Simultaneous effect of office noise, heat, and stuffy air on employees' work performance

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Summary

The aim of our study was to investigate how office noise (irrelevant speech), temperature, and ventilation rate together affect cognitive performance and subjective perception of the open-plan office. Sixty-five subjects participated in the experiment involving two experimental conditions. In condition A, the temperature was neutral (23.5˚C), the intelligibility of irrelevant speech was low, and the fresh air flow rate was high (30 l/s per person). In condition B, the room temperature was high (29.5˚C), the intelligibility of irrelevant speech was high, and the fresh air flow rate was low (2 l/s per person). Performance was lower in condition B than in condition A in four out of six tasks. Distraction of environmental factors and symptoms were higher and environmental satisfaction was lower in condition B. Our study supports the view that special care should be paid to the holistic design of indoor environment in open-plan offices.

PACS no. 43.55.Hy

1. Introduction

High temperature, insufficient ventilation rate (causing poor air quality and stuffy air), office noise (colleagues' irrelevant speech), and lack of speech privacy are among the most complained environmental factors in open-plan offices. The effects of these factors on work performance and satisfaction are usually studied independently [1–3]. There is little research regarding their combined effects although office employees can be exposed to stuffy air, heat, and noise simultaneously.

The aim of our study was to investigate how irrelevant speech, temperature, and ventilation rate together affect cognitive performance and subjective perception of the open-plan office environment. Two experimental *conditions* were studied. In *condition* A, the temperature was neutral (23.5˚C), the intelligibility of irrelevant speech was low (higher speech privacy), and the fresh air flow rate was high (30 l/s per person). In *condition* B, the temperature was high (29.5˚C), the intelligibility of irrelevant speech was high (lower speech privacy), and the fresh air flow rate was low (2 l/s per person). Our hypothesis was that *condition* B would be inferior to *condition* A with respect to the various subjective and objective measures. The full version of this paper is published in Ref. [4].

2. Materials and methods

The independent variable of our study was *condition*. Room temperature, air quality, and acoustic characteristics of *conditions* A and B are shown in **Table I**.

Table I. Measured properties of *conditions* A and B.

	Condition A	*Condition* B
Room temperature		
Average over all test days [°C]	23.6	29.5
Air quality		
Fresh air flow rate [l/s per person], at least	30	2
CO_2-concentration: mean [ppm]	580	1470
TVOC concentration: mean [μg/m^3]	110	420
A-weighted level of speech [dB]		
Equivalent level over the session	45	51
Minimum level (speaker 6 m away), $L_{Aeq,15s}$	42	49
Maximum level (speaker 2 m away), $L_{Aeq,15s}$	48	53
A-weighted level of masking sound [dB]		
Equivalent level over the session	45	36
Speech Transmission Index STI		
Mean value over the session	0.37	0.67
Minimum value (speaker 6 m away)	0.22	0.62
Maximum level (speaker 2 m away)	0.52	0.72
Room acoustic conditions by ISO 3382-3		
$D_{2,S}$ [dB]	5.5	1.8
r_D [m]	2.9	24.1[a]
L_{pAS4m} [dB]:	51.5	55.6

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Table II. Room acoustic design of *conditions* A and B.

	Condition A	*Condition* B
Area of class A ceiling absorbers [m^2]	75	0
Area of class A wall absorbers [m^2]	18.0	0.0
Screen height [m]	1.3	1.3
Screen absorption	No	No
Textile floor covering	No	No
Sound masking system	On	Off

Table III. Procedure in the 1st session (the first *condition* where the participant arrived) and the 2nd session (the second *condition* where the participant arrived). The exposure to the *condition* A or B started in the Acclimatization phase.

1st session
Baseline phase (90 min)
Questionnaire A
Practicing of tasks 1-3
Break (20 min)
Acclimatization phase (30 min)
Questionnaire B
Practicing of tasks 4-6
Experimental phase (90 min)
Serial recall task (7 min)
Operation span task (12 min)
Story-writing task (5 min)
Questionnaire C
Break (a few minutes)
Information search task (20 min)
Typing task (10 min)
N-back task (20 min)
Questionnaire of thermal comfort
Questionnaire D
2nd session
Acclimatization phase (30 min)
Questionnaire E
Practicing of tasks
Experimental phase (90 min)
Like in 1st session

Sixty-five participants were tested in *conditions* A and B. The experiment was carried out using a repeated measures design, i.e., all participants were tested in both experimental *conditions* thus acting as their own controls. The order of *conditions* was counterbalanced between participants. The dependent variables were cognitive performance and various subjective outcomes.

