Open-plan office environments: A laboratory experiment to examine the effect of office noise and temperature on human perception, comfort and office work performance

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SUMMARY
A human subject experiment was performed to examine the effect of office noise and temperature on human perception, comfort and office work performance. The experiment concerned offices of two different sizes with three different acoustical treatments. An open-plan office environment was simulated by playing office sounds through a surround-sound speaker system. The sound background was created by the ODEON room acoustic simulation software: I) a real open-plan office; II) an office as (I) but with a reflective ceiling; and III) an office as (I) but with the addition of acoustically absorbent surfaces. A cellular office environment was created by no sound being played. Subjects experienced all office environments at a comfortable temperature of 23°C and in the case of the cellular office and open-plan office (I) they experienced a second exposure at 28°C. A total of 15 subjects were exposed to the conditions and each exposure lasted for 6 hours. The presence of office noise and the type of office environment were found to have a significant effect on office work tasks that involved processing words. Results indicate that an excessive noise absorption in open-plan offices may have a negative impact on occupants' perception of noise, the acceptability of noise and the performance of office work.

KEYWORDS
Open-plan office, Noise, Heat stress, Productivity, Comfort

INTRODUCTION
Open-plan offices are widely used in today's office buildings. The main argument for an open-plan office is to improve communication and knowledge-sharing between workers, and therefore promote performance. Reconfiguration is also easier and managers are able to continuously supervise the activities of their staff without the restriction of walls and doors. However, the sharing of one space by many people carries some drawbacks that, apart from discomfort and lack of privacy, may result in a decrease in the performance of office workers. De Croon et al. (2005) carried out a literature review of the effects of open-plan offices and found strong evidence that working in open-plan offices reduces workers' perception of privacy and job satisfaction. There was some evidence that working in open-plan offices can intensify the cognitive workload and worsen interpersonal relationships. The review did not deal with the issue of work performance. Noise has been recognized as one of the main problems in open-plan offices (Pejtersen et al., 2006; Sundstrom, 1986). Masking of distracting noise by other sounds has been used as a remedy to reduce noise annoyance, with

controversial results. Some studies demonstrated positive effects of masking noise on human perception and performance (Veitch et al., 2002; Loewen and Suedfeld, 1992), while other studies, on the contrary, found the masking noise ineffective or even unacceptable (Keighley and Parkin, 1979). The use of screens between workstations is a more traditional way to attenuate the noise and shield the receiver (Moreland, 1988), and such a screen provides a degree of privacy in an open space. Thermal discomfort presents another issue that is more likely to be experienced in open-plan offices than in cellular offices (Pejtersen et al., 2006). Effects of thermal conditions alone on human performance have been studied and several studies showed that thermal load may have a negative impact on mental performance (Wyon, 1996a). In open-plan offices, it is likely that at times employees are exposed to both noise and thermal discomfort at the same time. Witterseh (2004) studied the effect of exposure to combinations of three air temperatures (22, 26 and 30ºC) and two acoustical conditions (background noise, 35 dB(A) or open-plan office noise, 55 dB(A)) on SBS symptoms and office work performance. Raised temperatures had negative effects on a wide range of SBS symptoms while in noisy condition only fatigue was reported as higher and the ability to concentrate as lower than in the quiet condition. The two negative factors, elevated temperature and office noise, which might be present in the open-plan office environment, were found to have some negative effects on both human comfort and performance.

The experiment presented in this paper was performed to examine the effect of office noise and temperature on human perception, comfort and office work performance. The factors and their interactions examined were: 1) office size - cellular office vs. open-plan office environment; 2) the acoustical properties of a large office - an open-plan office environment with different acoustical treatments and 3) thermal conditions – temperature within the comfort range vs. elevated temperature as commonly experienced in offices without cooling. This paper presents some of the results obtained in the experiment.

METHODS

The experiment was carried out in a simulated office (Figure 1). The room was equipped with 5 workstations, each comprising a chair, a desk and a computer. The workstations were arranged in the centre of the room and were surrounded by a 7+1 speaker system so each subject was sitting at approximately the same distance from all speakers and as close to the centre of the room as possible. The ventilation and the required operative temperature (23ºC and 28ºC) in the room were ensured by a mixing ventilation system in the office. The ventilation provided 100 L/s (2.8 L/s.m^2) of outside air.

Figure 1. Set-up in the laboratory office.

Fifteen Danish subjects (six females and nine males) were recruited to participate in the experiment and completed the exposures in groups of 2 to 5 persons. The subjects were recruited among students of universities around Copenhagen. A hearing test was conducted to ensure that only persons with normal hearing were chosen to participate. The average age of the group was 22 years. The subjects were allowed to adjust their clothing during the exposures.

