# The influence of exposure to multiple indoor environmental parameters on human perception, performance and motivation

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## SUMMARY

The impact of simultaneous short-term exposure to three environmental parameters (temperature, noise and air quality) on human perception and performance was studied in two identical climate chambers. Eight conditions were created exposing the subjects for 20 minutes to combinations of two levels of operative temperature (23,5 ºC and 28,0 ºC), two noise levels (52 dB(A) and 60 dB(A)) and two pollution loads (pollution load absent, pollution load present). 56 participating subjects performed simulated office work (addition) and completed questionnaires concerning their perception of the environment and adverse symptoms in each combination of conditions. The subjects were informed of the conditions so they were able to make a conscious or unconscious choice to work more or less according to their perception of the conditions and their attitude to them. Despite the short time allocated for performance of the addition task a significant decrease in performance in warm noisy, warm polluted and warm noisy polluted conditions could be demonstrated. Subjects reported a highly significant reduction in the acceptability of the indoor environment, in self-reported performance and in their ability to concentrate in all deteriorated conditions, i.e. they tended to overestimate the negative effects of each factor. This was especially the case for noise.

## INTRODUCTION

The impact of indoor climate parameters on human comfort, health and performance has been studied for decades. Most of this research has evaluated the influence of one environmental parameter at a time. Very little research has been performed on the effects of exposure to multiple indoor environmental parameters as they occur in real life. In real buildings, interventions to improve one factor may fail to achieve a positive effect when several other factors are causing discomfort or they may not achieve as large a positive effect as if more factors had been altered simultaneously. An intervention that reduces one negative factor may even increase the discomfort caused by other factors. A familiar example of this is when opening windows to refresh the air in the room causes increased discomfort due to the traffic noise that can be heard through the open windows. It is therefore essential to study not only the influence that each individual parameter has but also what interactions exists between them in terms of their effects on occupants, and what influence they have on each other.

Toftum [1] concluded in a literature review that there is only limited evidence for the existence of significant interactions between different aspects of the indoor environment. Only for the effect of air temperature and air humidity on perceived air quality are well-established relationships available. Fang et al. [2,3] showed that the acceptability of inhaled air decreased with both increasing air humidity and air temperature, whereas the odour intensity of the air was independent of its psychrometric properties. Furthermore, Fang et al. [4] showed that a decrease in outdoor air supply rate could be compensated for by decreasing indoor air enthalpy so as to avoid reducing perceived air quality. The effects of other combined factors were described by Clausen et al. [5], who determined the relative importance of sensory air pollution, thermal load and noise. Their study showed that a 1 ºC change in operative temperature had the same effect on comfort as a change of 2,4 decipol in the perceived air quality or a change of 3,9 dB in the noise level. Witterseh [6] investigated the impact of combinations of the same three parameters on environmental perception, SBS symptoms and the performance of office work. The combination of ventilation noise and emissions from carpet was found to cause significantly more self-reported fatigue and there was a tendency for a negative effect on performance. The interaction between noise and temperature was found to have a significant effect on the performance of office tasks and on self-estimated performance, ability to think clearly, ability to concentrate and fatigue. Banhidi at al. [7] studied the effect of combinations of two levels of temperature (20 and 30ºC), noise (60 and 70dB) and lighting (280 and 920lux) on performance and physiological measures. A significant effect was found for elevated noise level negatively affecting the performance of a game (Tetris, a falling blocks puzzle video game requiring high concentration and logical thinking) and interaction between lighting and temperature affecting the number of characters written. The influence of a combination of irrelevant speech and indoor lighting on performance was examined by Knez and Hygge [8]. No interactions between noise and light were shown but there were negative effects of presence of noise and cool-white light on long-term memory recall. Furthermore, unpleasantness increased over time in the silence condition and decreased when the subjects were exposed to irrelevant speech. Clausen and Wyon [9] further investigated the influence of 6 combined factors on the acceptability of the environment and on the performance of office work. One group of subjects performed simulated office work in a set of poor environmental conditions with overhead fluorescent lighting, recorded traffic noise, 27 ºC operative temperature, supply air polluted by emissions from linoleum, recorded open office noise, and almost no daylight. The realistic annual cost of improving each of the six conditions was estimated and expressed as a percentage of the total sum. A second group of subjects briefly experienced all poor and improved conditions and individually selected the improvements they preferred, up to a 50%-budget, while the members of a third group of subjects were randomly paired with each of these subjects. The fourth group was exposed to 100%-budget conditions. Significant improvements in subjective assessments of the environment occurred at high budget levels and when individual choice was provided, and the self-reported performance of office tasks improved, but no effects on performance could be shown.

