Office noise reduces work performance – A tool to assess the payback time of room acoustic investments

Valtteri Hongisto[1]

[1]Turku University of Applied Sciences, Turku, Finland
valtteri.hongisto@turkuamk.fi

Abstract

Office noise consists mainly of colleagues' irrelevant speech. It disturbs employees in open-plan offices. Hongisto (Indoor Air, 15, 2005) presented a model that expressed a relationship between work performance and Speech Transmission Index (STI) of irrelevant speech. The model stated that performance reduces with increasing STI, i.e., with increasing subjective intelligibility of speech. The model was based on limited experimental evidence. Haapakangas et al. (Indoor Air, 30, 2020) published a systematic literature review to revise the model of Hongisto. The revised model was based on strong scientific evidence supporting that increasing STI leads to decreasing performance for tasks requiring verbal short-term memory. The maximum performance decrement at high STI values reached 16% instead of 7% suggested by Hongisto. The revised model enables the assessment of the payback time of room acoustic investments based on STI data.

Keywords: Business premise design, productivity, noise annoyance, open-plan offices, acoustic design.

1 Background

Open spaces have been applied in office work since the beginning of 19th century. At that time, the office work was industrial work since clerical workers did those routine tasks that computers nowadays do. It was acknowledged already in 1950's, that acoustic problems may arise from colleagues' speech in open working areas [1]. Therefore, professionals were mainly working in private rooms.

When computers became popular in 1980's, the share of clerical workers reduced, and the share of professional workers increased. Professional work requires better acoustic privacy due to confidential conversations and concentration demanding work tasks. Building private office rooms for all professionals was found to be too expensive and inflexible. Therefore, landscape and open-plan offices were developed. They were said to reduce rental costs, increase flexibility of space, and increase collaboration and communication compared to private office rooms. Open-plan office contains modular office workstations, which can be surrounded by fixed or mobile screens.

Because the share of concentration demanding tasks can be large in professional work, office noise became an issue. In Finland for example, media increasingly published articles about the office noise problem in 1990's. At the same time, many other challenges of indoor environment (draught, heat, smells, glare, etc.) could be identified. Therefore, a large national research project was funded in 2001–2004 called "Productive Office 2005". The purpose of the project was to develop models that explain how the indoor environment affect work performance. The models could be used to foster investments on qualified physical indoor environment. One work package focused on office noise.

A literature review was conducted in 2004. It revealed a couple of interesting points, which were used in the development of the office noise model:

- Steady-state noise affects cognitive performance only at high levels, above 85 dB [2], but the sound level in offices was typically much lower (50–55 dB L_{Aeq8h}) and the noise was dominated by speech and human activities, not by steady-state sounds;
- Irrelevant speech deteriorated work performance [3] even at low sound level such as 40 dB L_{Aeq} [4];
- Performance loss due to speech increases with increasing signal-to-noise ratio of speech [5], i.e., the sound level difference between speech and steady-state background noise;
- Subjective speech intelligibility in a room could be determined by a physically measurable quantity called Speech Transmission Index, STI [6], which depends on signal-to-noise ratio and reverberation time of the room;
- STI in an open-plan office depends strongly on its room acoustic quality and distance from the speaker [7];
- SII (Speech Intelligibility Index, a relative to STI) was already used in Canada as an objective variable to predict acoustic privacy in open-plan offices [8].

Because STI was increasingly used in 2004 among acousticians to describe the room acoustic conditions in communication rooms, the time was found to be mature to use STI as a primary objective quantity also in offices. If STI would be associated with performance, the quantity would be even more valuable since office workplaces could be objectively assessed according to their quality regarding work performance. This approach would facilitate the discussion about the profitability of acoustic investments.

The first psychological experiment using STI as an independent variable was conducted in 2004 [9]. Thirty-six subjects participated in an experiment where different tasks were conducted in three conditions: STI 0.00, 0.30, and 0.80. In all of them, the overall sound level was 48 dB L_{Aeq} – only the signal-to-noise ratio of speech was modified between the conditions. Proof-reading performance reduced with increasing STI. However, performance of simple tasks was not affected by STI (such as simple reaction time, stroop, vigilance, and simple calculations). The study confirmed the findings of Colle [4] and Ellermeier and Zimmer [5]. Moreover, it justified the development of a hypothetic model.

