Task performance and speech intelligibility - a model to promote noise control actions in open offices

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ABSTRACT

According to several independent field surveys, noise is the most adverse factor of indoor environment in open offices. Speech has been rated as the most distracting sound source. Laboratory experiments have shown that speech impairs the performance of cognitively demanding tasks, e.g. verbal and memory recall tasks. Speech intelligibility determines the distracting power of speech primarily, not the sound pressure level of speech. These results should be translated into common language to promote the importance of noise control in open offices. The aim of this study is to suggest a new model that predicts the decrease in work performance as a function of Speech Transmission Index, STI. Subjective speech intelligibility can be evaluated by measuring the STI between office workstations. Work performance is best when speech is absent (STI=0.00), and worst when speech is perfectly understood (STI=1.00). The shape of the performance loss versus STI between 0.00 and 1.00 was based on previously known relation of subjective speech intelligibility and STI. The performance loss starts to increase strongly when STI exceeds 0.20. The increase ceases when STI exceeds 0.60. The model was validated using recent experimental data. Although the model ignores, e.g., task demands, habituation, aural effects and loudness of speech, it seems to work as a link between environmental psychology and acoustic design. It can be used directly to promote noise control since the payback time of investments can be estimated by means of improved work performance.

INTRODUCTION

According to several independent field surveys, noise is often the most detrimental factor of the indoor environment in open offices (Becker et al. 1983; Danielsson 2005; Jensen et al. 2005; Pejtersen et al. 2006; Haapakangas et al. 2008). Speech is the most distracting sound source since it occurs unpredictably, its loudness is varying and it has the highest possible information content. After speech, distraction is caused also by phone ringing tones, footsteps and other activities. But ventilation, computer and traffic noises are seldom complained about since they are constant, predictable, free of information and easy to habituate to.

Although the detrimental effects of speech are well-known in basic research of memory, building sector is not aware of it because the results should be translated into general language. It must be understood by building owners (decisions during construction), company managers (decisions about premises to be rented) and architects (room level proposals). Most of the brainwork is done in offices and the distraction of unwanted speech is a serious problem worldwide. Thus, the need to reduce the adverse effects of speech and noise from activity is obvious. But in the current situation, investments on room acoustical conditions are difficult to justify economically because estimation of the "payback time" cannot be made.

One way to emphasize the benefit of acoustic design might be to show that noise reduction, i.e. improvement of speech privacy, improves work performance. Such a model was introduced by Hongisto (2005). The model suggests that the work performance depends on speech intelligibility. At the time of publication, there was very little experimental evidence to support the model. The aim of this study is to present an updated version of this model using recent experimental data.

MATERIALS AND METHODS

Literature review

The model was based on the analysis of published laboratory experiments. In the following, a short review of literature is presented.

The effects of continuous steady noise, such as ventilation noise or pink noise, on work performance have been studied several decades. Continuous and steady noise does not affect work performance directly at moderate noise levels. In practice, average noise levels do not differ very much from office to office, while speech privacy and spatial attenuation of speech can vary significantly. Thus, the sound level of noise is not the main explanation to acoustic distraction.

Colle and Welsh (1976) were among the first researchers who found the dramatic effect of speech on the performance of working memory. Their study has been repeated by many researchers using similar or modified tasks and sound environments. Thereafter, Colle (1980) studied the serial recall performance using different speech-to-noise ratios. Speech-to-noise ratio, L_{SN}, expresses the difference between the sound pressure levels of speech and background noise. The decrease in performance was almost independent of speech level within 40 to 80 dBA. It was concluded that speech intelligibility explains the distraction, not sound pressure level. However, the speech intelligibility conditions cannot be used to create a general model because only one low speech intelligibility condition was used. However, this study was the starting point to the creation of the current model based on speech intelligibility.

More than 30 laboratory studies were reviewed to evaluate the performance decrements caused by speech or office noise (Hongisto 2005). The effect of speech on performance is indisputable, see Table 1. Performance decrements due to speech have been between 4 and 41 % compared to performance in silence. Large variation of performance loss is caused from, e.g. different task demands, task lengths and sound environments. Speech seems to interfere only with the performance of cognitively demanding work tasks and not on routine tasks. The exact mechanism how speech interferes with memory during different tasks is still under research.