The studies reviewed above showed that the acceptability of the indoor environment and human performance decreases with deteriorating conditions, although in some of them the decrement in performance was not always significant or as large as could have been expected. This might be due to the motivation of people to counteract the uncomfortable conditions and perform well in the experimental setting. However, in reality, if people are aware that their working conditions vary from day to day or during a day, it is conceivable that they will avoid working hard in poor conditions and choose to work better in more comfortable conditions.

The purpose of the present experiment was to study the impact of exposure to three environmental parameters (temperature, noise and air quality), occurring individually or at the same time, on the overall acceptability of the indoor environment and on office work performance, taking into account subjects' motivation to work. It is presumed that if the subjects are aware of the conditions they are about to encounter, and are aware that conditions will later improve or deteriorate, they will make a choice (consciously or unconsciously) to exert more or less effort in their work according to the conditions prevailing at the time.

## METHODS

The experiment was carried out in two identical climatic chambers at the International Centre for Indoor Environment and Energy, DTU in June 2006. Both chambers were equipped with four workstations, each comprising a chair, desk and computer.

56 subjects participated in the experiment. The participants were recruited among students attending DTU. The average age of the group was 24 years and it consisted of 26 females and 30 males. The participants were paid for their participation.

Eight conditions were created and the subjects were exposed in groups of four to all combinations of two levels of operative temperature, two noise levels and two states of indoor air quality (Table 1.).

Table 1. Environmental parameters

| Environmental parameter | | Reference condition | Deteriorated condition |
|---|---|---|---|
| 1 | Operative temperature | 23,5 ºC<br>(PPD 5 %) | 28,0 ºC<br>(PPD 38 %) |
| 2 | Traffic noise | 52 dB(A) | 60 dB(A) |
| 3 | Air quality | Pollution load absent | Pollution load present<br>23 $m^2$ of old carpet |

The eight experimental conditions are shown in the Table 2. The groups of subjects were exposed to these conditions in randomized balanced order.

Table 2. Combinations of exposures

| Symbol | Pollution load | Operative temperature | Noise level |
|---|---|---|---|
| C1 | Absent | 23,5 ºC | 52 dB(A) |
| C2 | Absent | 23,5 ºC | 60 dB(A) |
| C3 | Absent | 28,0 ºC | 52 dB(A) |
| C4 | Absent | 28,0 ºC | 60 dB(A) |
| C5 | Present | 23,5 ºC | 52 dB(A) |
| C6 | Present | 23,5 ºC | 60 dB(A) |
| C7 | Present | 28,0 ºC | 52 dB(A) |
| C8 | Present | 28,0 ºC | 60 dB(A) |

A recording of traffic noise was played inside the chambers using a CD player and one speaker in each chamber. In the reference condition of 52 dB(A) the traffic noise was barely audible as through a closed window; in the deteriorated condition of 60 dB(A) the traffic noise was clearly audible as if the window was open. An old carpet taken from an office was used as a source of pollution; 23 $m^2$ of carpet were used corresponding to the floor area of the chamber. The carpet was placed in a "pollution chamber", through which the supply air to one chamber was passed. The outdoor air supply rate was kept constant at a high level of 26 l/s per person to eliminate the effect of bioeffluents and other pollution sources than the old carpet. Prior to the experiments the subjects participated in a one-hour preliminary session. During the preliminary session 10 minutes were allowed for experiencing the environmental conditions and the subjects performed an olfactory ranking test [10] to ensure they had a normal sense of smell.