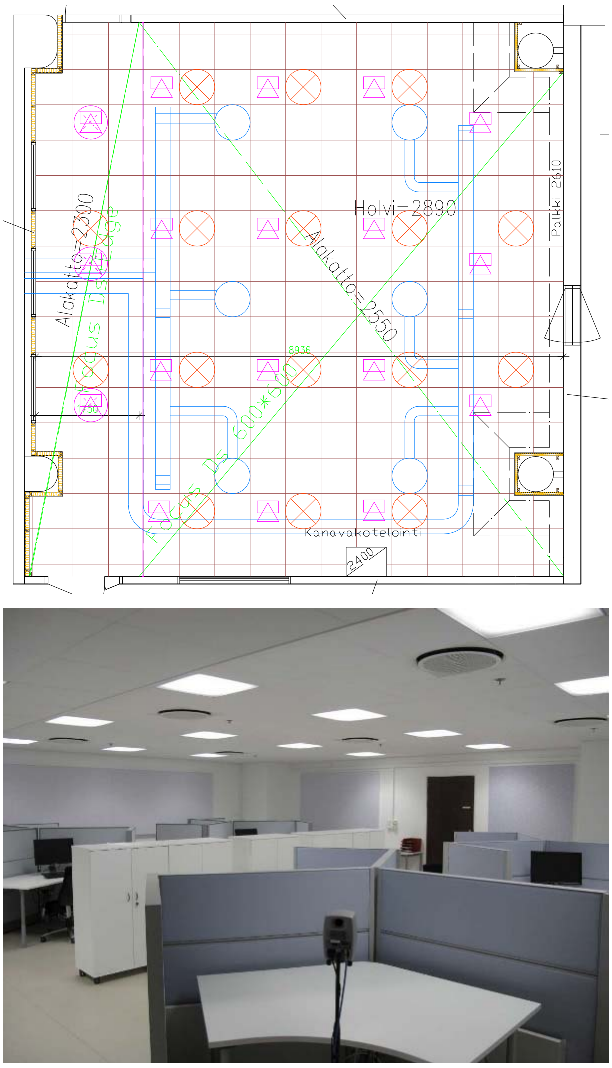

Figure 1. Top) The floor layout of the office. Speech was produced from loudspeakers of the corner workstations. Bottom) The ceiling drawing showing the positions of 18 sound masking speakers (red triangles) above the suspended ceiling, six ventilation inlet supplies (blue lines), and 16 luminaires (red crossed circles). Bottom) A photograph of the open-plan office. One of the corner loudspeakers is shown in front.

The study was conducted in a full-scale open-plan office which was built in an office building (**Figure 1**). Six participants were experimented at a time.

Both *conditions* A and B involved speech sounds played from four corner loudspeakers having a directivity close to normal mouth. The level range is depicted in **Figure 2**. Each speaker produced speech with the same equivalent sound power level in both *conditions* (casual speech effort, 63 dB L_{WA}). The speech consisted of short sentences, which had very little to do with each other. The sentences were chosen randomly from various independent radio discussions. Sentences were produced from one loudspeaker at a time in a random order.

The room acoustic difference of *conditions* A and B were achieved by building two completely different room acoustic environments (**Table II**). In addition, sound masking was louder in *condition* A. Sound masking was produced in both *conditions* from 16 speakers above the suspended ceiling. The spectrum had a slope of -5 dB per octave doubling within 100 and 10000 Hz. The *conditions* were measured according to ISO 3382-3 using an omnidirectional loudspeaker (**Table I**, **Figure 3**).

Neutral temperature was achieved in *condition* A by six chilling air supply units in the ceiling. High temperature was achieved in *condition* B by heat radiators hidden under the tables of the corner workstations. Low ventilation rate was achieved in *condition* B by circulating the exhaust air back to the room and by blocking the fresh air supply entirely. Furthermore, eight researchers were working in the room for two hours right before the participants arrived to create the desired carbon dioxide level 1500 ppm CO_2.