2 Original model

The original model [11] was based on a literature review of 28 studies investigating the decrement of performance, DP, between highly intelligible speech (STI=1.00) and silence. DP was 4–41% due to speech. Furthermore, the model development was driven by a strong intuition that performance decrement depends on intelligibility of speech as does the annoyance of irrelevant speech. Fortunately, some scientific evidence was available to support the model [5,9,10]. The sigmoidal shape of the curve was adopted from IEC 60268-16 [6], which gives the association between STI and subjective intelligibility of sentences.

The original model [11] suggests that the performance of cognitively demanding tasks reduces with increasing STI. DP was calculated by

$$DP = \frac{-7}{1+\exp\left[\left(STI-0.4\right)/0.06\right]}+7 \tag{1}$$

The graphic presentation is shown in Fig. 1a. The maximum DP was conservatively set to 7%. The model was only suitable for situations where the background noise (sound masking) had a steady-state nature.

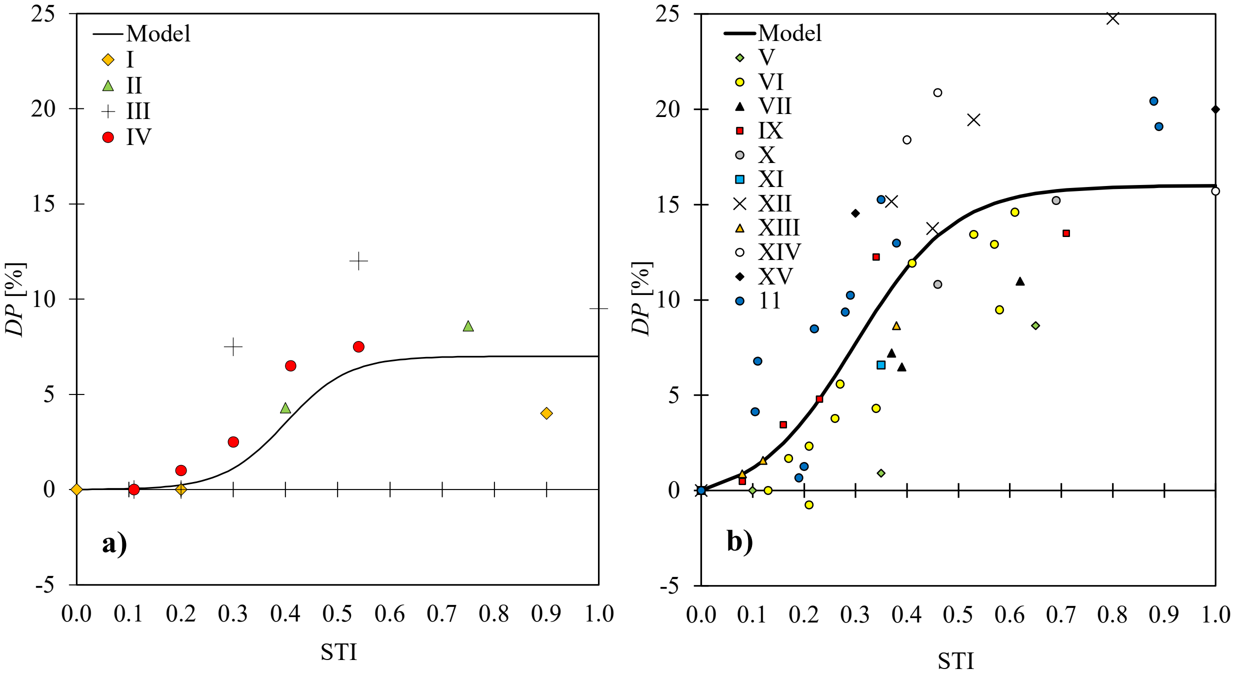

Figure 1 – a) Original [11] and b) revised [12] model presenting the association between Speech Transmission Index, STI, and decrement of performance, DP. The underlaying data is shown by symbols.

