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A Comparative Study of Discomfort caused by Indoor Air Pollution, Thermal Load and Noise

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Abstract

The relative importance of sensory air pollution, thermal load and noise was studied under controlled conditions in two identical environmental chambers. In one chamber subjects were exposed to various levels of either thermal load or poor indoor air quality. For each condition tested in this chamber, the subjects were exposed to a number of noise levels in an adjacent chamber with neutral thermal conditions and good indoor air quality in order to determine a noise level causing the same degree of discomfort. A total of 68 comparisons of the conditions in the two chambers were made by the same group of 16 subjects after one-minute exposure in each chamber. In the operative temperature range of 23–29 C, a 1 C change in operative temperature was found to have the same effect on human comfort as a change in perceived air quality of 2.4 decipol or a change in noise level of 3.9 dB. For levels of perceived air quality up to 10 decipol, a 1-decipol change in perceived air quality had the same effect on human comfort as a change in noise level of 1.2 dB. A relationship between traffic noise level and percentage dissatisfied was established.

KEY WORDS:
Perceived air quality, Noise, Thermal load, Discomfort, Comparative study

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Background

Most research on indoor air quality and on thermal and acoustic environments has focused on the impact on human comfort of individual elements of these parameters. But in practice people are often exposed to combinations of two or more environmental parameters simultaneously. Interventions to reduce one cause of discomfort may increase other types of discomfort. When opening an office window to a noisy outdoor environment, acoustic comfort is sacrificed for increased thermal comfort or better air quality.

The effect of thermal load and noise on human performance has been studied in numerous experiments (Viteles and Smith, 1946; Wyon et al., 1979; Dean and McGlothen, 1965; Bell, 1978). In the experimental work of Viteles and Smith (1946), an increase in effective temperature from 22.8°C to 30.6°C led to a 5% decrease in the average score of seven performance tasks while no systematic change in the performance score was found when increasing the noise level from 72 dB to 90 dB. A later comprehensive literature review by Hancock and Pierce (1985) concluded that heat and noise to a large extent act indpendently on human performance. In two experimental series on stressor interactions Grether and co-workers studied extremes of thermal, acoustic and vibration stresses (Grether et al., 1971; Grether et al., 1972). The experiments involved subjective rating of stress from the three environmental parameters. Even for the extreme conditions tested in this study, only small and inconclusive differences in subjective stress levels were observed when the subjects were exposed to different combinations of the three environmental parameters. Fanger et al. (1977) studied whether colour and noise influence the ambient temperature preferred by man. They concluded that neither colours nor noise had any significant influence on man's thermal comfort.

In a Japanese study by Horie et al. (1985), the combined effect of noise, lighting and thermal conditions on man's comfort was investigated. Experiments were carried out in a room where the three factors could be altered. Subjective ratings of the occupants' comfort were recorded over a period of three years. Responses to each change of a factor were converted into a combined comfort score. Room temperatures outside the subjects' comfort range turned out to be the dominant factor determining the comfort score. A three-degree increase in the room temperature from 28°C to 31°C had the same (negative) effect on the comfort score as an increase in the noise level of 30 dB from 40 dB to 70 dB. Room temperatures in the subjects' comfort range were of only minor importance for the comfort score. As no direct comparison between the individual parameters was made, the study was inconclusive in determining the relative importance of the individual parameters. The purpose of the present study was to determine the relative importance of sensory air pollution, noise and thermal loads on human comfort by direct comparison of the individual parameters.