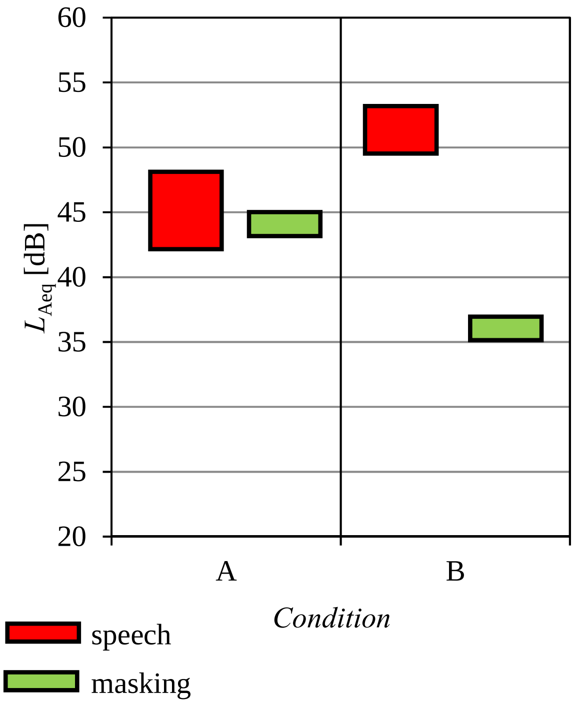

Figure 2. The measured equivalent A-weighted sound pressure levels, L_{Aeq}, of both speech and masking sounds during the whole experiment in *conditions* A and B.

Six tasks were used to assess cognitive performance: a serial recall task, an operation span task, an N-back task, an information search task, a typing task, and a story-writing task. The tasks cover a range of cognitive processes required in many types of office work.

The subjective experience of the environment was measured with five different questionnaires assessing e.g. occurrence of symptoms, distraction of environmental factors, environmental satisfaction, thermal comfort and acoustic satisfaction, and workload.

The experimental procedure is shown in **Table III**.

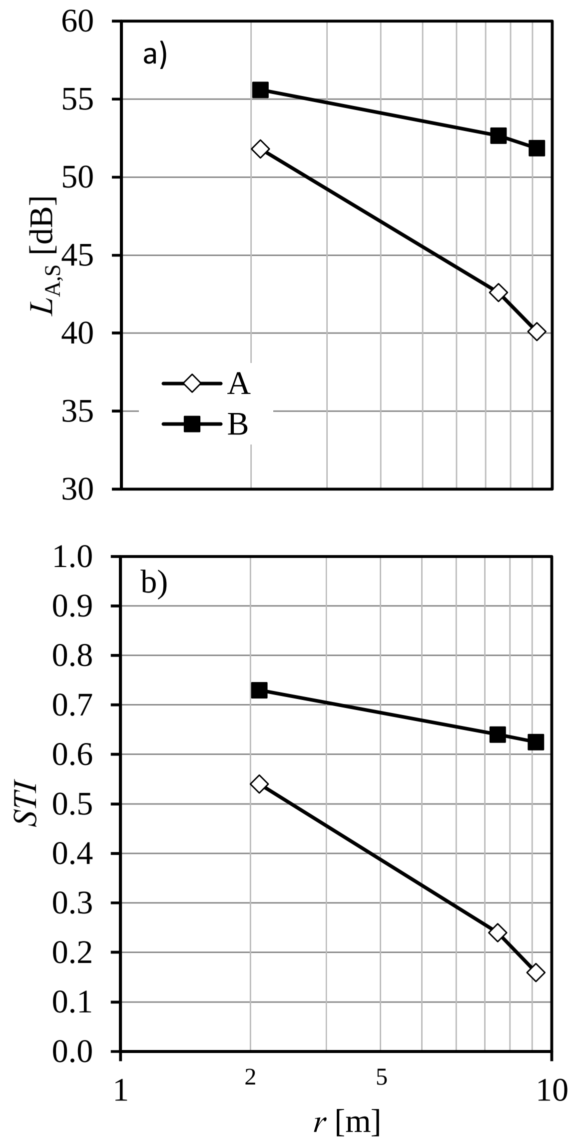

Figure 3. Spatial attenuation of a) A-weighted level of speech, $L_{A,S}$, and b) Speech Transmission Index, *STI*, in *conditions* A and B. The measurements were conducted according to ISO 3382-3 (ISO, 2012).