Six experimental conditions were created by combining four different acoustic environments and two operative temperature levels: 1. Cellular office and 23°C; 2. Open-plan office I and 23°C; 3. Open-plan office II and 23°C; 4. Open-plan office III and 23°C; 5. Cellular office and 28°C; and 6. Open-plan office I and 28°C. The acoustic environments comprised:

1) Cellular office: no recording played - the acoustic environment created by background noise and by noise caused by the work of the exposed subjects (subjects instructed not to talk to each other in all conditions); average sound level 47.7 dB(A);
2) Open-plan office I: sound from the model based on the parameters obtained by the in-situ measurements – replica of the real office (Pop and Rindel, 2005); average sound level 52.0 dB(A);
3) Open-plan office II: sound from the model (I) with a longer reverberation time achieved by strong reduction of the ceiling absorption coefficient to make the ceiling very reflective; average sound level 54.0 dB(A);
4) Open-plan office III: sound from the model sharing the same characteristics as model (I) with the geometry of the office modified by adding sound baffles perpendicular to the ceiling and sound screens between desks; average sound level 49.0 dB(A).

The six conditions and the randomized order, in which they were presented to the groups of subjects, are shown in the Table 1.

Table 1. Experimental conditions and their sequence of presentation to groups of subjects.

Group	Conditions					
	Cellular office 23ºC	Open-plan office I 23ºC	Open-plan office II 23ºC	Open-plan office III 23ºC	Cellular office 28ºC	Open-plan office I 28ºC
	Order of presentation					
1	6	2	3	1	4	5
2	1	6	5	3	2	4
3	2	3	1	4	5	6
4	5	4	2	6	1	3

The open-plan office environment was simulated by playing a recording made in a working office (Witterseh et al., 2004) through a surround-sound speaker system. The recording contained sounds originating from typical office activities, i.e. two sided conversations and one sided phone conversations in Danish (i.e. intelligible by the subjects), telephones ringing, steps of persons passing by, opening and closing of the door, shuffling of paper etc. The sources of the sounds were distributed throughout the office at different distances and in different positions in relation to the listener. The simulations of the three different open-plan offices was created using ODEON room acoustic simulation software (Odeon 9.0). The additional background noise from ventilation and computers in the laboratory office was constant in all conditions.

The exposure to each of the conditions lasted for 6 hours, with a 25-minute lunch break outside the laboratory office dividing the exposure into two 3-hour parts. During each exposure the subjects completed questionnaires concerning their perceptions of different factors in the environment, their comfort sensations, their perceived ability to perform office work and the intensity of any SBS symptoms they experienced, while working on computer-presented office work tasks. The tasks simulating office work comprised creative thinking (i.e. writing down as many alternative uses as possible for a set of specified and familiar objects (Wyon, 1996b)), text typing, proof-reading (i.e. reading of text and marking words that were wrong from a grammatical or contextual point of view) and addition of numbers. The paper presents results of the latter three tasks. Measures analyzed in the text-typing task were speed (number of characters typed per minute), and errors (determined by Levenshtein's distance (Levenshtein, 1966)). Measures analyzed in the proof-reading task were speed (number of words read per minute), number of correctly marked errors in text (true positive), number of false detections of errors (false positive), number of omitted errors (missdetect) and error, which was calculated as ("number of omitted errors" + "number of false detections")/(total number of wrong words inserted). In addition, task speed (number of calculations completed per minute), number of correct additions and percentage error were analyzed.

In the statistical analyses, the data were tested for normality using the Kolmogorov-Smirnov test. Linear Mixed Effects models were used for data that were normal and non-parametric Friedman Two-Way Analysis of Variance was used for not normally distributed variables.

RESULTS

Figure 2 shows the acceptability of the overall environment in all six conditions. Increased temperature had a highly significant effect on the perception of the overall environment ($p<0.0001$). The type of office environment had no significant effect on the assessment.