Method

Research Plan

The experiments were performed in two identical environmental chambers, A and B. In the first part of this investigation (experiments 1 to 7), different combinations of thermal load and sensory air pollution in chamber A were sequentially compared with a range of noise levels in chamber B. In the second part of the investigation (experiments 8 to 10), different levels of sensory air pollution in chamber A were sequentially compared with a range of thermal loads in chamber B. The levels of thermal load and sensory air pollution were selected to correspond to 10, 20, 40 and 60% dissatisfied. The corresponding values of operative temperature (ISO 7730, 1984) and perceived air quality (Fanger, 1988) are listed in Table 1. A similar relation between noise level and percentage dissatisfied was not available from the literature. For determination of the operative temperatures used in the experiments, the subjects were estimated to have a metabolic rate of 1.6 met corresponding to the activity level of "standing light activity" described in ISO 7730 (1984). Although the subjects were seated between assessments, 1.6 met is a reasonable estimation of the metabolic rate as the activity during the assessments involved climbing stairs on the way to the chambers and entering and exiting the chambers. During the experiments the subjects wore their own clothing. As the experiments were performed in the winter, an insulation value of 1 clo (typical of indoor winter clothing (ISO 7730, 1984) was estimated.

Table 1 Operative temperatures and perceived air quality corresponding to the selected levels of dissatisfaction.

Level of dissatisfaction (%)	Operative temperature (°C)	Perceived air quality (decipol)
10	21.3	0.6
20	23.3	1.4
40	26.0	4.1
60	28.4	8.9

Table 2 shows the combinations of environmental parameters selected for the ten experiments performed.

Sensory Panel

A panel comprising eight men and eight women performed the sensory assessments. All subjects passed a selection test to ensure that they had normal auditory, olfactory and chemical senses. Instruction in the use of questionnaires was the only training given to the panel.

Facilities

The study was performed in two identical, adjacent environmental chambers (Albrechtsen, 1988). In each chamber, a curtain was used to hide the sound-generating equipment and the sources of air pollution. The operative temperatures in the chambers were measured with a Brüel & Kjær Comfort Meter, Type 1212.

The noise used in the experiments was road traffic noise. A two-minute recording of traffic noise was repeatedly played back through loudspeakers in the chambers. In chamber A the sound level was adjusted to maintain a constant A-weighted equivalent sound pressure level L_{Aeq} of 40 dB. This was then considered to be the background level. A calibrated attenuator was installed so that L_{Aeq} in chamber B could be varied between 40 and 75 dB SPL in steps of 5 dB.

A mixture of carpet, rubber, fresh paint and cigarette butts was used to generate air pollution in chamber A. Different amounts of the mixtures of materials were used to obtain the desired levels of perceived air quality.

Table 2 Experimental plan showing the combinations of operative temperature, perceived air quality and noise levels chosen for the ten experiments.

Experiment	Chamber A			Chamber B		
	Operative temperature (°C)	Perceived air quality (decipol)	Noise level L_{Aeq} (dB)	Operative temperature (°C)	Perceived air quality (decipol)	Noise level L_{Aeq} (dB)
1	23.3	0.6*	40*	21.3*	0.6*	40–75
2	26.0	0.6*	40*	21.3*	0.6*	40–75
3	28.4	0.6*	40*	21.3*	0.6*	40–75
4	21.3*	1.4	40*	21.3*	0.6*	40–75
5	21.3*	4.1	40*	21.3*	0.6*	40–75
6	21.3*	8.9	40*	21.3*	0.6*	40–75
7	28.4	8.9	40*	21.3*	0.6*	40–75
8	21.3*	1.4	40*	21.3–28.4	0.6*	40*
9	21.3*	4.1	40*	23.3–30.8	0.6*	40*
10	21.3*	8.9	40*	23.3–30.8	0.6*	40*

* Neutral or background value.

Procedure

In experiments 1 to 7, a given combination of thermal load and sensory air pollution in chamber A was compared with eight noise levels in chamber B with L_{Aeq} ranging from 40 to 75 dB. The noise levels in chamber B were presented in random order. The subjects were divided into four groups of four persons each. All ten experiment series followed the same procedure. After steady-state condition had been obtained in the chambers, one of the four groups entered chamber A while another group entered chamber B. After a one-minute exposure, all subjects left the chambers and waited one minute outside the chambers. Then the first group entered chamber B and the second group entered chamber A. After a one-minute exposure, the subjects left the chambers and proceeded to a nearby waiting area. The two remaining groups then repeated the procedure. The conditions in chamber B were then changed and the next comparison was made with the groups entering the chambers in reverse order until all eight noise levels or four operative temperatures in chamber B had been compared with the condition in chamber A.