3 Revised model

The original model inspired several research groups to test the influence of STI on performance using psychological experiments. Furthermore, the model strongly affected the revolution of the room acoustic measurements of open-plan offices during 2000–2010: the model was used in ISO 3382-3 [13] standard to justify STI measurements. ISO 3382-3 describes a method to determine the room acoustic conditions in open-plan offices. The method reports single-number quantities describing the spatial decay of a single speaker. One of the single-number quantities is distraction distance, r_D, which describes the distance beyond which the STI falls below 0.50. There is evidence from 21 offices that shorter distraction distance is associated with smaller percentage of employees being highly annoyed by office noise [14].

Recently, Haapakangas et al. [12] reviewed the studies concerning STI and performance, which have been published in peer-reviewed journals during 2005–2018. The searches included the following terms: (Speech Transmission Index OR speech intelligibility OR masking sound) AND (performance OR task OR cognitive). In addition, publications citing Ref. [11] in Google Scholar were included. Altogether, 1256 papers fulfilled these criteria. However, only 14 papers fulfilled the inclusion criteria: laboratory experiment, original research, manipulation of STI, steady-state sound masking, natural speech, constant STI during the condition, speech was irrelevant to the task, and normal hearing adults. These 14 studies included, altogether, 34 different tests because many studies involved several psychological tests testing different areas of cognition. DP was defined as the relative difference in performance by DP=100 $(P_0\text{-}P_y)/P_0$ where P_0 is the performance observed in the reference condition STI = 0.00 (no performance decrement due to speech) and P_y is the performance observed in the condition STI = y. The 34 tests were categorized, and the scientific evidence concerning the DP vs. STI relationship was analysed in each category. The outcome is shown in Table 1.

There was strong evidence about the functional relationship between STI and DP in one task category: simple verbal short-term memory tasks. Such a task is the visual serial recall task, where one needs to remember 9 digits in a correct order. Because short-term memory is needed in all cognitively demanding office work tasks, the finding has very broad practical implications. The data from the 11 tests in this category and the model fitted over them are shown in Figure 1b. The functional form of the revised model is

$$DP = \frac{-16.7}{1+\exp\left[\left(STI-0.298\right)/0.0964\right]}+16.0 \qquad (2)$$

Table 1 – Categorization of the 34 tasks reviewed by Haapakangas et al. [12].

Description	No. of tests	Outcome
Simple verbal short-term memory tasks	11	Strong evidence
Simple verbal tasks with simultaneous processing demands (working memory processes)	8	Some evidence
Complex verbal tasks requiring semantic processing and the use of long-term memory	8	Limited evidence
Simple verbal tasks requiring the use of long-term memory	3	No evidence
Simple verbal perceptual tasks	2	Insufficient research
Simple non-verbal perceptual tasks	1	Insufficient research
Simple non-verbal short-term memory tasks	1	Insufficient research

4 Exploiting the model in room acoustic design

The revised model (Eq. 2) can be used to assess, how different room acoustic conditions affect the productivity of office occupants if the STI is known. STI can be determined either by measurements or by room acoustic modelling software. Because the revised model has strong evidence, it is better suited for engineering calculations than the original model.

The utilization of the revised model is demonstrated in a real open-plan office shown in Figure 2. Acoustic measurements were conducted in two room acoustic conditions: A (before improvements), and B (after improvements). In condition A, the room was treated with sound absorbers and soft floor covering. In condition B, both electronic sound masking and sound-absorbing screens were added. Details about the conditions are given in Table 2.

Table 2 – Room acoustic solutions of conditions A and B

Measure	Condition A	Condition B
Ceiling absorption	90% coverage. Class A (ISO 11654)	90% coverage. Class A (ISO 11654)
Wall 1 absorption	90% coverage. Class A (ISO 11654)	90% coverage. Class A (ISO 11654)
Wall 2 absorption	Curtains.	Curtains.
Wall 3 absorption	None.	None.
Wall 4 absorption	None.	None.
Floor	Textile (soft)	Textile (soft)
Screens	None	Sound-absorbing screens. Height 140 cm. Class B (ISO 11654).
Tables	Hard	Hard
Sound masking	Ventilation 33 dB LAeq	Electronic sound masking 43 dB LAeq

