The effect of acoustic design on performance in office rooms

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ABSTRACT

The purpose was to determine the optimum acoustic conditions of a single-person office room with respect to cognitive performance and acoustic satisfaction when speech is transmitted from the neighboring similar room. 32 students participated in a laboratory experiment which simulated two adjacent office rooms. Speaker and listener were located in rooms 1 and 2, respectively. Four conditions were investigated. Condition A corresponded with the typical situation where the weighted sound reduction index was 35 dB R'_w and background noise level from building services was 33 dB L_{Aeq}. Conditions B and D had a 10 dB greater sound insulation than condition A. Conditions C and D had 9 dB larger background noise level in room 2 than condition A. Working memory performance was the worst in condition A. Acoustic satisfaction and several other subjective measures indicated that conditions B-D were superior to condition A. The results give clear guidelines how the target values of sound insulation and sound masking should be written for single-person office rooms.

INTRODUCTION

Scope

Private office rooms, or more generally, single-person office rooms can provide significantly better acoustic privacy than open-plan offices or shared offices (two to four employees per room) [1,2]. However, consultative work in offices has shown that single-person office rooms are not necessarily free from noise distraction: sound insulation can be too low, masking background noise level can be too low, or the room can be highly reverberant.

Single-person office rooms are often available only for employees whose work tasks involve long-term periods of concentration or high level of speech privacy due to e.g. confidential matters. In many organizations, the single-person office rooms are anonymous and they are reserved for those periods when the tasks presume better acoustic privacy. Even though single-person office rooms are less frequent nowadays than 20 years ago, the expectations for acoustic quality for single-person office rooms may be even higher than 20 years ago, because the work tasks moved to them can be very demanding. To our knowledge, only two studies have investigated how the sound insulation affects cognitive performance in single-person office rooms [3,4]. This paper summarizes the findings of Ref. [4].

Acoustic target values for single-person office rooms

It is very common at least in Finland, Germany, Sweden and Norway, that the acoustic target values are set using two quantities:

- **Airborne sound insulation:** the minimum apparent weighted sound reduction index between office rooms is 35 dB R'_w. It depends mainly the performance of partition walls [5].
- **Background noise level:** the maximum background noise level of building service appliances is 33 dB L_{Aeq}. The level is usually caused by ventilation devices.

These quantities affect together the intelligibility of speech behind the partition. However, these quantities interact in a complex way. Recent progress has supported the use of an objective quantity, Speech Transmission Index, *STI*, because it predicts the subjective intelligibility of speech (*STI*=0 No intelligibility, *STI*=1 Perfect intelligibility). Hongisto [6] has suggested that *STI* could explain how speech affects cognitive performance. His hypothesis was that *STI* values under 0.20 would not reduce performance, while values above 0.50 would. After 2005, several experiments have supported the hypothesis, see review in Ref. [4]. However, some tasks are more sensitive to speech effects than the others.

A Finnish guideline [7] has presented a graph (Figure 1) which can be used to explain how *STI* is related to the two quantities (bullet points above). The graph suggests that when the target values are met, the *STI* value can be even as high as 0.30. Based on the hypothesis of Hongisto [6], there is a need to investigate, whether the conditions (bullet points) are sufficient with respect to cognitive performance.

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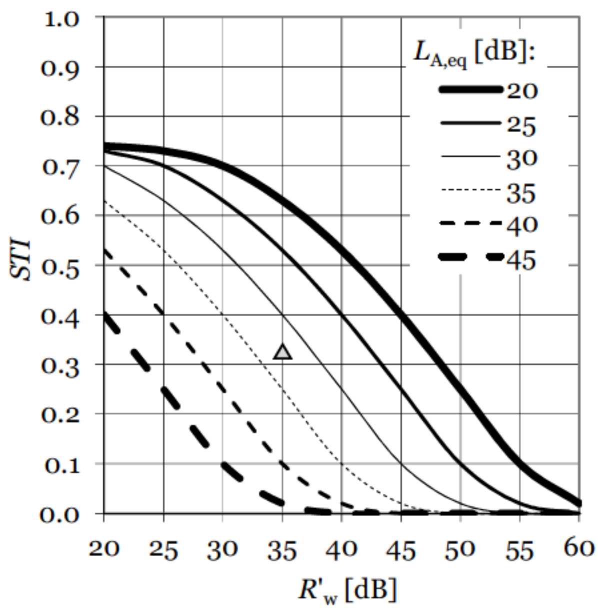

Figure 1: The schematic dependence of Speech Transmission index, *STI*, on background noise level, L_{Aeq}, and weighted sound reduction index, R'_w. The figure is based on a Finnish standard [7]. The curves are calculated using typical room volumes, reverberations and sound insulation spectra. The triangle represents the position of typical target value (bullet points in Introduction).