3. Results

The *condition* had an effect on performance in four out of six tasks (**Figure 4**). Performance was better in *condition* A than in *condition* B in serial recall task (percentage of recalled digits: $F_{1,64}$=5.86, p=.018, η^2=0.08), operation span task (percentage of correctly recalled words: $F_{1,63}$=10.84, p=.002, η^2=0.15), N-back task (response accuracy: $F_{1,63}$=4.01, p=.049, η^2=0.06), and typing task (total number of errors: $F_{(1,64)}$=4.03, p=0.49, η^2=0.06).

The subjective ratings were systematically in favour of *condition* A. The results concerning distraction, perception of the work environment, and symptoms are shown in **Figures 5-7**, respectively. Subjective workload was significantly higher in *condition* B (p<0.001). Both acoustic satisfaction and thermal comfort were significantly lower in *condition* B (p<0.001).

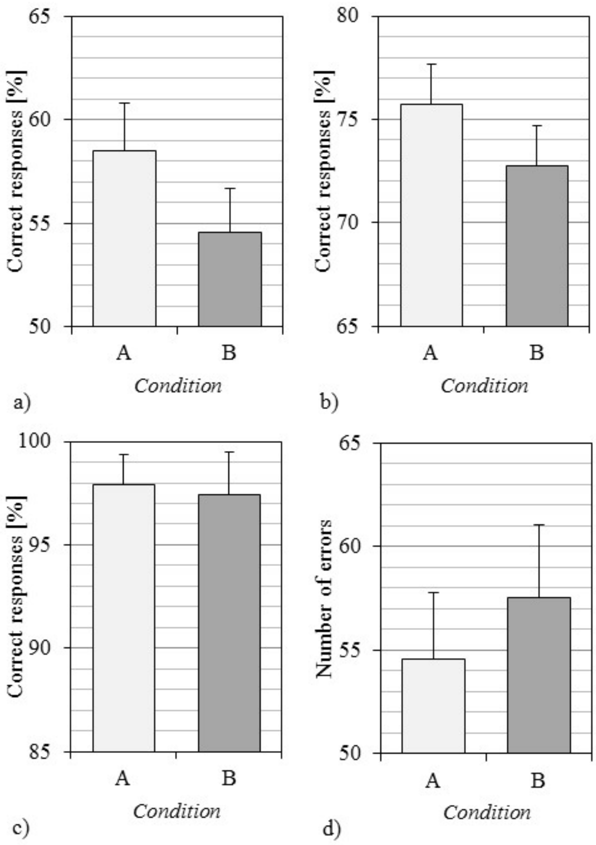

Figure 4. Percentage of correct responses in a) serial recall task, b) operation span task, and c) N-back task in *conditions* A and B. d) The number of errors in typing task. Mean and standard error of the mean is shown.

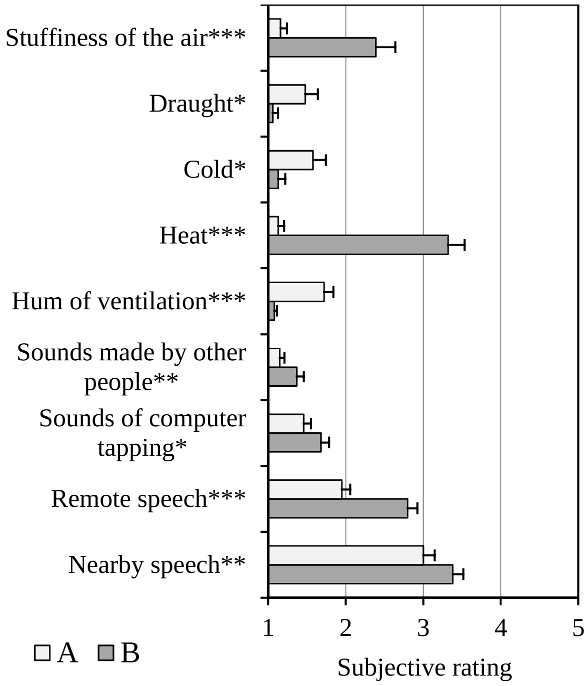

Figure 5. Self-rated distraction of work performance due to different environmental stressors in *conditions* A and B. Means and the standard errors of the means. Scale: 1 = Not at all, 5 = Very much. *p<0.05, **p<0.01, ***p<0.001.