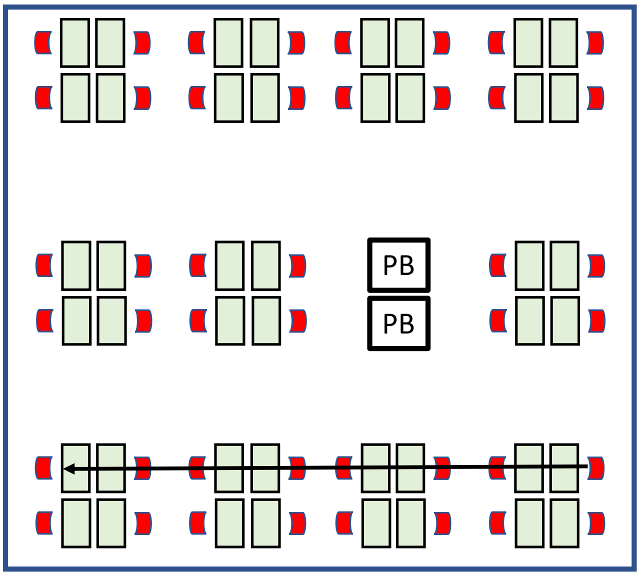

Figure 2 - Principal workstation layout of the open-plan office demonstrated in Sec. 4. The floor dimensions were 14x14 m. The number of workstations was 44. PB is a phone booth. Measurement path is indicated by black line.

The STI was measured according to ISO 3382-3 on a path shown in Fig. 2 in both conditions. The spatial decay of STI is shown in Fig. 3a. Objectively taken, the speech privacy is significantly better in condition B than in condition A. Our demonstration is to assess how the work performance of occupants could differ between the conditions.

Equation (2) was applied to assess the DP of employees working in the five workstations along the measurement path (dots in Fig. 3a). It was assumed that they work 100% of time with tasks requiring verbal short-term memory processing. The workstations were separated approximately by 2 m from each other. The DP is shown in Fig. 3b. Condition B does not give any benefit on performance in the workstation nearest to the speaker (2 m). The benefit of acoustic refurbishment on DP can be seen at distances beyond 2 m.

Decisions of voluntary investments are usually based on payback time calculations. Based on the idea explained above, the lost monthly salary cost was first estimated for the five distances of Fig. 3. The following assumptions were made:

- salary cost is 5.000 eur per employee (total direct costs for the employer),
- employees are present in the office for 50% of month (75 hours per month),
- employees work for tasks requiring verbal short-term memory processing 50% of time,
- single employee is speaking in the room corner continuously and speech is irrelevant for the others.

The lost monthly salary cost is shown in Fig. 3c. In condition A, the lost is the same at all distances from the speaker. In condition B, the lost is negligible at distances beyond 6 m.

The same calculation principle was applied for all 44 occupants of the office. To do this, the STI was predicted for each workstation using the distance between the workstation and the sound source and the experimental relationship between STI and distance of Fig. 3a. The total salary costs were 220.000 eur/month. The lost monthly salary cost was 8.500 eur in condition A and 2.500 eur in condition B. That is, the refurbishment from condition A to B could benefit the employer by 6.000 eur every month.

The investment cost from condition A to condition B was approximately 28.000 eur including sound masking (30 eur/m^2), and sound-absorbing screens (500 eur/workstation). Thus, the payback time of the investment could be 5 months.