MATERIALS AND METHODS

Description of sound conditions

The study simulated the condition of Figure 1 where two employees are located in adjacent single-person office rooms. Speech is produced in room 1 and the subject is working in room 2. To achieve a realistic simulation, recorded speech was produced in room 1 using a loudspeaker, and the speech was recorded in room 2 using head-and-torso simulator (B&K 4100). Speech was originated from radio programmes with several speakers including also occasional short breaks. This way, we could achieve realistic binaural recording of speech transmitting through a full-size wall to the listeners' ears in the nearby room involving the normal acoustic echo of both rooms 1 and 2. The actual sound insulation of the wall between the rooms did not play any role in the experiment because the desired sound insulation spectra were later processed using digital filters.

Thereafter, masking sound (pink noise from pseudo-random noise generator) was recorded in room 2 separately from speech recordings. The sound was produced using three loudspeakers fed by individual noise generators.

During the recordings of speech and masking, the playback level was very high, more than 80 dB L_{Aeq} to achieve a large signal-to-noise ratio which facilitated the later digital processing of sounds to produce the desired sound conditions with specified spectra and levels.

The experiment was conducted in a psychoacoustic laboratory room (Turku, Finnish Institute of Occupational Health) where the background noise level was under 20 dB L_{Aeq}. The sound conditions were presented using headphones.

The study included four conditions (Table 1, Figure 2). All conditions were mixtures of speech and sound masking recorded with head-and-torso. Speech spectra was simulated with two different sound insulation levels of the partition wall between the rooms 1 and 2: low (35 dB R'_w) and high (45 dB R'_w). Two spectra of background noise level were also simulated: low (33 L_{Aeq}) and high (42 dB L_{Aeq}). Altogether, four combinations of background noise level and sound insulation were studied.

The *STI* values of the conditions were determined using the signal-to-noise ratios and reverberation time of the room 2, where the speech and masking sounds were recorded [8].

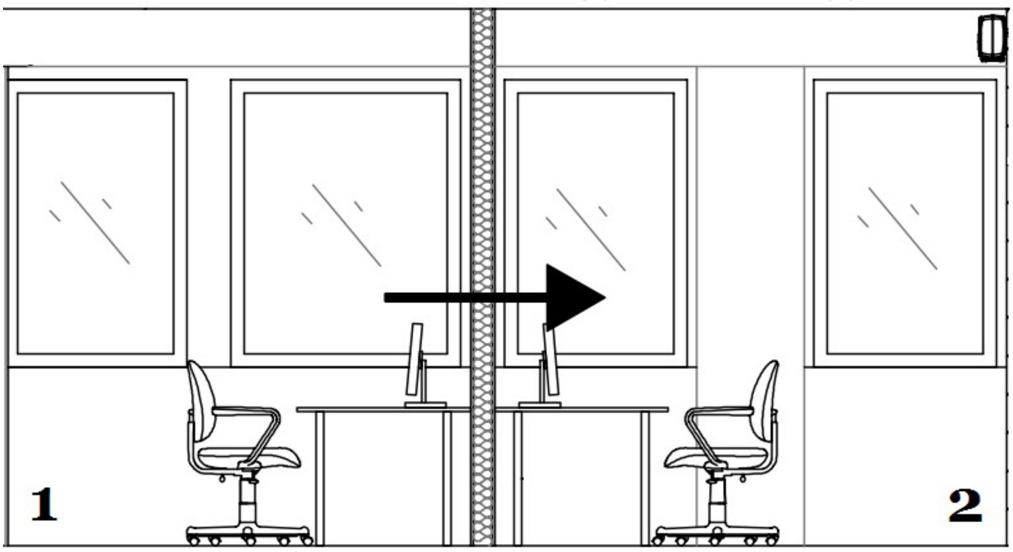

Figure 1: The experiment included four simulated conditions how the speech from room 1 could be heard through the partition wall in room 2.

