principles. The speech and masking noise paths are presented in Figure 1. Speech through the screen (1), reflected speech via ceiling (2), diffracted speech over the screen (3) and reverberant speech (4) were involved. Masking noise sources comprise, e.g., ventilation, office equipments, and artificial masking system (5-7). The full description of the theory is given in our recent paper [2] of which a summary is given below.

The signal-to-noise ratio of speech (speech-to-noise ratio, *SNR*) is defined by

$$L_{SN} = L_S - L_N \tag{1}$$

The speech level, L_S, in the receiver's position is calculated by

$$L_S = 10 \lg \sum_{i=1}^{n} 10^{L_{p,i}/10} \tag{2}$$

where $i=1\ldots4$ (see Fig. 1). The short form of the speech level is for paths 1-4 as follows:

$$L_S = 10 Lg \left[\begin{array}{c} 10^{\frac{L_W}{10}} \cdot 10^{-\frac{R}{10}} \cdot \frac{1}{4\pi d_1^2} + 10^{\frac{L_W}{10}} \cdot \frac{1}{4\pi d_2^2} \cdot (1-\alpha_c) \\ + 10^{\frac{L_W}{10}} \cdot \frac{1}{4\pi d_1^2} \cdot \frac{1}{3 + 40\dfrac{x_3 + x_4 - d_1}{\lambda}} + 10^{\frac{L_W}{10}} \cdot \frac{4(1-\alpha_R)}{S\alpha_R} \end{array} \right] \tag{3}$$

where R (dB) is the sound insulation of the screen (dB), d_1 (m) is the head-to-head distance between the workers, d_2 (m) is the path length of the ceiling reflection, α_c is the Sabine's absorption coefficient of the ceiling, x_3 (m) is the distance between the speaker's head and the top of the screen, x_4 (m) is the distance between the listener's head and the top of the screen, λ is the wavelength of sound (m), S (m^2) is the effective room surface area coupled to the pair of workstations, and α_R is the average room absorption coefficient. The sound power level of speech, L_W, is in conformance with ANSI S3.5:1997 (59 dBA at a distance of 1 m).

Path 1 is nearly negligible in the presence of a screen but it is the most important if screen is used. The amplitude of the reflected path 2 depends on the room height and the absorption coefficient of the ceiling. The importance of path 2 is the stronger, the lower screens are used and the harder ceiling we have. Path 3 is calculated by a simple diffraction model of ISO/DIS 17624. Path 4 is the reverberant path and it gives the diffuse speech reflections not mentioned above. α_R can be determined indirectly by measuring the reverberation time. Then, we need also the effective room volume.

The masking level, L_N, is calculated as the sum of paths 5-7.

The speech transmission index is calculated with MTF method (*modulation transfer function*). The first step is the calculation of the modulation reduction factor $m(F,f)$ at 14 modulation frequencies F_i (0.63, 0.80, 1.00, 1.25, 1.60, 2.00, 2,50, 3.15, 4.00, 5.00, 6.30, 8.00, 10.00 ja 12.5 Hz) and at seven octave bands f_j (125, 250, 500, 1000, 2000, 4000 and 8000 Hz) as follows:

$$m(F,f) = \frac{1}{\sqrt{1 + (T(f) \cdot 2\pi F/13.8)^2}} \cdot \frac{1}{1 + 10^{-L_{SN}(f)/10}} \tag{4}$$

where $T(f)$ is the local early decay time (*EDT*, T_{10}). Here we assume that only diffuse sound is involved. If the effect of direct sound has to be considered, see reference [4]. The apparent signal-to-noise ratio is calculated for the 98 *m*-values by

$$SN_{app} = 10 \lg \frac{m}{1-m} \tag{5}$$

If SN_{app}>15 dB, we use SN_{app}=15 dB. Correspondingly, if SN_{app}<-15 dB, we use SN_{app}=-15 dB. *STI* is then

$$STI = \frac{1}{30}\left\{15 + \sum_{j=1}^{7} k_j \cdot \left(\frac{1}{14}\sum_{i=1}^{14} SN_{app}\left(F_i, f_j\right)\right)\right\} \qquad (6)$$