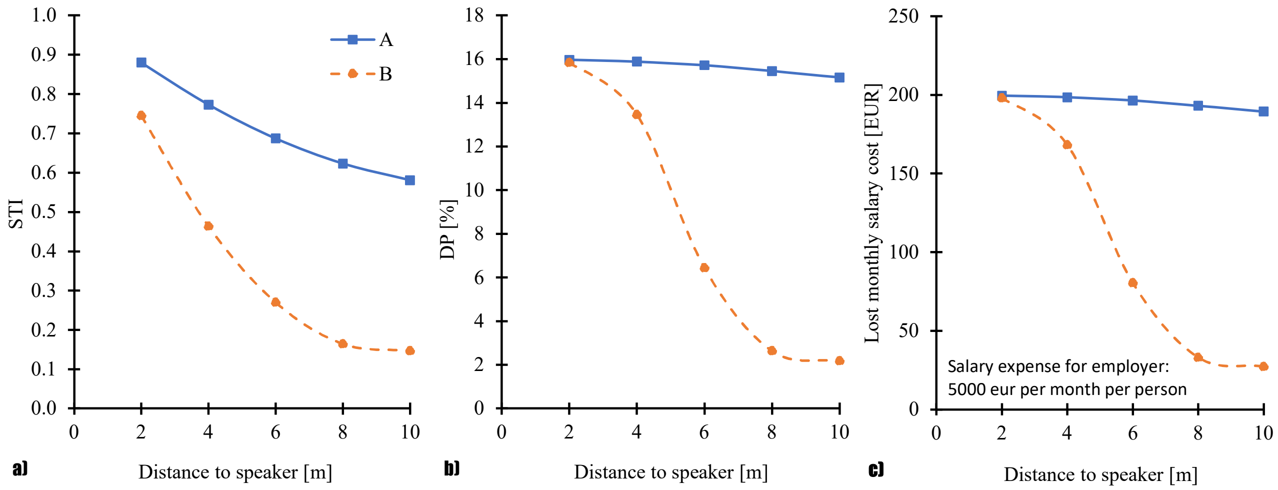

Figure 3 – Comparison of conditions A and B regarding a) spatial decay of STI at distances 2–10 m from single speaker, b) decrement in performance, DP, and c) lost monthly salary cost.

5 Discussion

The revised model suggests that the maximum decrement in performance is even 16% while it was only 7% for the original model. One reason for this is that the revised model involves only one category of cognitive tasks, while the original model was not based on solid experimental evidence. The effect of irrelevant speech on cognitive performance is very large. Further research is needed to obtain similar models also for the other task categories of Table 1.

The calculation principle of Sec. 4 was coarse and simplified: it ignores individual variations in salary, presence, and job type. Furthermore, the number of speakers, their loudness, and their locations vary within time. The accuracy of such calculations can be improved by collecting precise data from the workplace.

On the other hand, the STI model ignores many other adverse effects that irrelevant speech and/or open-plan office solution have been found to cause:

- Fatigue: occupants must focus more on the task to avoid the disturbance if people speak around. This causes fatigue [15];
- Stress: Irrelevant speech elevates physiological stress already after 45 min exposure time [16];
- Sick-leaves: sick-leaves have been found to be higher in open-plan offices [17]. Office noise has been assessed to be one potential reason for this finding;
- Risk of disability retirement: Risk of disability retirement is higher in open-plan offices than in private office room [18].

Lack of a mathematical model prevents the use of these effects in payback time calculations.

Office noise and lack of speech privacy are the most frequent sources of dissatisfaction in offices [19]. Noise produces the largest disturbances in offices [20,21]. In addition, low STI in the office is associated with lower prevalence of high noise disturbance [14]. These important findings manifest that all means affecting the acoustic quality of work environment should be implemented when new offices are designed, and existing offices are refurbished.

However, realization of an office depends on, e.g., available know-how, economic resources, and national regulations. For example, in Finland, new building regulations [22,23] require that STI shall be under 0.50 in unfurnished open-plan offices, when the distance to speaker is larger than 8 meters. In terms of ISO 3382-3, distraction distance, r_D, shall be smaller than 8 m. Unfurnished office means that the office is otherwise ready (acoustic floor, acoustic ceiling and walls, sound masking system) but the furniture and curtains owned by the user are not present. The new regulation forces the building owners to reach a certain level. In Finland, the building owner funds the fixed acoustic treatments belonging to the building (ceiling and wall absorbers, sound masking) and the user funds the acoustic properties of the furniture (screens, storage units, curtains, and phone booths). Similar regulations are not used in most other countries and the room acoustic investments are “voluntary”. In such cases, the model presented in this study can be very useful.

This study attempts to facilitate the work of acoustic designer by providing conceptual tools to justify why a certain room acoustic level would be beneficial for the user in the first place. One must keep in mind that if the room acoustic quality of the office is good, the office is easier to rent for the next user. Therefore, also the building owners benefit from good room acoustic design.

Acknowledgements

This work was funded by Finnish Academy (grant 314788) and Business Finland (grant 2682/31/2019).

References

[1] Hardy, H.C.; A guide to office acoustics. Architectural Record, February, 1957, 235-240.

[2] Smith, A.P., Jones, D.M. Noise and performance. In Handbook of human performance (Vol. 1, pp. 1□28). Academic Press, London, UK.

[3] Colle, H. A., Welsh, A.; Acoustic masking in primary memory. J. Verbal Learn. Verbal Behav., 15, 1976, 17-31.