The subjects were asked to evaluate the conditions in each chamber and to compare them. They did this by filling in questionnaires. The first question was:

Imagine that during your daily work in an office you experienced the same air quality, noise and temperature as in this chamber. How annoying do you find these conditions?

The scale employed for answering this question was a continuous annoyance scale, with six annotations ranging from "No annoyance", "Slight annoyance", "Moderate annoyance", "High annoyance", "Very high annoyance" to "Overpowering annoyance". The second question was:

Do you think that the conditions in this room are acceptable for carrying out office work?

The scale used for this question was a continuous scale ranging from "Clearly acceptable" to "Clearly not acceptable". The subjects answered the two questions after a one-minute exposure in each of the two chambers. After exposure in both chambers they answered the final question:

Which of the two chambers would you rather be in?

They answered this question by circling either chamber A or chamber B.

The final question of preference was answered when the subjects had left both chambers. When all eight noise levels in chamber B had been compared with the given environment in chamber A, the operative temperature and air quality in chamber A were altered and the next experiment started.

In experiments 8 to 10, a given level of sensory air pollution in chamber A was compared with four levels of operative temperature in chamber B, by using a procedure similar to the one outlined above.

Results

The measured values of operative temperature during experiments 1 to 7 were within ±0.3°C of the values of the experimental plan. For experiments 8 to 10, the measured operative temperatures were within ±0.8°C of the planned values. The measured noise levels during the experiments were within ±0.4 dB of the planned values. For perceived air quality the maximum deviation from the planned values was 1.6 decipol in experiment 6, where the planned value was 8.9 decipol and the actual value assessed was 7.3 decipol.

Figure 1 shows the relationship between the percentage of subjects preferring chamber A as a function of the noise level in chamber B for experiment 5. The actual perceived air quality in chamber A was assessed to be 5.1 decipol and the operative temperature 21.3°C (neutral). As the noise level in chamber B increases, the percentage of subjects preferring chamber A also increases. Probit analysis revealed that at a noise level of 58 dB in chamber B, the panel displays equal preference for the two chambers. Similar relationships were found for the other combinations of perceived air quality and operative temperature in chamber A.

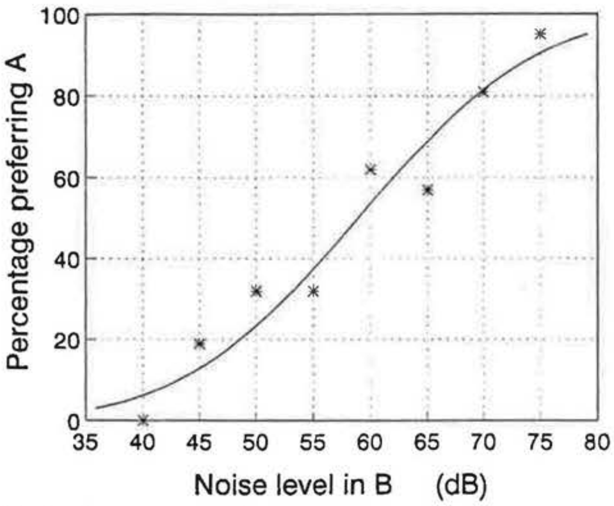

Fig. 1 The percentage of subjects preferring chamber A as a function of the noise level in chamber B for experiment 5. Each point on the figure is the mean of 16 assessments and the line is the result of probit analysis. The perceived air quality in chamber A was 5.1 decipol.