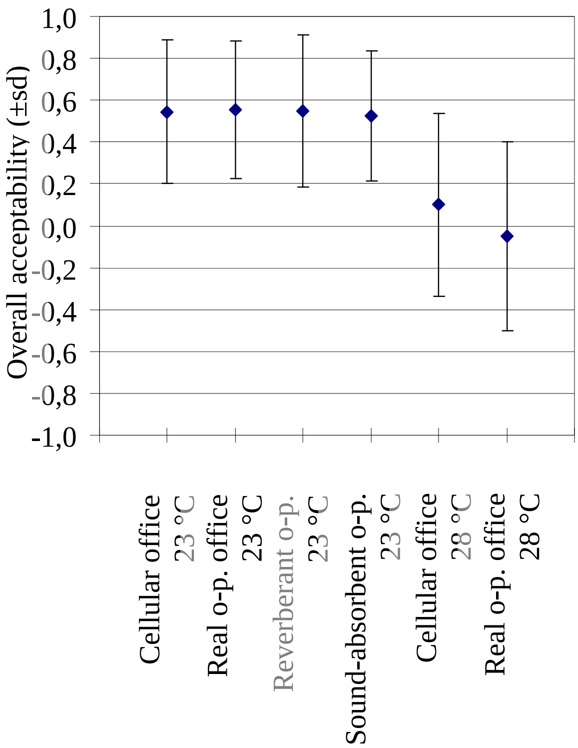

Figure 2. Acceptability of the overall environment (effect of temperature $p<0.0001$) rated on continuous scale +1 = clearly acceptable; -1 = clearly unacceptable.

The subjects' thermal sensation and acceptability of the thermal environment are presented in Figure 3. In cooler conditions (23°C) the average thermal sensation was 0.08; in warm conditions (28°C) the average thermal sensation was 1.63. Both thermal sensation and thermal acceptability were significantly affected by temperature ($p<0.0001$).

Figure 4 presents the results of the subjects' perception of the loudness of noise in the environment and of the acceptability of noise. Both office noise and office type had a significant effect on the perception of loudness and the acceptability of noise ($p<0.0001$). No adaptation to noise was observed in the course of the exposures (effect of time $p>0.1$).

Table 2 shows a summary of subjects' perceptions, performance measures where significant effects were detected, subjects' self-estimated performance and their ability to concentrate. The presence of office noise had a significant effect on speed of text typing ($p<0.01$). Office type significantly affected speed of text typing ($p<0.001$) and number of falsely detected errors in the text in proof-reading task ($p<0.0001$). No effect was found on the addition task. When subjects assessed their performance subjectively, they reported lower performance in all conditions compared to the reference cool cellular office condition. There was a highly significant effect of office noise ($p<0.01$), office type ($p<0.05$) and temperature ($p<0.001$) on their assessment. There was a highly significant effect of both office type and temperature on the subjects' ability to concentrate. No effect of temperature and office noise interaction was found. Large standard deviations of the presented results indicate a large variation in the data.