Most of the experiment reviewed had been carried out by brain researchers being primarily interested in the operation of working memory. Speech stimulus was used to test suggested memory hypotheses. Therefore, most experiments had been carried out only in two situations, with speech and in silence. All of these studies are valuable since they prove that unwanted speech undoubtedly impairs task performance. However, they cannot be applied to promote noise control in open offices where speech intelligibility values between 0 and 1 are all equally probable.

To utilize this research area in the promotion of noise control of open offices, such studies are necessary where speech intelligibility is varied, preferably in such a way that the speech intelligibility scores can be directly transformed into numbers used in room acoustics measurements, i.e. Speech Transmission Index.

Table 1: Summary of literature review showing the decrease in performance depending on task type and sound environment. *N* is the number of published studies. The change in performance, ΔP, is defined in Equation (1).

		ΔP [%]		
Task type, sound environment	***N***	**AVERAGE**	**Minimum**	**Maximum**
Memory for letters presented visually, speech	4	-19	-5	-29
Memory for 9 digits presented visually, speech	7	-10	-5	-13
Reading comprehension, speech	1	-10		
Proof-reading, speech	3	-7	-4	-10
Other tasks, speech	9	-15	-7	-29
Varying tasks, office noise with or w/o speech	5	-26	-13	-41
Short-term memory of digits, music with or without voice	1	-10	-4	-14

Colle (1980) started the discussion about the importance of speech intelligibility. Thereafter, speech intelligibility has been the descriptor of speech stimulus, in a way or another, in at least four published studies which are referred in the following. They are used in the validation of the current model.

Ellermeier and Hellbrück (1998) studied the serial recall in four different speech-to-noise ratios in two separate experiments. They found a clear improvement of task performance with reducing speech-to-noise ratio. The problem of using speech-to-noise ratio is that it does not alone explain speech intelligibility, see next chapter. However, the speech-to-noise ratios could be translated into *STI* values, with certain reservations, and utilized in the validation of the model.

The experiment of Venetjoki et al. (2006) determined the exact Speech Transmission Index, *STI*. The three sound conditions corresponded with real situations in offices: private room and doors closed (STI=0.00), private room and doors open (STI=0.30) and open office with poor acoustic design (STI=0.80). Total sound level was quite low, 48 dB(A), in all cases. Different values of STI were obtained by modifying the relative sound levels of speech and masking. Proof-reading performance was lowest in the highest *STI* value while performance was not affected between 0.00 and 0.30. Performance of cognitively non-demanding tasks were not affected by speech.

Schlittmeier et al. (2008) continued the work of Ellermeier and Hellbrück using serial recall and arithmetic reasoning. Four different conditions were tested: bad, good and perfect intelligibility and silence having sound pressure levels 35, 35, 55 and 20 dB(A), respectively. The speech spectra in two first situations were based on realistic listening situations between office rooms. Performance of both tasks reduced monotonously with increasing speech-to-noise ratio. The speech-to-noise ratios could be translated into *STI* values, with certain reservations, and utilized in the validation of the model.

Haapakangas et al. (2008) continued the work of Venetjoki et al. (2006). The test arrangements were similar but narrower STI range was used (0.10, 0.35 and 0.65) and five different tests were used. Task performance in serial recall and complex working memory reduced with increasing *STI*. Three other tasks were independent of speech.

These studies included also subjective feedback which indicated clearly the negative effects of speech on acoustic comfort, concentration and other factors.

Speech intelligibility theory

Speech intelligibility is a subjective measure that describes the percent of correctly heard items, like syllables, words or sentences. Speech intelligibility must be determined by using listening tests including many listeners, which is laborious. A good estimation of speech intelligibility can be made by measuring the Speech Transmission Index, *STI*, between the speaker and listener.

The subjective meaning of *STI* is presented in Table 2. It should be noted that the aim of acoustical design of offices is good speech privacy, that is, poor speech intelligibility.

STI is determined in the frequency range 100 to 10000 Hz. *STI* depends mostly on the speech-to-noise ratio, L_{SN}, but also on early decay time, which is very much the same as reverberation time in open offices, Figure 1. Exact frequency-dependent method to determine STI is described in, e.g. Hongisto et al. (2004). The direction of speaker and listener affect STI as well but they can be ignored in open offices because speaker and listener seldom see each other.