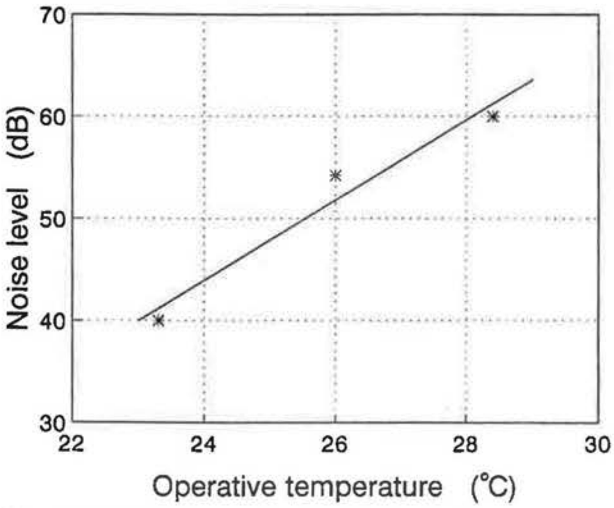

Fig. 2 Noise levels in chamber B and operative temperature in chamber A resulting in equal preference for the two chambers.

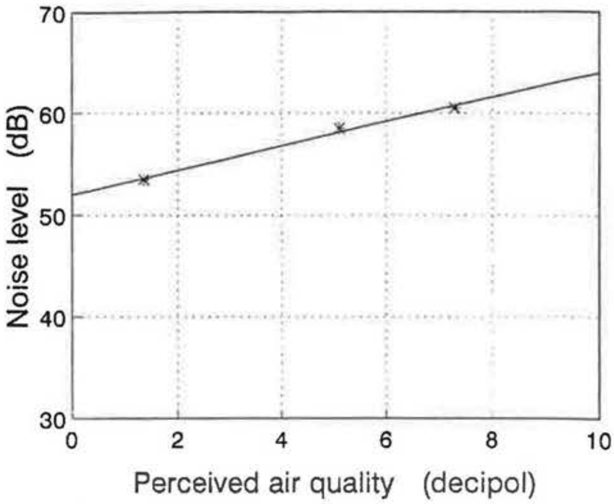

Fig. 3 Noise levels in chamber B and perceived air quality in chamber A resulting in equal preference for the two chambers.

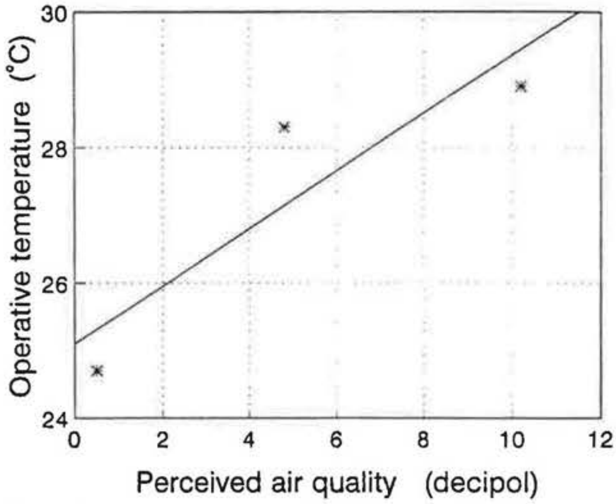

Fig. 4 Operative temperatures in chamber B and perceived air quality in chamber A resulting in equal preference for the two chambers.

Figures 2 and 3 show the noise levels in chamber B and operative temperature or perceived air quality in chamber A resulting in equal preference for the two chambers. The linear regression lines shown in the figures are crude first approximations of the relationships of equal preference for the different environmental parameters.

Figure 2 shows that a 1°C temperature change in a space with good air quality has on average the same effect on human comfort as a 3.9 dB change in noise level. Figure 3 shows that a change in perceived air quality of 1 decipol at neutral operative