Experimental design

The experiment was conducted using a repeated measures design, i.e. all subjects participated in all four sound conditions, thus acting as their own controls. The order of sound conditions was counter-balanced. Thirty-two healthy students (21 female, 11 male, mean age 24 years) participated in the experiment, one at a time. The length of the experiment was approximately 3½ hours including the background questionnaire, rehearsal of three cognitive tests in silence (60 min) and four sound conditions (30 min each).

During each sound condition, the participant conducted three cognitive tests using a personal computer. The tasks were all paced and they were designed to measure different cognitive dimensions:

- *The serial recall task* is a classic short-term memory task where subjects have to recall randomly presented digits from 1 to 9 in the correct order. The percentage of digits recalled in the correct serial position was measured indicating the accuracy of serial recall task. Numbers were presented on the screen at the rate of 1 per second with an inter-digit interval of 1.5 seconds. Recall was possible after a delay of 10 seconds. The subject had 15 seconds time to respond, after which a new trial began.
- *The mental arithmetic task* is a working memory task where subjects have to apply a certain calculation rule to an arithmetic problem. The experiment involved altogether 24 problems. A modified version of the Konzentrations-Leistungs-Test [9] and Schlittmeier et al. [3] was developed. Accuracy of mental arithmetic task was measured by error rate in percentages. Speed of mental arithmetic task was measured by the reaction time (milliseconds) for the correct answers. An example of a problem is as follows. First three simple problems are conducted: C1: 7+1-3, C2: 4+6+9; C3: 6+1+3. Intermediate results I1=5, I2=19, I3=10 have to be remembered. If I1<I3, I4=I1+I3. Otherwise, I4=I1-I3. Thereafter, if I4<I2, then the result is I4+I2, Otherwise, the result is I4-I2. In this example, I4=15 and the result is 15+19=34. Thus, the result is always a positive integer. Each number was presented for 0.7 seconds followed by a pause of 0.3 seconds. After all three problems had been presented, the subject had 15 seconds to give the final result, after which a new arithmetic problem began.
- *The text producing task* requires psychomotor performance, creativity and the ability to produce text in writing. The subject was required to type a coherent expository text about a given title presented on the screen. The topic of the titles concerned common, well-known themes (Hobbies provided by the sea, mountains as tourist attraction, parks from recreational viewpoint, and forests as the source of nutrition). The subject had 5 min to write the text. The subject was instructed to write as much as possible but correct their typing mistakes. Length, pauses, corrections and fluency were measured.

The participants filled a short questionnaire after each sound condition (in silence). The questionnaire focused on acoustic perception and subjective workload.

Statistical analyses

The serial recall, mental arithmetic and text producing tasks were analyzed using a repeated measures ANOVA with sound condition (later: condition) as the within-subjects variable. The normality of data was tested with the Shapiro-Wilkin test. Whenever needed, the homogeneity of variance was estimated with Mauchly's test of sphericity. When the test indicated a violation of sphericity, the Greenhouse-Geisser correction was applied and the corresponding *p*-values were reported. When a main effect or an interaction was found, paired comparisons between conditions were performed using t-tests or the Wilcoxon signed-rank test. An alpha level of 0.05 was used in all analyses. The Benjamini-Hochberg procedure [9] was used for alpha-error adjustment in paired comparisons. One-tailed tests were applied in paired comparisons of task performance when the condition A was compared to the other conditions. This was justified because previous studies [11,12] supported the model of Ref. [6] suggesting that the effect of speech on performance is usually negligible when *STI* is under 0.20. Two-tailed tests were applied for other paired comparisons. Critical level of statistical significance was set to $p<0.05$.

Table 1: Acoustic description of the experimental conditions A-D in the simulated room 2.

QUANTITY	CONDITION A	CONDITION B	CONDITION C	CONDITION D
Weighted apparent sound reduction index R'_w [dB]	35	45	35	45
L_{Aeq} of speech from nearby room [dB]	30	22	30	22
L_{Aeq} of masking sound inside the room [dB]	33	33	42	42
Overall L_{Aeq} [dB]	35	33	42	42
Signal-to-noise ratio, A-weighted [dB]	-3	-11	-12	-20
Speech Transmission Index, STI	0.38	0.12	0.08	0.00