where the weighting factors, k_j, at 125 … 8000 Hz are 0.13, 0.14, 0.11, 0.12, 0.19, 0.17 and 0.14. The short version of *STI*, or *RASTI* (*rapid speech transmission index*) uses only 9 data points:

$$RASTI = \frac{1}{30}\left\{15 + \frac{1}{9}\left(\sum_{i=3,6,9,12} SN_{app}\left(F_i, 500\,Hz\right) + \sum_{i=2,5,8,11,13} SN_{app}\left(F_i, 2000\,Hz\right)\right)\right\} \qquad (7)$$
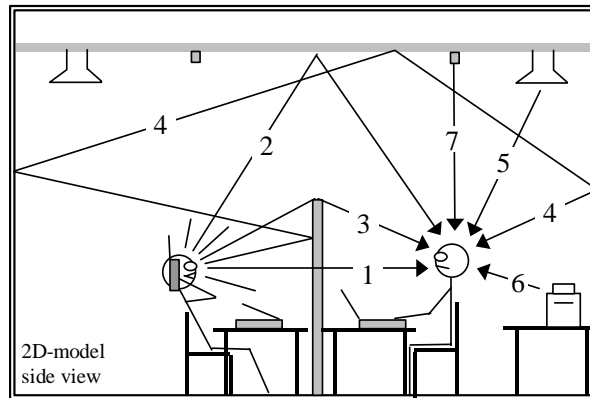
Figure 1. *Principle of the model. Speech paths (1-3), reverberant speech (4) and masking sound (5-7).*

2.2. Measurements in situ

The model was validated using 30 randomly selected workstations *in situ*. The *RASTI* value was measured as shown in Figure 2 (Bruel & Kjaer 3361). For the modelling, the background noise level L_N, room height h_C, screen height h_S, room volume V, early decay time T_{10}, and ceiling absorption coefficient α_C were recorded. Ceiling absorption material was identified visually and material databases were applied.

Figure 2. *Measurement of RASTI between workstations. The screen is behind the palm.*

3. RESULTS

The correlation between measured and predicted *RASTI* between 30 office workstations is presented in Figure 3. The prediction accuracy of *RASTI* was -0.03±0.04. The standard error of *RASTI* measurements was approximately ±0.02 in constant background level. Thus, the prediction accuracy of the model was satisfactory.
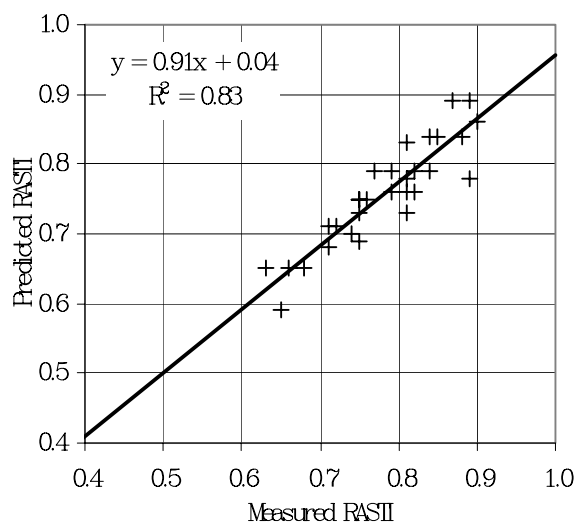
Figure 3. - *Measured vs. predicted RASTI (n=30).*

4. DISCUSSION

We assumed that the abovementioned accuracy holds at least in the *RASTI* range 0.40 … 1.00, while the validation was done only in the range 0.63 … 0.90. Unfortunately, we could not find adjacent workstations with lower values of *RASTI* because background noise levels were seldom higher than 40 dBA. The reason for that is the present regulation for the HVAC noise, which is in offices $L_{Aeq} \leq 35$ dB. There were no workstations where all design factors (absorption, masking and screens) had been considered simultaneously. Screens heights varied between 0 and 210 cm. Ceiling absorption coefficients varied from 0.03 to 0.85. The variation of background noise level was 29…42 dBA, but high background noise level never occurred in connection with high screen and high ceiling absorption. The extrapolation of the accuracy of the model below 0.60 is justified because the effect of background noise on *STI* is very straightforward according to the MTF-theory.