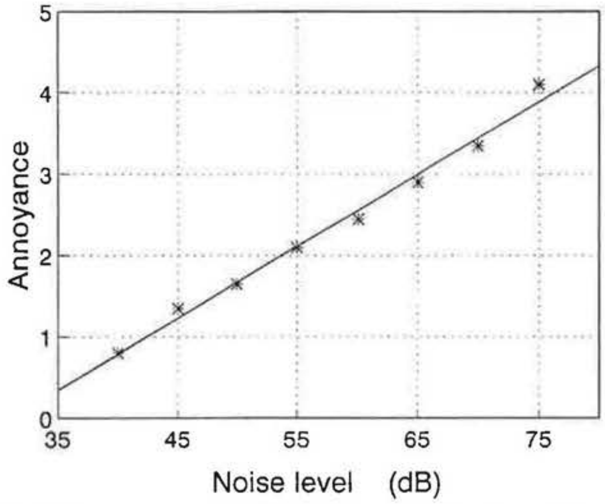

Fig. 5 Annoyance as a function of noise level. The data points represent the mean of 112 assessments. The line shown is the result of linear regression.

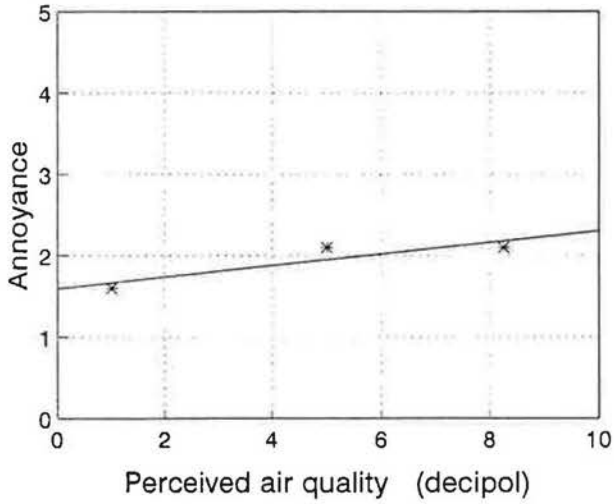

Fig. 6 Annoyance as a function of perceived air quality. The data points represent the mean of 192 assessments. The line shown is the result of linear regression analysis.

temperature has on average the same effect on human comfort as a 1.2 dB change in noise level.

Figure 4 shows the operative temperature in chamber B and the perceived air quality in chamber A resulting in equal preference for the two chambers. As in Figures 2 and 3, the linear regression line shown in the figure is a crude first approximation of the relationship of equal preference between the two environmental parameters.

The figure shows that a 1°C temperature change in spaces with low background noise level has on average an effect on human comfort equivalent to a change in perceived air quality of 2.4 decipol.

In Figures 5, 6 and 7 the relations between annoyance and the three environmental parameters are shown. For the linear regression analysis performed, the annotations on the scale used were transformed to numerical values in the following way: 0: No annoyance, 1: Slight annoyance, 2: Moderate annoyance, 3: High annoyance, 4: Very high annoyance and 5: Overpowering annoyance.

The figures reveal linear relations between the degree of annoyance and the three environmental parameters. In fact, the relation between degree of annoyance and noise level displayed in Figure 5 is remarkably linear. Figure 6 shows that the degree of annoyance appeared to change only slightly with the air quality in the chamber.

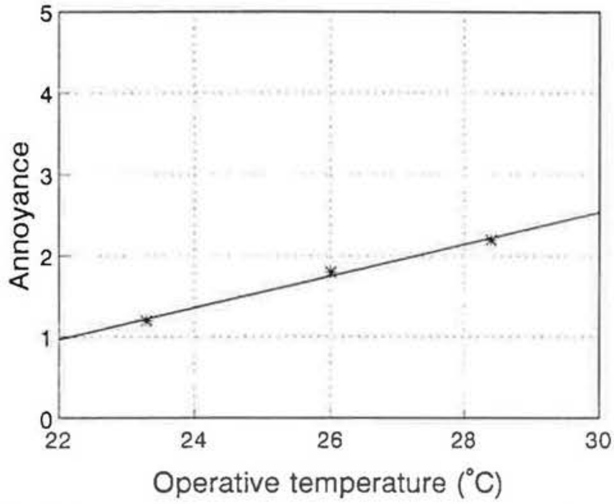

Fig. 7 Annoyance as a function of operative temperature. The data points represent the mean of 128 assessments. The line shown is the result of linear regression analysis.