During the experiment the subjects were exposed to sequentially changing combinations of conditions while working on a computer. Only minor breaks disturbed the continuity of the subjects' work when they exited one combination of conditions and entered another. The subjects performed simulated office work (addition) for 15 minutes in each combination of conditions. In the last 5 minutes of each exposure they then completed a questionnaire concerning their perception of the environment, thermal comfort and adverse symptoms. The task and questionnaires were administered using the DTU software tool "Remote Performance Measurement" (RPM) [11]. At the end of the exposure period the experimenter signalled the subjects to exit the chamber. In this very short break the subjects were asked to state which of the environmental parameters they considered it would be the most important to improve if they were working in such an environment and which would be the second most important to improve. They then received a notice describing in informal terms the next conditions they were to work in and returned to work in one of the chambers where the respective conditions were set. This break served also as an exercise to keep the activity of subjects at approximately the same level as in a real office. The whole experimental session lasted for 3 hours.

The data obtained in the experiment and their residuals were analysed for normality using the Kolmogorov-Smirnov test. Paired t-tests and the Wilcoxon matched-pairs signed-rank test were then used for analyzing normally and not normally distributed data respectively. The results of a comparison analysis between the reference condition C1 (23,5 ºC; 52 dB(A); pollution load absent) and the seven deteriorated conditions and between the deteriorated conditions themselves are presented.

## RESULTS

The results of an addition test, i.e. the number of completed additions per exposure, are presented in Figure 1. The difference from the result obtained in C1 was significant in conditions C4 and C7 at the level of significance $p<0,05$ and in the condition C8 at the level of significance $p<0,01$. No significant difference was found between conditions in terms of the percentage errors committed. Self-estimated performance showed a significant drop in all deteriorated conditions compared to C1 ($p<0,001$) (Figure 2).

Figure 1. Number of completed additions per exposure ± standard deviation

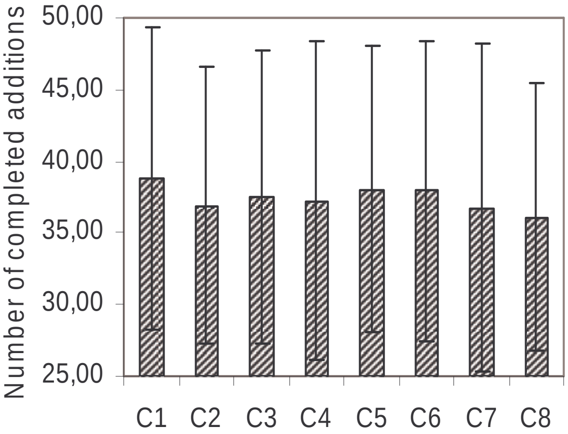
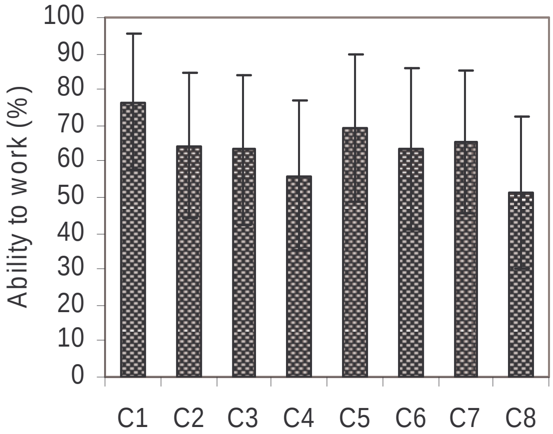