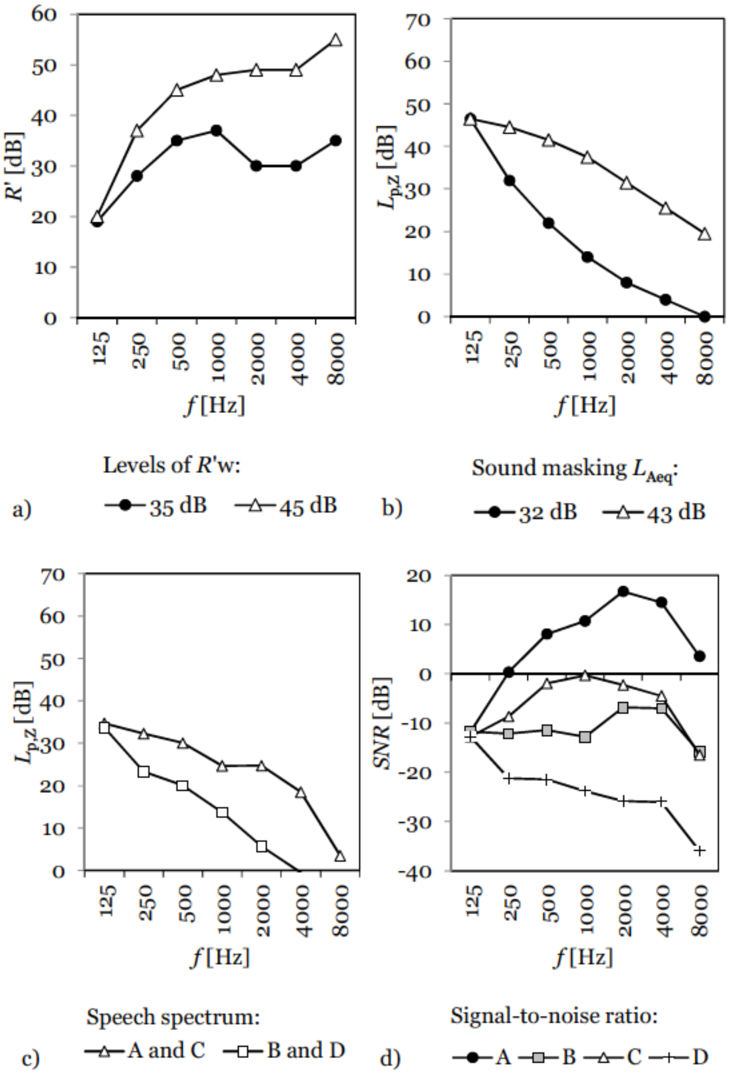

Figure 2: a) Airborne sound reduction index *R*' of the simulated partition walls. b) The spectra of the masking sounds, c) Two speech spectra caused by the two *R*' values. d) The signal-to-noise ratio, *SNR*, of the conditions (difference of speech and masking level).

RESULTS

Condition had a significant effect on performance in serial recall task ($F_{3,93}$=2.84, p=0.042, η^2=0.08; Figure 3). Paired comparisons revealed a significant difference between the *conditions* A and C (p=0.035, one-tailed) and an almost significant difference between *conditions* A and D (p=0.057, one-tailed). Differences were not found between *conditions* B-D. *Condition* had no effect on performance in text producing task or mental arithmetic task.

Condition had a significant effect on several subjective ratings (Figures 4-6). Paired comparisons revealed that subjective measures were in favor of *conditions* B-D and against *condition* A.

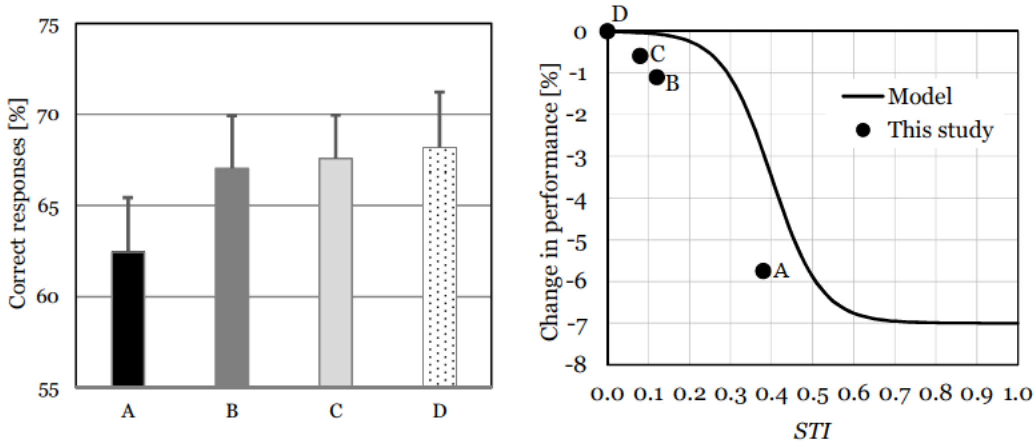

Figure 3: Left) Percentage of correct responses in serial memory task. Means and standard errors of the means. Right) Comparison of the model of Ref. [6].