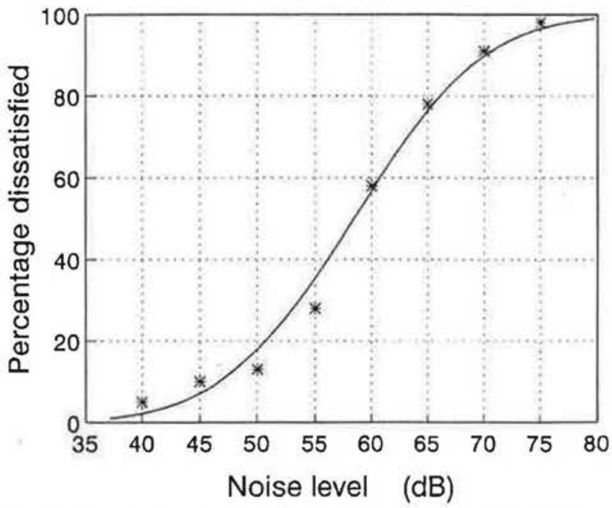

Fig. 8 Percent dissatissfied as a function of traffic noise level. The data points represent the mean of 112 assessments and the curve is the result of probit analysis.

An interesting additional result of the study was the establishment of a relation between noise level and percentage of dissatisfied (Figure 8).

The relation is only valid for traffic noise and is based on the unadapted impression (one-minute exposure). The equation for the relationship is

$$\textit{Percentage Dissatisfied} = 4.35 \int_{-\infty}^{\textit{noise level}} \exp\left(-\left(\frac{x - 58.6}{13.0}\right)^2 \right) dx$$

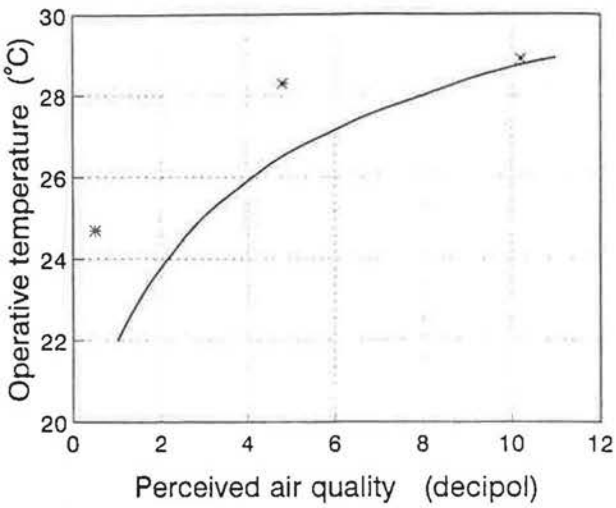

Fig. 9 The curve shows operative temperature (with the given clothing and activity level) and perceived air quality leading to the same level of dissatisfaction according to the literature (ISO 7730, 1984, Fanger, 1988). Also shown in the figure are the data points obtained from the present study based on preference.

Discussion

The design of the present study allowed the subjects to evaluate the relative importance of poor indoor air quality, thermal load and noise based on simple preference statements from the subjects. The operative temperature turned out to be important compared with perceived air quality. A small change of 1°C in the operative temperature was found to have the same effect on human comfort as a considerable change of 2.4 decipol in the perceived air quality. However, thermal load differs from the other parameters tested in that an occupant in practice can respond to the discomfort experienced by adjusting his clothing and, in some cases, his activity level. Furthermore, previous research has shown that the perception of air quality depends on air temperature (Berglund and Cain, 1989). The same air is perceived as less acceptable with increasing air temperature. This may have influenced the results of the present study. Although the level of sensory air pollution was kept constant in the experiments with elevated operative temperatures in chamber A (experiments 1, 2 and 3), the interaction between air quality and temperature may have influenced the overall perception of the environment in chamber A. The effect of changing the operative temperature may thus have involved a combined thermal and air quality effect. Also noise turned out to be of importance, as a 1.2 dB change in the noise level had the same effect on human comfort as a 1.0 decipol change in perceived air quality.