Figure 2. Self-estimated performance (%) ± standard deviation

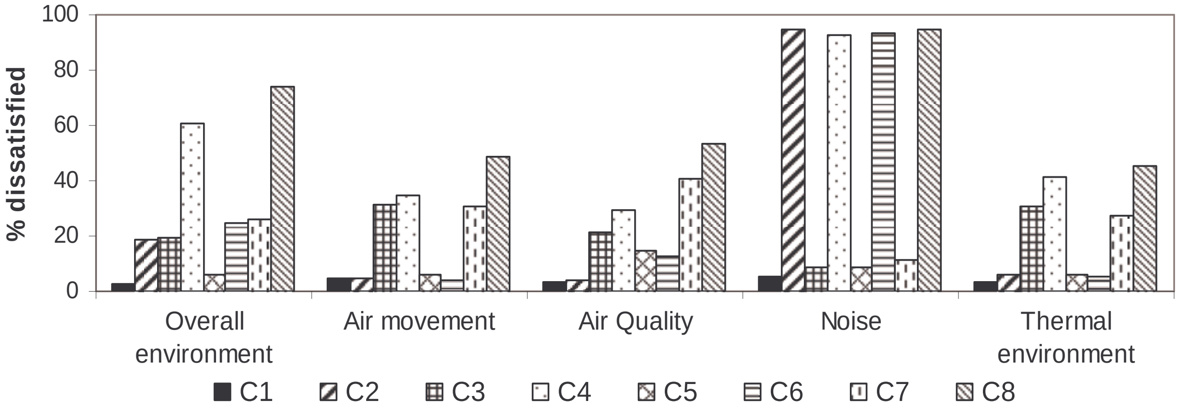



The mean acceptability votes are shown in Table 3 and the percentages dissatisfied with the overall environment, air movement, air quality, noise and thermal environment are presented in Figure 3.

Table 3. Acceptability of the environment and its factors

| | **Mean acceptability ± standard deviation** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **C1** | **C2** | **C3** | **C4** | **C5** | **C6** | **C7** | **C8** |
| Overall indoor environment | 0,64 ±0,30 | 0,25 ±0,36 | 0,24 ±0,40 | -0,11 ±0,47 | 0,48 ±0,35 | 0,18 ±0,45 | 0,16 ±0,42 | -0,24 ±0,50 |
| Air movement | 0,55 ±0,32 | 0,55 ±0,33 | 0,12 ±0,46 | 0,09 ±0,47 | 0,49 ±0,33 | 0,55 ±0,28 | 0,12 ±0,43 | -0,02 ±0,44 |
| Indoor air quality | 0,61 ±0,31 | 0,56 ±0,33 | 0,21 ±0,41 | 0,13 ±0,45 | 0,30 ±0,43 | 0,33 ±0,45 | 0,04 ±0,46 | -0,06 ±0,43 |
| Noise | 0,51 ±0,38 | -0,57 ±0,38 | 0,41 ±0,42 | -0,52 ±0,49 | 0,41 ±0,33 | -0,54 ±0,40 | 0,36 ±0,43 | -0,58 ±0,39 |
| Thermal environment | 0,61 ±0,30 | 0,49 ±0,39 | 0,12 ±0,42 | 0,03 ±0,41 | 0,48 ±0,39 | 0,51 ±0,34 | 0,15 ±0,45 | 0,00 ±0,45 |

Figure 3. Percentage of dissatisfied with the environment and its factors



The acceptability of the overall environment was significantly lower in all deteriorated conditions compared to the reference condition C1 (p<0,001; except C5 where p<0,01). However, when the deteriorated conditions that differ only in pollution load were compared between each other (i.e. C2 against C6, C3 against C7, C4 against C8), the analysis did not show a significant difference in acceptability. A major drop in acceptability can be observed in the two conditions exposing subjects to both elevated operative temperature and elevated noise level (i.e. C4 and C8).

The air movement was significantly less acceptable in the conditions with elevated temperature C3, C4, C7 and C8 (p<0,001) than in the reference condition C1.