Recently, *STI* has been applied in open offices to evaluate speech privacy between workstations, e.g. Hongisto et al. (2007), Virjonen et al. (2007) and Hongisto et al. (2004). The *STI* between workstations is easy to determine and most acoustic consultants are able to make it as well. Therefore, the use of *STI* as the explaining room acoustical parameter of performance decrement was justified.

The correlation between *STI* and subjective speech intelligibility is shown in Figure 2.

Table 2: The subjective meaning of Speech Transmission Index, *STI*. Good speech intelligibility is desired in auditoria. In open offices, the opposite situation is appropriate.

STI	Speech intelligibility	Speech privacy	Examples in offices
0.00 … 0.05	very bad	confidential	Between two single-person office rooms, high sound insulation
0.05 … 0.20	bad	good	Between two single-person office rooms, normal sound insulation
0.20 … 0.40	poor	reasonable	Between workstations in a high-level open-plan office Between two single-person office rooms, doors open
0.40 … 0.60	fair	poor	Between desks in a well designed open-plan office
0.60 … 0.75	good	very poor	Between desks in an open-plan office, reasonable acoustical design
0.75 … 0.99	excellent	no	Face-to-face discussion, good meeting rooms Between desks in an open-plan office, no acoustical design

Model and validation

The model should predict the change of performance as a function of STI. The model was based on three assumptions:

1. Highest performance is obtained when speech is absent, *STI*=0.00.
2. The largest decrease in performance is A % and this is reached when speech is perfectly heard, i.e. *STI*=1,00.
3. The dependence of performance in the range *STI*=0.00-1.00 is based on the sentence intelligibility vs. STI curve of Figure 2.

The mathematical model was created by normalizing the curve of Figure 2 to the maximum estimated change of work performance.

The model was validated against four studies, including seven experiments. In each experiment, either the performance during condition "silence" or "lowest speech intelligibility" represented the best work performance (lowest error rate), P_0 [%]. The percentage of errors, P_i, in each sound condition, i, was determined and the change of performance, ΔP [%], was determined as

(1) $\Delta P = P_0 - P_i$

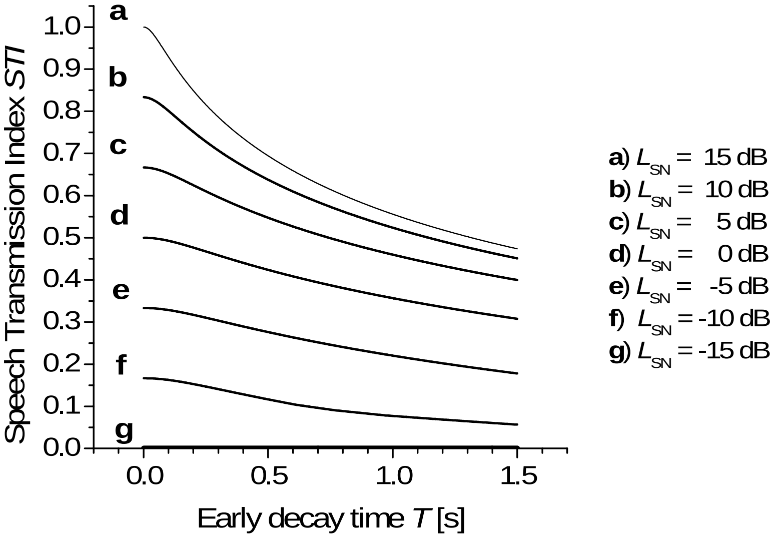

Figure 1: Dependence of STI on speech-to-noise ratio L_{SN} and early decay time. This graph is valid when the shapes of speech and background spectra are equal and reverberation time is independent on frequency. Typically, the graph predicts STI with an accuracy of 0.05.