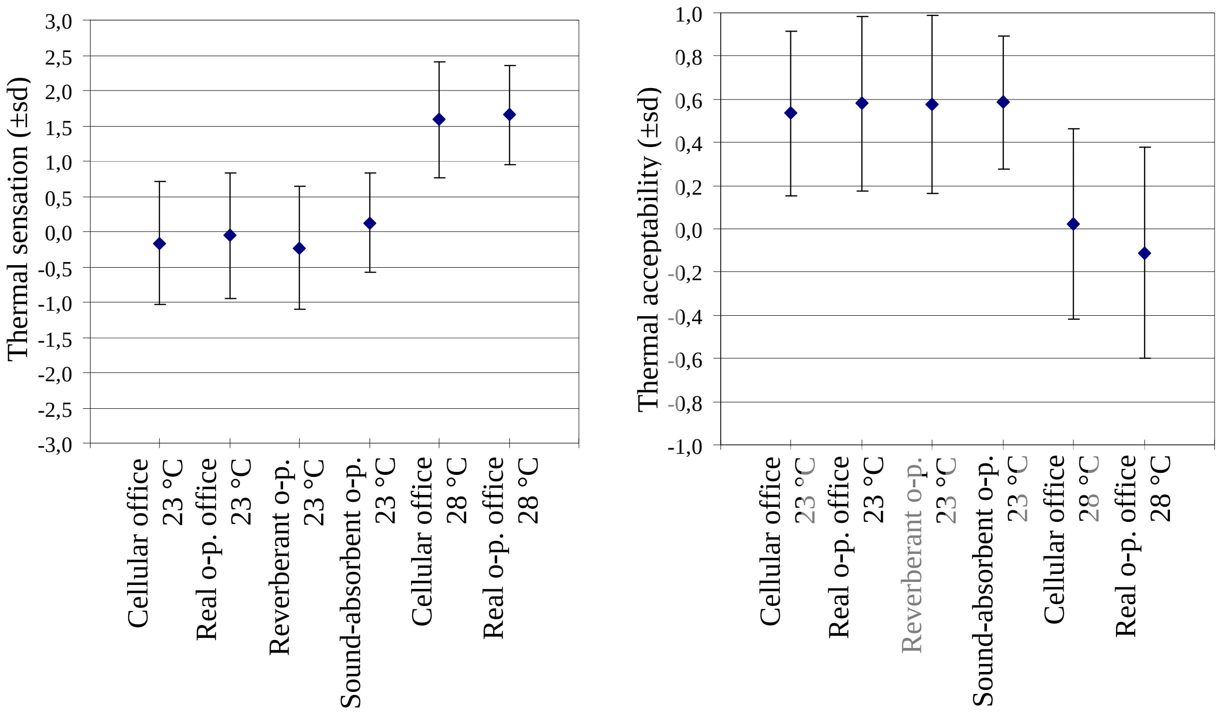

Figure 3. Subjects' thermal sensation and thermal acceptability; thermal sensation +3=hot; -3=cold and thermal acceptability rated on continuous scale +1=clearly acceptable; -1=clearly unacceptable.

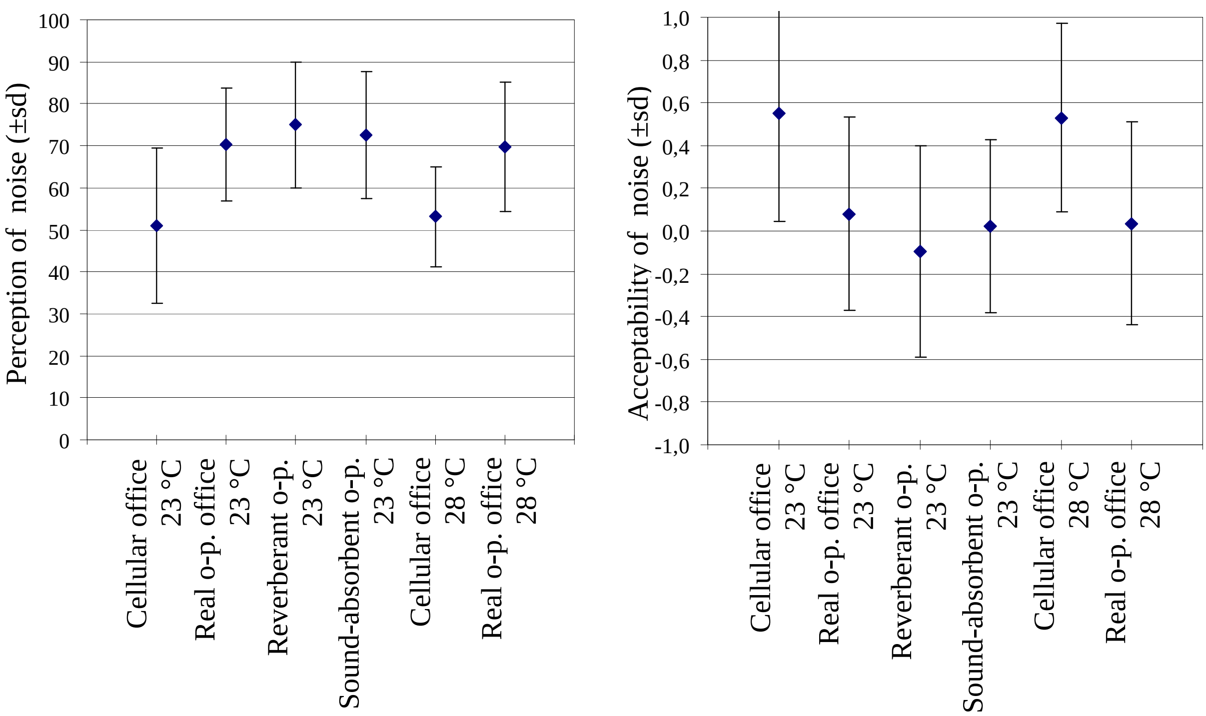

Figure 4. Subjects' perception of noise and acceptability of noise; perception of noise 0=too quiet; 100=too loud and acceptability of noise rated on continuous scale +1=clearly acceptable; -1=clearly unacceptable.

Table 2. Average values (± standard deviation) of performance measures significantly affected by conditions and subjects' ability to concentrate