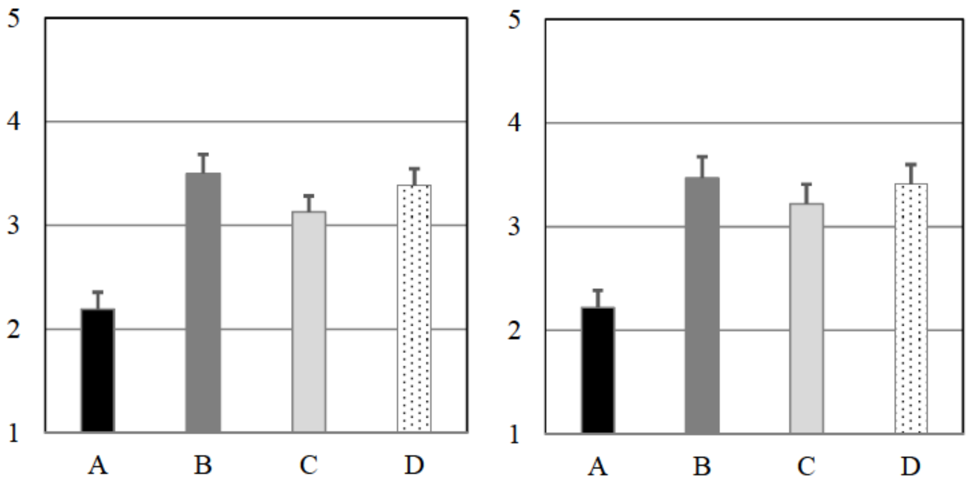

Figure 4: Left) Acoustic satisfaction (*How satisfied were you with the previous acoustic environment as a whole?*). Right) Self-rated efficiency (*I could work in a sound environment like this effectively for long periods of time.*) Response scale: 1 Not at all, 5 Very much. Means and standard errors of mean. NOTE: The graphs are nearly but not exactly identical.

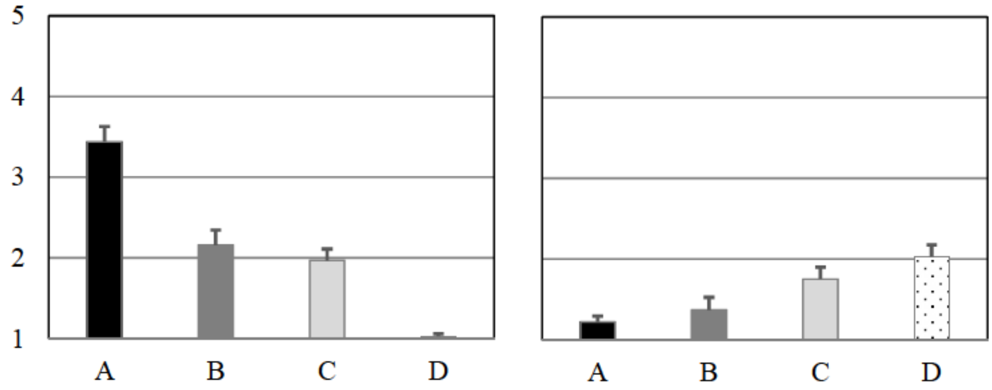

Figure 5: Left: Performance loss by speech (*How much your performance was distracted by speech?*). Right: Performance loss by ventilation (*How much your performance was distracted by ventilation sounds?*). Response scale: 1 Not at all, 5 Very much. Means and standard errors of mean.