Linear regression was used to calculate the crude first estimation of the relative importance of the three environmental parameters from the equal preference observations. The relevance of using such a simple model can be discussed. Using linear regression to describe the relative importance of the operative temperature by comparing with perceived air quality, as shown in Figure 4, appears to be particularly questionable. However, the literature does not offer much guidance as the concept of preference used in the present study differs from the normally used scales of discomfort, annoyance, etc. Figure 9 shows the relation between operative temperature (with the given clothing and activity level) and perceived air quality leading to the same level of dissatisfaction according to the literature (ISO 7730, 1984, Fanger, 1988). Also shown in the figure are the data points obtained from the present study based on preference.

The figure suggests a non-linear relation between the importance of operative temperature and perceived air quality. Near the comfort temperature the operative temperature appears to be of less importance compared with perceived air quality but the importance increases with increasing operative temperature. However, these considerations are based on equal levels of dissatisfaction caused by the two environmental parameters. In situations with equal levels of dissatisfaction, the preference for the two conditions may be different.

The results reveal the relative importance of the three environmental parameters after one-minute exposures to the different environments. Different results may be obtained with longer exposure time, e.g. a full eight-hour working day. This would be an interesting subject for a future study. Adaptation may play an important role in such experiments.

Research has shown that adaptation to indoor air pollution is strongly dependent on the dominant type of pollution (Gunnarsen and Fanger, 1989). Whereas substantial adaptation may occur when human bioeffluents are the main pollutants, only slight adaptation may occur when emissions from building materials are the dominant pollutants, as in the case of the present study. For the thermal environment, no difference between short-term and long-term exposure would be expected as humans experience the new steady-state thermal sensation after operative temperature up-steps immediately (Knudsen and Fanger, 1990). This is in contrast to operative temperature down-steps, where the thermal sensation drops to a level cooler than the later steady-state sensation which is reached within 30 minutes. Adaptation is unlikely to be of major importance when assessing annoyance from noise.

In an experiment designed to study the difference in perception between short-term and up to 30-minute exposure to the same traffic noise as used in the present study, subjects were asked to assess how annoying they would find the noise if they were to experience it indoors at home. The level of annoyance was found to be independent of the exposure length (Poulsen, 1991).

The reported levels of perceived air quality were calculated from the percentage of dissatisfied (Fanger, 1988). This method gives greater uncertainties in the values obtained for perceived air quality compared with the values obtained from a trained panel of the same size assessing the air quality directly in decipol (Pejtersen and Mayer, 1993). However, it is conceivable that thorough training of the subjects in assessing perceived air quality in decipol may bias their attention to the perceived air quality. In future similar studies the uncertainty of the perceived air quality assessments may be reduced by increasing the panel size.

The experimental design allowed the three environmental parameters to be compared one by one. However, one experiment (experiment 7) was included to study the combined effect of more than one parameter. In this experiment the combination of a 28.4°C operative temperature and a perceived air quality of 8.9 decipol was compared with a range of traffic noise levels. When tested individually, both environmental conditions had the same effect on human comfort as traffic noise with L_{Aeq} equal to 60 dB. When the two environmental stressors were combined, the equivalent noise level was 71 dB. Interestingly, this increment of 11 dB correspond approximately to a subjective doubling of the loudness.

Conclusions

- In spaces with good air quality and with an operative temperature in the range of 23 to 29°C, a 1°C change in the operative temperature was found to have the same effect on human comfort as a change of 2.4 decipol in the perceived air quality or a change of 3.9 dB in the noise level. At neutral temperature and for levels of perceived air quality up to 10 decipol, a 1-decipol change in perceived air quality had the same effect on human comfort as a change of 1.2 dB in noise level.
- A relationship between noise level and percentage dissatisfied has been established for road traffic noise.

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