The air quality was significantly less acceptable in all deteriorated conditions compared to C1 (p<0,001), except C2. The acceptability of air quality decreased significantly when the pollution load was present in conditions C5, C6, C7 and C8 but also in the conditions where the pollution load was absent but the temperature was elevated (C3 and C4). In the condition with pollution load present and low temperature (C5), 15% occupants were dissatisfied with the air quality. Elevating the temperature only (C3) had an even greater impact on the acceptability of the air quality, with 21% dissatisfied; however the difference between the acceptability of the air quality in C3 and in C5 is not significant. As many as 41% were dissatisfied with the air quality in the combination of elevated temperature and presence of pollution load (C7). The effect of the combination was significant comparing to both the effect of elevated temperature only in C3 (p<0,05) and to the effect of pollution load only in C5 (p<0,01). The addition of an elevated noise level had a significant effect on the acceptability of air quality only when noise was added to both elevated temperature and pollution load (p=0,04) (C7 compared against C8).

The conditions with elevated noise level caused the acceptability of noise in the environment to decrease (p<0,001). Similarly, the acceptability of thermal environment was significantly lower in the conditions with elevated temperature (p<0,001) than in the reference condition C1.

The ability to concentrate was negatively affected in all deteriorated conditions (p<0,001; except C5 where p=0,01). The subjects felt worse (subjective feeling marked on a continuous scale from feeling bad to feeling good) in all deteriorated conditions (p<0,001; except C5 where p=0,02).

The subjective importance of the three deteriorated conditions is summarised in Table 4. The results shown were obtained after the last exposure when the subjects had already experienced all possible combinations of conditions and were making the final decision on the relative importance of the three factors.

Table 4. Ranking of the deteriorated conditions by subjects after the last exposure

| **Condition** | **Chosen by subjects (%) to be** | |
|---|---|---|
| | **The most important to improve** | **The second most important to improve** |
| Elevated noise level | 42 | 40 |
| High temperature | 36 | 35 |
| Deteriorated air quality | 22 | 25 |

## DISCUSSION

Despite the very short time allocated for performance of the addition test in each condition, it was possible to demonstrate a deterioration in the subjects' performance in conditions C4, C7 and C8 compared to the reference condition C1. It seems likely that in longer exposures the effect on performance would be larger.

The highly significant differences in the acceptability of the indoor environment and its component factors may have been due to the experiment not being blinded. This was the expected bias. The subjective overall ranking of the three deteriorated conditions are supported by the acceptability ratings: the air quality seemed the least important to subjects when they were asked directly and the addition of air pollution did not cause a significant drop in the acceptability of the overall environment. The assignment of lower importance to air quality may also have been due to the subjects completing the questionnaires at the end of each exposure when they were fully adapted to the air quality in the climate chamber.

The air movement was considered significantly less acceptable in the conditions with elevated temperature, compared to the reference condition. The subjects were not asked whether they would prefer more or less air movement but it is likely that they would have preferred more air movement to provide some cooling in the warm conditions.

The results on acceptability of air quality show a decrease in acceptability when the pollution load was present or the temperature was elevated. These results are in agreement with the findings of Fang [2,3] on how perceived air quality is affected by raised temperature. The results indicate that moderately raised air temperature may have even greater influence on acceptability of the air quality than the pollution caused by an old carpet.

The subjects' choice of the noise level being the most important to improve and the air quality the least important accords with the results of the experiment conducted by Clausen and Wyon [9]. However, subjects still differed as to which of the three conditions it was the most essential to improve.

The most important implications of these results for practice are that: 1) Although self-estimated performance predicted environmental effects on actual performance quite well, it exaggerated the magnitude of the effect (33% in the most negative condition instead of 7%); 2) Warm air had almost the same negative effects as polluted air on SBS and on environmental perceptions, providing support for the widespread practice of lowering the temperature in offices to improve perceived air quality; and 3) Although noise had a large and consistent negative effect on the perceived ability to concentrate, clearly more than that of any other factor, it had virtually no other effect of any kind, i.e. subjects tended to over-estimate the importance of noise, so more selected it as the most important to change, even though it was not the most important.

## CONCLUSIONS

- The addition test was performed significantly less well in the warm noisy condition, the warm polluted condition and the warm noisy polluted condition.

- Self-estimated performance and the overall acceptability of the environment were both significantly worse than in the reference condition when any negative factor was present.
- Poor air quality had less of an effect than elevated temperature or noise on the overall acceptability of the environment.

## ACKNOWLEDGEMENTS

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