[4] Colle, H. A.; Auditory encoding in visual short-term recall: effects of noise intensity and spatial location. J. Verbal Learn. Verbal Behav. 19, 1980, 722-735

[5] Ellermeier W., Hellbrück J.; Is level irrelevant in irrelevant speech? Effects of loudness, signal-to-noise ratio, and binaural unmasking. J. Exp. Psychol.: Human Percept. Perform. 24(5), 1998, 1406-1414.

[6] IEC 60268-16. Sound system equipment □ Part 16: Objective rating of speech intelligibility by speech transmission index. Ed. 3. International Electrotechnical Commission. Geneva, Switzerland; 2003.

[7] Hongisto, V., Keränen, J., Larm, P.; Simple model for the acoustical design of open-plan offices, Acta Acust Acust, 90, 2004, 481–495.

[8] Bradley, J.S.; The Acoustical Design of Conventional Open Plan Offices. Can. Acoust., 27(3), 2003, 23□30.

[9] Venetjoki, N., Kaarlela-Tuomaala, A., Keskinen, E., Hongisto, V.; The effect of speech and speech intelligibility on task performance, Ergonomics 49(11), 2006, 1068–1091.

[10] 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 52 (11), 2009, 1423–1444.

[11] Hongisto, V.; A model predicting the effect of speech of varying intelligibility on work performance. Indoor Air 15, 2005, 458–468.

[12] Haapakangas, A., Hongisto, V., Liebl, A.; The relation between the intelligibility of irrelevant speech and cognitive performance—A revised model based on laboratory studies. Indoor Air 30, 2020, 1130–1146.

[13] ISO 3382-3:2012 Acoustics — Measurement of room acoustic parameters — Part 3: Open plan offices.

[14] Haapakangas, A., Hongisto, V., Eerola, M., Kuusisto, T.; Distraction distance and disturbance by noise – An analysis of 21 open-plan offices. J. Acoust. Soc. Am. 141(1), 2017, 127–136.

[15] Witterseh, T., Wyon, D. P., Clausen, G.; The effects of moderate heat stress and open-plan office noise distraction on SBS symptoms and on the performance of office work, Indoor Air, 14(8), 2004, 30□40.

[16] Radun, J., Maula, H., Rajala, V., Scheinin, M., Hongisto, V.; Speech is Special. The Stress Effects of Speech, Noise, and Silence during Tasks Requiring Concentration. Indoor Air 31(1), 2021, 264–274.

[17] Pejtersen, J.H., Feveile, H., Christensen, K.B., Burr, H.; Sickness absence associated with shared and open-plan offices – a national cross sectional questionnaire survey. Scand. J Work Environ. Health, 37(5), 2011, 376–382.

[18] Nielsen, M.B., Emberland, J.S., Knardahl, S.; Office design as a risk factor for disability retirement: A prospective registry study of Norwegian employees. Scand. J. Work Environ. Health 47(1), 2021, 22-32.

[19] Frontczak, M., Schiavon, S., Goins, J., Arens, E., Zhang, H., & Wargocki, P.; Quantitative relationships between occupant satisfaction aspects of indoor environmental quality and building design, Indoor Air, 2012, 22, pp. 119–131.

[20] Pejtersen, J., Allermann, L., Kristensen, T.S., Poulsen, O.M.; Indoor climate, psychosocial work environment and symptoms in open-plan offices. Indoor Air, 16, 2006, 392-401.

[21] De Croon, E.M., Sluiter, J.K., Kuijer, P.P.F.M., Frings-Dresen, M.H.W.; The effect of office concepts on worker health and performance: a systematic review of the literature. Ergonomics. 2005;48:119-34.

[22] Decree 796-2017 of the Ministry of the Environment on the acoustic environment of buildings. 24 November 2017, Helsinki, Finland. Online at: https://www.finlex.fi/fi/laki/alkup/2017/20170796 (In Finnish).

[23] Kylliäinen, M., Hongisto, V.; Planning and implementation of the acoustic conditions of buildings. Publications of the Ministry of Environment 2019:28, 50 pp., 2019, Helsinki, Finland. In Finnish. Online at: https://julkaisut.valtioneuvosto.fi/handle/10024/161953.