The prediction model should be extended to the far field in the future. In addition, the model should be validated against the recent laboratory data, where the effect of open-plan office parameters on *STI* was studied experimentally [3]. In practical design, it would be very valuable to provide also the disturbance area of speech in the office, e.g. expressed in square meters around the talker where *RASTI*>0.50. This supplementary information together with workstation-to-workstation *STI* would facilitate the application of the new model because the concept of *STI* is not familiar to most people.

The workstations of the experimental part represent typical Finnish open-plan offices. In general, background noise levels are too low, ceiling absorption materials are used ineffectively, and screens are low. In order to have acoustically good open-plan offices with high speech privacy, the signal-to-noise ratio should be close to zero or even below it. According to MTF-theory, the reverberation time should be very long to obtain low *STI*. However, this is not recommended in offices because people start to complain about poor conversational acoustics. Long reverberation will lead to inherent raising of voice level which, in turn, will reduce speech

privacy. Therefore, it is recommended to have a short reverberation time in offices. To reach high speech privacy, all factors (masking noise, absorption screens) should be considered simultaneously. The design of one or two factors is not enough.

Figure 4 was drawn to elucidate the combinatory effect of speech level, masking level and reverberation on *STI* in different office designs (limiting cases). We assumed that the speaker-to-listener distance is 2,4 m, and the room size is 20x20x2.5 m. The direct speech and directivity of speech and hearing were considered in the calculation of *STI* in Cases A, B and E by Reference [4].

Case A corresponds to the hypothetical initial situation where no acoustical treatments are used. The speech level is 55 dBA and the background noise level, caused by HVAC and office equipment (paths 5 and 6), is low, 35 dBA. *SNR* is high leading to fairly high *STI*. In Case B, the ceiling is covered with absorbents leading to a reduction of reverberation time, and a 3 dB reduction both in speech level and HVAC-level. *SNR* remains the same as in Case A so that the net effect of ceiling absorption is the increase of *STI* (reduction of speech privacy). This demonstrates that *STI* is very sensitive to *EDT*, if *SNR* is large. In Case C, where we have only screens without absorbing ceiling treatment, the effect on *STI* is apparently more beneficial than in Case B because long *EDT* and the reduced *SNR* together cause a reduction in *STI*. However, workers do not like this situation because the reverberation itself is annoying and conversation with a normal voice level can be difficult, like also in Case A.
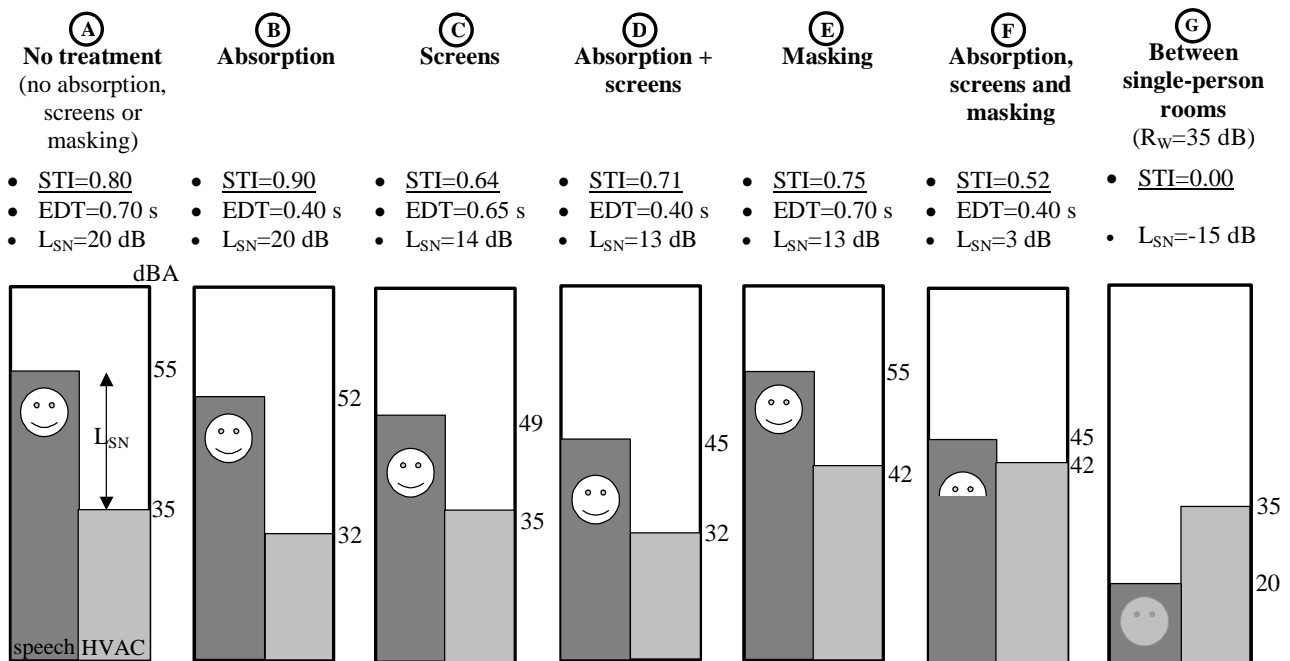
Figure 4. *The effect of different acoustical designs on STI in offices.*