Office Type		Cellular office	Real open-plan office	Reverberant open-plan office	Sound-absorbent open-plan office	Cellular office	Real open-plan office	Effects*
Temperature		23 °C	23 °C	23 °C	23 °C	28 °C	28 °C	
Text typing	Speed	167.32 (±30.7)	163.14 (±28.8)	160.37 (±26.3)	147.59 (±34.4)	158.07 (±28.7)	152.33 (±29.5)	O_t: p<0.001 O_n: p<0.01
Proof reading	False positive	5.07 (±3.74)	4.27 (±3.03)	8.13 (±6.36)	4.83 (±4.94)	4.37 (±3.72)	4.03 (±3.20)	O_t: p<0.0001
Self estimated performance Continuous scale: 0=0%; 100=100%		78.65 (±14.4)	69.81 (±16.2)	70.26 (±16.6)	69.56 (±16.5)	69.08 (±16.6)	61.63 (±20.0)	T: p<0.001 O_t: p<0.05 O_n: p<0.01
Ability to concentrate Continuous scale: 0=difficult to concentrate; 100=easy to concentrate		69.34 (±23.2)	50.51 (±24.8)	50.01 (±26.2)	48.64 (±25.4)	54.89 (±26.7)	36.82 (±24.1)	T: p<0.0001 O_t: p<0.0001 O_n: p<0.0001

*T- temperature; O_t- office type; O_n- office noise

DISCUSSION

The present experiment can be partially compared to the study by Witterseh et al. (2004) on combined exposure to heat stress and office noise. These authors found that both temperature and noise negatively affected the overall acceptability of the environment. In the current experiment presented here, the results show that only temperature made subjects express increased dissatisfaction with the overall environment. However, when subjects were asked directly about the acceptability or perception of the noise in the environment, the negative effect of office noise was clear. It could be that the subjects mistakenly excluded noise from their assessment of the overall environment, considering its effects only in questions directly addressing the issue of noise. In the combined warm and noisy condition, the addition of noise did cause a further decrease in the acceptability of the overall environment. Warm conditions caused an expected decrease in the acceptability of the thermal environment and an increase in thermal sensation from neutral to slightly warm/warm even though subjects were allowed to adjust their clothing.

In Witterseh's experiment, both temperature and noise were found to have a negative effect on the addition task. The current experiment failed to show an effect of temperature on office work performance but found a strong effect of office type on speed of text typing and false detection of mistakes in the proof-reading task. This indicates that tasks requiring processing of words might be more sensitive to the presence of office noise. It is likely that this effect is due to the presence of intelligible speech that interferes with performance tasks in general and might interfere with word processing even more (Knez and Hygge, 2002; Jones et al., 1990; Weinstein, 1977). This is further supported by the subjects' assessment of their ability to concentrate, which was significantly affected by office noise and also by temperature. Self-estimated performance was affected by both temperature and office noise; the effect was similar when the negative factors were present separately and subjects indicated a further decrease in their ability to perform well when the office noise and elevated temperature were combined.

The results suggest that it might be possible to "overdo" the improvements in offices that are achieved by acoustic baffling. The conventional wisdom is that if there is too much noise in the space it needs to be damped in order to improve working conditions. The present results, however, suggest that damping may have some negative impacts. This trend was found in several different dependent measures. The sound-absorbent office was found to cause a larger decrease in the acceptability of noise than the real open-plan office ($p<0.05$). Similarly, subjects perceived the noise in the sound-absorbent office as louder than in the real open-plan office ($p<0.01$), even though the objectively measured sound level in the sound-absorbent office was lower. The speed of text typing showed a clear and unexpected decrement in the sound-absorbent open-plan office compared to both the real ($p<0.01$) and the reverberant open-plan office ($p<0.05$). The self-estimated performance in the sound-absorbent office is no different from in the real open-plan office. A possible explanation of this effect is that the acoustic treatment of the office reduces the overall noise level and therefore cancels the masking effect of noise from sources at a distance. The close sources become more apparent, which causes more annoyance, more disruption and an increase in dissatisfaction with noise in the space. It would be very useful to know how much sound absorption is required to cause this negative effect, i.e. what level of sound absorption would result in the maximum positive effect. Further research is needed to confirm the observed trends and to provide more insight into the relation between the degree of sound absorption and the positive/negative effects that result.

Due to the design of the experiment not being fully balanced, some learning might have been expected to occur for the whole group of subjects. Data were analyzed for learning effect and it did not occur in the performance measures, which were significantly affected by physical conditions in the exposures.

CONCLUSIONS

Office noise and type of office environment were found to have a significant effect on office tasks that included processing words. Compared to a cellular office, the open-plan offices caused significantly higher dissatisfaction with noise in the environment and decreased subjects' ability to concentrate. Assessment of the effect of different acoustical treatments in open-plan offices indicates that an excessive noise absorption in open-plan offices may have a negative impact on occupants' perception of noise, the acceptability of noise and performance. Warm conditions caused significantly more dissatisfaction with the overall environment than cool conditions and combining the elevated temperature with office noise caused a further decrease in the assessment. No effect of temperature on the performance of simulated office work could be demonstrated. Subjects' ability to concentrate was negatively affected by elevated temperature and in combination with office noise the perceived ability to concentrate was further decreased.

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