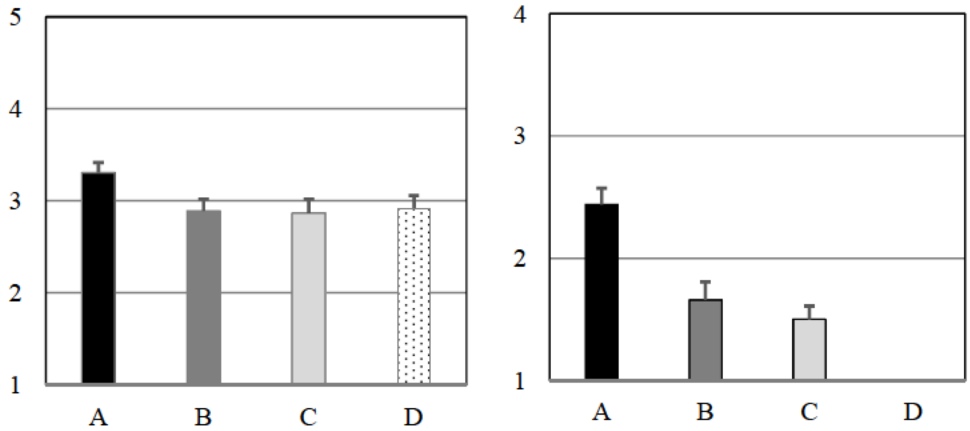

Figure 6: Left: Subjective workload (Sum variable of four items: mental demand; frustration; performance and exertion). Response scale: 1 Not at all, 5 Very much. Right: Attention capture by speech (How often the speech totally captured your attention away from the tasks in the previous sound environment). Scale: 1 Never, 2 A couple of times, 3 Several times, 4 Almost continuously. Means and standard errors of the means.

4 DISCUSSION

Results in serial memory task supported the model of Hongisto (Figure 3). However, other tasks were not affected by condition which agrees with earlier findings which suggest that the speech effects could be task dependent [11,12]. Subjective measures were more clearly in favor of *conditions* B-D than objective measures.

The results suggest that *STI* value should be less than 0.38 (*condition* A) between office rooms to achieve ideal conditions for work performance and acoustic satisfaction. Examples of lower *STI* values were represented by *conditions* B and C.

The results suggest that the acoustic target values shown in the Introduction should be tightened.

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REFERENCES

[1] Kaarlela-Tuomaala, A., Helenius, R., Keskinen, E., Hongisto, V. (2009). Effects of acoustic environment on work in private office rooms and open-plan offices - longitudinal study during relocation, *Ergonomics* 52 (11) 1423-1444.

[2] Lee, Y.S. (2010). Office layout affecting privacy, interaction, and acoustic quality in LEED-certified buildings, *Building and Environment* 45 1594-1600.

[3] Schlittmeier, S.J., Hellbrück, J., Thaden, R., Vorländer, M. (2008). The impact of background speech varying in intelligibility: Effects on cognitive performance and perceived disturbance. *Ergonomics*, 51, 719-736.

[4] Hongisto, V., Varjo, J., Leppämäki, H., Oliva, D., Hyönä, J. (2016). Work performance in private office rooms: The effects of sound insulation and sound masking. *Building and Environment*, 104, 263-274.

[5] ISO 717-1:2013 Acoustics. Rating of sound insulation in buildings and of building elements. Part 1: Airborne sound insulation, *International Organization for Standardization*, Geneva, Switzerland.

[6] Hongisto, V. (2005). A model predicting the effect of speech of varying intelligibility on work performance. *Indoor Air*, 15, 458-468.

[7] SFS 5907:2004 Acoustic classification of spaces in buildings, *Finnish Standards Association*, Helsinki, Finland.

[8] IEC 60268-16 3rd edition: Sound system equipment. Part 16: Objective rating of speech intelligibility by speech transmission index. *International Electrotechnical Commission*, Geneva, Switzerland, 2003.

[9] Lukesch, H., & Mayrhofer, S. (2001). KLT-R: Konzentrations-Leistungs-Test, Revidierte Fassung. Göttingen: Hogrefe.

[10] Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: A practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society, Series B (Methodological)*, 57, 289-300.

[11] Haka, M., Haapakangas, A., Keränen, J., Hakala, J., Keskinen, E., and Hongisto, V. (2009). Performance effects and subjective disturbance of speech in acoustically different office types – a laboratory experiment. *Indoor Air*, 19(6), 454-467.

[12] Jahncke, H., Hongisto, V., and Virjonen, P. (2013). Cognitive performance during irrelevant speech: Effects of speech intelligibility and office-task characteristics. *Applied Acoustics*, 74(3), 307-316.