In Case D, we combine both absorption and screens, which leads to a further reduction in *SNR* but an increase of *STI* compared to Case C. The reason for that is the reduction of *EDT*. In Case E we choose only artificial masking, with a spectrum of approximately -5 dB/octave within 125 … 8000 Hz. (Paths 5-7 were assumed to have the same spectrum as for speech.) Because of reduced *SNR* and high *EDT*, we get *STI*=0.75.

When we combine all factors, absorption, screens and masking, *SNR* reduces down to 3 dB and we get a

reasonably good speech privacy, *STI*=0.52. Case F is the recommended design in open-plan offices, where high demands are placed to the room acoustics, e.g. due to high requirements for concentration.

It should be noted, that when we have two adjacent single rooms with a typical sound insulation, like in Case G, the *SNR* falls below -15 dB and *STI* is 0.00. When doors are open, we get typically *STI*≈0.40, which is still below the *STI* of Case F. In open-plan offices, we can get *STI*<0.50 only by increasing the background noise, by reducing the speech level or by increasing the distances between workstations. However, igher masking levels than 43…46 dBA are not recommended because the annoyance of masking becomes too high. We assume that Case G is economically more effective way to obtain good acoustics than Case F.

A recent study [5] gives evidence that the speech levels in open-plan offices can be a few decibels lower than the standard speech level of ANSI S3.5, which was used in this study. This means that the *SNR* becomes automatically lower and low *STI* values are easier to reach than expected, e.g. in Figure 4. However, standard speech level is, at the moment, the most appropriate starting point for the modelling.

Successful design of open-plan offices requires also other things than proper workstation-to-workstation acoustics. They are, e.g. proper isolation of meeting and break rooms, building of anonymous retiring rooms for intensive work periods, soft carpets at least in main corrodors, isolation of common office equipments, and rules for general behavior in the open-plan office, which promote the use of lowered voice and lowered levels of phone rings. Wall absorbers become the more important the smaller rooms we have because the lateral reflections are as important as ceiling reflections. Acoustical consultant should not forget these tools during practical work because all room-acoustical points of view can seldom be put into practice because of economical or architechtural reasons.

5. CONCLUSIONS

A simple and accurate model for the prediction of *STI* in open-plan offices could be developed. The prediction model can be applied in the acoustical design of adjacent workstations in open-plan offices.

6. ACKNOWLEDGEMENTS

7. REFERENCES

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