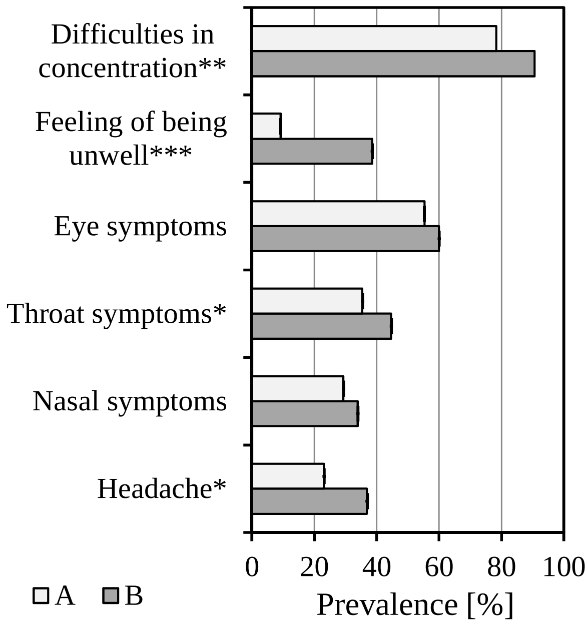

Figure 6. The percentage of participants reporting symptoms in the end of the exposure in conditions A and B. *p<0.05; **p<0.01; ***p<0.001.

4. Discussion

Our experimental *conditions* were carefully designed to meet two extreme physical conditions that are realistic in open-plan office workplaces. The environment was a normal open-plan office without a sign of a laboratory. The room was always occupied by six participants so that the participants were not working alone although there was no communication between the participants. The exposure time was long (2 hours), resembling a typical uniform working period in an office workplace. Therefore, our research has probably a better ecological validity than many other experiments in this field, except Refs. [1-3] which were conducted in the same environment. On the other hand, the building of the *conditions* took very much effort in the full-scale office. The participant groups had to enter twice to the laboratory since it took one week to build the next *condition*.

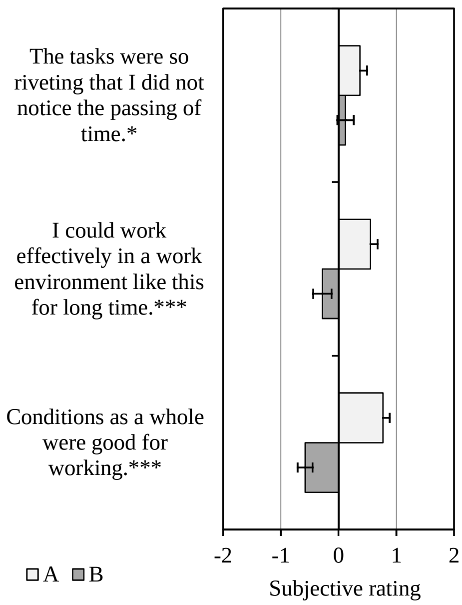

Figure 5. Subjective ratings of the working conditions in *conditions* A and B. Means and the standard errors of the means. Scale: -2 = Disagree completely, 2 = Agree completely. *p<0.05, **p<0.01, ***p<0.001.

Our results provide strong evidence that the combination of high intelligibility of irrelevant speech (i.e. poor speech privacy), high room temperature, and low ventilation rate impairs the perceived working conditions and cognitive performance of working memory tasks. Previous findings concerning only single factors [1-3] showed that high speech intelligibility reduced performance more than high temperature and low ventilation rate. Therefore, it is feasible to suggest that high speech intelligibility in *condition* B explained a significant part of the observed performance effects.

On the other hand, we have no direct evidence supporting the abovementioned suggestion. Therefore, future research is highly justified to better understand how these three factors, ventilation rate, temperature, and speech intelligibility, affect performance as separate exposure agents and as combined agents.

We would conduct future research in two parallel chambers where the thermal and ventilation rate could be controlled so that the same participant can be tested during the same day in two thermal or air quality conditions. Acoustic conditions can be produced using headphones instead of using built room acoustic conditions and loudspeakers.

5. Conclusions

Our study supports the view that special care should be paid to the holistic design of the indoor environment of open-plan offices. By designing room acoustic conditions, thermal conditions and ventilation rate adequately, satisfaction with work environment is increased, somatic symptoms are decreased and the possible impairments of work performance might be avoided.

Acknowledgements

This study was a part of TOTI (User-oriented office spaces) funded by Business Finland, Finnish Institute of Occupational Health, and 15 companies.

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