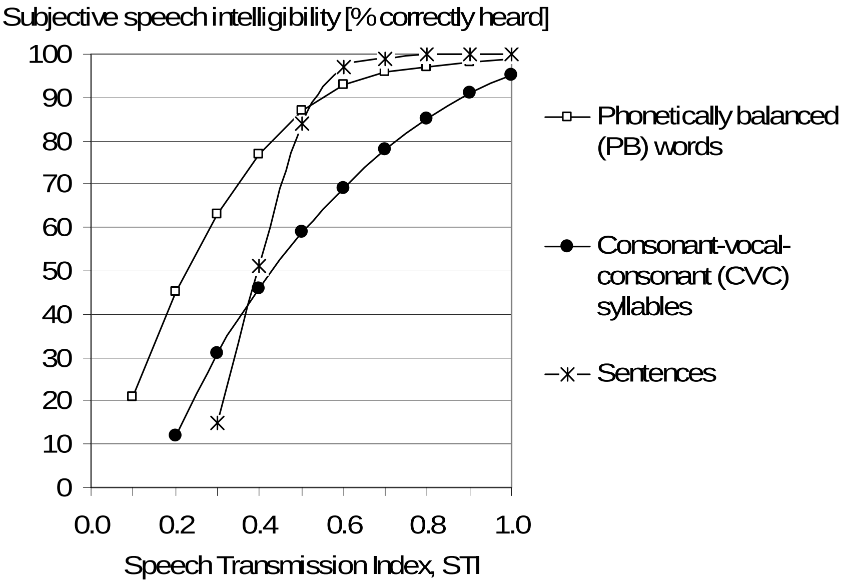

Figure 2: Experimental relations between subjective speech intelligibility and *STI* according to IEC 60268-16:2003

RESULTS

The prediction model gets the following mathematical form

(2)

$$\Delta P = \frac{A}{1 + \exp[(STI - 0.4)/0.06]} - A$$

The model is outlined in Figure 3.

The constant *A* is the highest estimated decrease of performance which occurs during highly intelligible speech. In this study, a value *A*=7 % was used as a compromise. It represents a general situation that can be used for many task types requiring cognitive efforts.

The model was validated using experiments where speech intelligibility was varied. They are indicated as individual points in Figure 3. The tasks are given in Table 3.

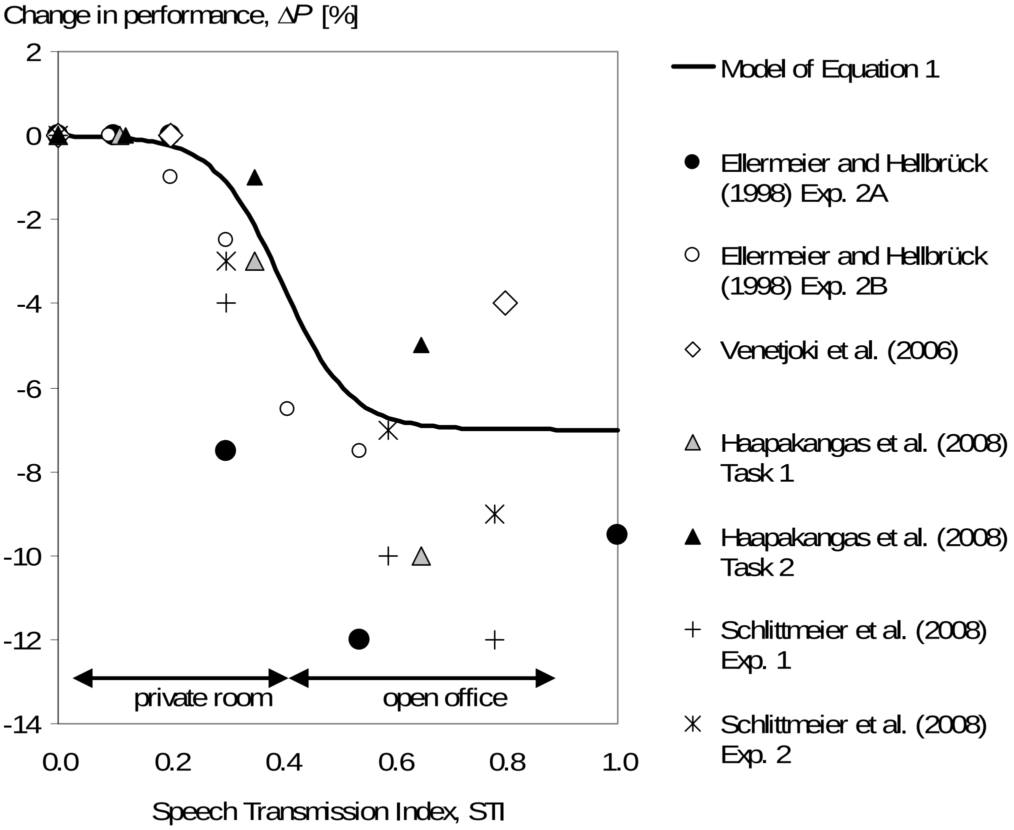

Figure 3: The change of task performance as a function of STI. The model was located to the safe side of the experimental points.

