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ROOM ACOUSTIC DESIGN AFFECTS OCCUPANTS' WORK PERFORMANCE AND ACOUSTIC SATISFACTION – THE FINGER STUDY

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ABSTRACT

Speech is the main source of disturbance in offices. Task irrelevant speech causes annoyance, reduces performance, and increases physiological stress. Good room acoustic design can reduce these adverse effects. Finnish building regulations require that the Speech Transmission Index (STI) in an unfurnished office space (furniture absent) is < 0.50. Our aim was to examine the benefits of good acoustic design regarding the room (building owner's costs) and furniture (user's costs) on cognitive performance, subjective experience, well-being, and stress (costs of employees). Identical laboratory experiments were performed in Finland and Germany. The conditions A-C were based on measurements in a real office during three stages of building, which differed in absorption, sound masking, and furniture. The simulated conditions were: A. Regulations violated (STI = 0.8); B. Regulations fulfilled (STI = 0.3), and C. Regulations surpassed (STI = 0.1). We measured cognitive performance, subjective experience, and physiological stress of participants. Finnish and German results were alike, and the samples were merged (N = 98). Conditions B and C appeared to lead to the best performance, and condition C further improved subjective experience. Therefore, office design fulfilling Finnish regulations is useful for performance. Surpassing the regulations can improve work experience.

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1. INTRODUCTION

A recently published global pre-pandemic survey showed that noise annoys almost 28% of office employees [1]. Speech is the most disturbing type of sound in open-plan office spaces. Working under exposure to task irrelevant speech reduces office work performance [2] and causes stress [3]. New Finnish building regulations were launched in 2018. They require that the room acoustic conditions of an open-plan office should meet internationally strict target levels [4]: the speech transmission index, STI, must be less than 0.50 in an unfurnished open office when the speaker is more than 8 meters away.

It has not been investigated how room acoustic conditions that significantly deviate from the Finnish regulations would affect a person working in an open-plan office space during task-irrelevant speech. Insufficient acoustic designs in open-plan offices were extremely frequent in Finland until 2018, when room regulations were not available. Since 2018, the situation has changed in Finland. Furthermore, there are also offices where the room acoustic conditions significantly surpass the new regulations. The situation is the same also abroad. According to the review of Ref. [5], room acoustic conditions in open-plan offices have been measured in several countries. The range of measured distraction distances, as measured by ISO 3382-3 standard [6], was between 2 and 18 m. It is an internationally relevant research question, how the task irrelevant speech affects human in different room acoustic conditions.

The results obtained in a single laboratory (single country, certain language) are sometimes questioned in other countries since there might be differences how people are used to disturbing sounds in general. Few research groups have investigated how well the results of one country represent the results obtained in another country (different language, communication culture, experimental environment) when the test setup is otherwise completely identical.
The first goal of our study was to examine the effects of different levels of room acoustic designs on employees. Specifically, we sought to answer two pragmatic questions: Is it useful to invest on room acoustic design that

1. fulfills the Finnish regulations (condition B)?
2. surpasses the Finnish regulations (condition C)?

Comparison was made to condition A that violated the Finnish regulations.
The second goal was to examine whether the data collected in two different countries differed from each other. Therefore, the experiments were performed in two countries, who have long experience of this kind of experimental research: Finland and Germany. Therefore, we call it FinGer study.

2. MATERIALS AND METHODS

The Finnish and German experiments involved 54 and 44 participants, respectively. The total number of participants was 98. The average age was 25 years (range 19–45 years). The ethical committees of both universities approved the study plans.
Turku University of Applied Sciences controlled that the experimental conditions (levels of experimental sounds and background, program of the psychological experiment, leadership procedure) were similar in both countries.
The experiment involved three *conditions*. Their acoustic descriptions are shown in Table 1 and clarified below:

A. Regulations violated. The ceiling was sound absorbing;
B. Regulations fulfilled. Sound masking was added over *condition* A;
C. Regulations surpassed. 140 cm high sound-absorbing table screens were added around workstations over *condition* B.

The *conditions* A–C correspond to real conditions that were measured in a single Finnish office (LähiTapiola Turku, 15x14x2.4 m) according to the ISO 3382-3-2012 standard at three stages of renovation (A–B: before furniture arrived, C: furnished, completed office). The distraction distances of conditions A–C are shown in Table 1.
The *conditions* A–C in the psychological experiment correspond to a situation where a speech sound power level 5 dB quieter than the normal effort of ISO 3382-3 since people do not speak with normal effort speech as ISO 3382-3 defines. The simulated sound pressure level (SPL) corresponds to the level at 6 m distance from the loudspeaker (or speaker in the office).
The total sound levels (sum of speech and masking) of the *conditions* did not differ significantly from each other (43–47 dB L_{Aeq}), but the intelligibility of the speech (STI) decreased significantly from *condition* A to C.
The speech of *conditions* A–C were created in the laboratory room by playing sentences of 3–8 words from one loudspeaker (1.5 m behind the participant). In Finland the sentences were presented in Finnish and in Germany in German, both read by one male speaker. The sentences originated from commercial audiobooks. In the experiment, the order of sentences was randomized so that there was no plot to follow. Masking had a broad-band spectrum within 200–8000 Hz conforming with the sound masking spectrum used in LähiTapiola Turku office. Masking was produced in the experiment with another loudspeaker (1.5 m behind the participant). The mutual levels of speech and masking (Table 1) were set so that they met the *conditions* measured in LähiTapiola Turku office.