Table 3: The tasks used in the experiments of Figure 2. N is the number of subjects in the experiment.

Experiment	Task	N
Ellermeier and Hellbrück (1998) Exp. 2A	Serial recall	24
Ellermeier and Hellbrück (1998) Exp. 2B	Serial recall	29
Venetjoki et al. (2006)	Proof-reading	36
Haapakangas et al. (2008) Task 1	Complex working memory	36
Haapakangas et al. (2008) Task 2	Serial recall	36
Schlittmeier et al. (2008) Exp. 1	Serial recall	20
Schlittmeier et al. (2008) Exp. 2	Mental arithmetic	24

DISCUSSION

The experimental data supports well the previously developed model. The original form of Hongisto (2005) did not need to be changed. It seems that performance is very little affected at small values of STI. But above STI=0.20, decrease of performance is strong. The model predicts that the decrease ceases above STI=0.70 but there is not much experimental evidence on that. However, it is very probable that performance will no longer reduce above 0.70 because syllable intelligibility is perfect and subjective differences do not appear (Figure 2).

The model includes an assumption that the maximum change of performance is -7 %, i.e. *A*=7 % It must be emphasized that the choice is not universal. The choice represents merely a safe estimate of the maximum change of performance. Most studies have resulted in larger absolute values of ΔP than Eq. (2), see e.g. Figure 3 and Table 1. Therefore, the present choice is practically credible.

Scientifically, the model is too simplified. Changes in performance depend on many other things in addition to speech intelligibility, like cognitive demands of the task, speech content, task length, learning, motivation and individual factors. In laboratory conditions, subjective speech intelligibility may also depend on speech production and listening condition.

The applicability of the model to real working conditions can be difficult. Firstly, the laboratory environment does not correspond to real office. But the experimental research aiming at reliable quantitative results is extremely difficult to carry out in office environments: work output is nearly impossible to measure accurately in real offices. STI varies significantly with speakers distance, direction and vocal effort. Other factors affect work performance more severely than noise.

Secondly, the tasks used in laboratory experiments do not correspond to real office work. But there is no universal definition for office work either. All psychological tasks used in laboratory experiments have used the same cognitive processes as typical office work. In the future, the development of tasks is still important to obtain better practical relevance.

The model should be validated in the future mainly using laboratory experiments. It is still important to find more data to the *STI* range 0.20 - 0.60 where the performance should change most dramatically. This range is also of main interest for the motivation of acoustic improvements in offices because field measurements have shown that the variation of *STI* between workstations is typically between 0.30 and 0.70, depending on distance (Hongisto et al. 2004, 2007). As shown in Table 3, also more versatile tasks should be used to represent better different cognitive demands of office work.

Although there is large scatter in the STI range 0.60 - 1.00, dependence of performance on STI is not expected because of the findings of Colle (1980). Instead, range 0.00 - 0.30 should be investigated to find confirmation to the model.

An important question is, could we find some supporting evidence from real office conditions, despite the difficulties of performance measurement? The cross-sectional survey of Haapakangas et al. (2008) showed that self-estimated daily waste of working time due to noise was almost twofold in open offices (*STI*=0.60...0.80) compared to private office rooms (*STI*=0.20...0.40). The results agree with the model but more similar studies would facilitate the distribution of the model in building sector.

Hongisto et al. (2007) have shown that there are enormous differences of STI between the open offices. Speech privacy improves (STI reduces) with increasing room absorption, increasing screen height and increasing masking sound level. The present study promotes strongly the profitability of acoustic design.

However, it must not be forgotten that room acoustic design is not the only way to improve acoustic conditions. Open offices can be equipped with special rooms for intensive work periods, long conversations or phone calls. The employment of office etiquette reduces unnecessary noises from the room. The effective use of mobile technology facilitates the use of these means.

The current model can be combined with a new room acoustical design tool of Keränen et al. (2007). It can be used to predict *STI* in an open office. Thereafter, the performance decrement can be estimated by Figure 3.

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