Table 1. The acoustic descriptors for the experimental *conditions* of the psychological experiment. STI is Speech Transmission Index, $L_{\mathrm{Aeq,B}}$ is the A-weighted equivalent SPL of background noise. $L_{\mathrm{Aeq,S}}$ is the A-weighted equivalent SPL of speech. Signal-to-noise ratio is defined as SNR = $L_{\mathrm{Aeq,S}} - L_{\mathrm{Aeq,B}}$. Distraction distance, r_{D}, was measured in LähiTapiola office. It describes the distance, beyond which the STI is below 0.50.

Condition	STI	$L_{\mathrm{Aeq,B}}$ [dB]	$L_{\mathrm{Aeq,S}}$ [dB]	SNR [dB]	r_{D} [m]
A	0.81	33	43	10	14
B	0.37	44	43	-1	5.4
C	0.11	44	35	-9	2.5

Participants' cognitive performance was examined with two serial recall tasks, which measured short-term memory. Digits 1–9 were presented in a randomized order one by one from the screen (visual serial recall) or loudspeaker in front of participant (auditory serial recall). Ten seconds after the presentation of the last number, the order had to be returned to the answer box. Eleven sets were presented in each *condition*. Accuracy was the number of correctly remembered numbers.
After each task, the participants rated the *annoyance* (How much does the speech disturb, annoy, or bother you?), *workload* (How stressful did you think doing the previous task was?), and *ability to concentrate* (How difficult was it for you to maintain your concentration?). The response scale ranged from 0 (not at all) to 10 (very much).
At the end of each *condition*, the participant rated the statements "The sound environment was pleasant" (*pleasantness*), "The sound environment hindered the ability to concentrate" (*concentration difficulty*), "The sound environment weakened my task performance" (*performance loss*), and "I could work for long periods in a similar sound environment" (*work efficiency*). The response scale ranged from 1 (totally disagree) to 5 (totally agree).
During the whole experiment, the participants wore a belt under the chest muscle line. It monitored the electrocardiogram (ECG) with 250 Hz sampling rate. The sensor was synchronized with the computer running the psychological tasks. The heart rate variability (HRV) analysis concerned the ratio of the LF power and HF power of heart rate, where LF and HF represent mean frequency bands 0.04 – 0.15 and 0.15 – 0.40 Hz, respectively.
Each participant performed all tasks and assessments in all *conditions* (within-subject design). The order of the *conditions* was balanced. Each *condition* lasted, on average, 21 minutes.
Analysis of variance was used to analyze the results, where the condition was the within-subject variable, and the *country* was the between-subjects variable. The limit of significance was $p < 0.05$.

3. RESULTS

Country was a between-subjects variable in all analyzes of variance. The main effect of *country* was not significant in any outcome variable ($p > 0.05$). Therefore, the data of both countries were merged in the following analyses.
The differences in the outcomes between the *conditions* are summarized in Figure 1. The *condition* affected all subjective variables ($p < 0.05$). *Condition* C differed from B in all subjective variables.
Condition A was worse than B with the variables *annoyance due to speech* and *ability to concentrate* ($p < 0.05$).
The *condition* affected the *visual serial recall accuracy* ($p < 0.05$). It was better in *conditions* B and C than in A. *Condition* had no effect on *auditory serial recall accuracy* ($p > 0.05$).
Condition did not affect the low frequency high frequency ratio of HRV ($HRV_{LF/HF}$).

Figure 1. Summary of experimental results.

Variable	***Condition***		
	A	**B**	**C**
Subjective			
Annoyance due to speech	-		+
Workload			+
Ability to concentrate	-		+
Pleasantness			+
Distraction			+
Performance loss			+
Work efficiency			+
Performance			
Visual serial recall accuracy	-		
Auditive serial recall accuracy			
Physiological			
Heart rate variability			

Less strain or improved performance	+
Neutral	
More strain or decreased performance	-

4. DISCUSSION

The distinct feature of this study is that it involves identical laboratory experiments in two different countries in different languages. Since the results did not differ between countries, it is likely that similar results would be achieved in other countries as well. This is a justified expectation since the work efficiency effects of speech sounds have previously been found to be the same, e.g., between Germany and Japan [7].

Our experiment shows that the room acoustic environment of an open-plan office affects the employees' subjective experience and cognitive performance. For workers performing verbal tasks that require concentration, room acoustic design that meets the regulations (B) is better than room acoustic design that violates them (A). Room acoustic design that meets the regulations (B) reduces the adverse effects of speech on performance, reduces annoyance due to speech, distraction, and improves the subjectively perceived ability to concentrate. However, the subjective perceptions can still be improved by acoustic design that surpasses the regulations – *condition* C was better than *condition* B in **all** subjective variables. This suggests that investing in the best possible room acoustic design (distraction distance is much smaller than 5 m) will significantly improve the subjective experience.

Offices like *condition* C have been built in Finland to an increasing extent during the last few years. The most important reason is probably the entry of force of the new building regulation in 2018 [4]. It is also estimated that the cost of better room acoustics is only a small fraction of the total cost of the building. It has been analyzed that investments in better room acoustics could pay itself back in a few months through improved work efficiency [8].

We hope that this study will accelerate the progress made in recent years that room acoustic target levels are considered in the early level of building design and budget is reserved to reach the target levels of Sec. 1 [4]. Room acoustics should not be seen as an expense, but as an investment that improves the workers' well-being and the organization's productivity.

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