Impact of Reduced Air Temperature and Increased Radiant Temperature on Perceived Air Quality, Thermal Comfort, SBS Symptoms and Performance

Master Thesis
MEK-I-EP-01-01
Peter Foldbjerg and Gregers Reimann

International Centre for Indoor Environment and Energy
Department of Mechanical Engineering
Technical University of Denmark
May 2001

MEK-I-EP-01-01
May 2001

International Centre for Indoor Environment and Energy
Technical University of Denmark
Building 402
Nils Koppels Allé
2800 Kongens Lyngby
Denmark

Preface

The present Master Thesis is the result of work carried out between September 2000 and April 2001 at the International Centre for Indoor Environment and Energy, Technical University of Denmark.

The Thesis investigates the impact of reduced air temperature and increased radiant temperature on perceived air quality, thermal comfort, SBS symptoms and productivity. A literature review led to the design of the experiment. Preparations for and conduction of the experiment in January 2001 constituted the majority of the work of the Thesis.

The Thesis covers a wide range of issues regarding the indoor environment in general, and indoor environment experiments in particular. The authors have a background in building physics. The motivation for writing the present Thesis was that we find that energy conservation in buildings and the indoor environment too often are treated separately, when a holistic approach often gives a better result. We found the process of preparing and performing the experiments and subsequently evaluating the results interesting and eye-opening.

The authors would like to thank Jørn Toftum for his interest and advice on our work, for many fruitful discussions and for his comments to the report. We would like to thank Geo Clausen for inspiration and for his comments to the report. We thank P. Ole Fanger for his ideas and perspective.

We also thank Henrik Spliid for his advice and help regarding the planning of the experiments, and for help on the statistical analysis. Thanks are due to Thomas Witterseh for inspiration and advice on the choice of performance tasks. We thank Richard de Dear for valuable input in the early stages of the process.

The main report is divided into chapters regarding the background and experimental method, the results, the discussion and conclusion. The first pages of the main report contain summaries in Danish and English, a list of frequently used terms and a table of contents. The main report is concluded with a list of references.

The appendices follow the main report. Appendix L contains the diary kept by the authors from day one until the completion of the Thesis. It provides insight into the process.

Lyngby, May 4, 2001

Peter Foldbjerg	Gregers Reimann
c958239	c958560

Table of Contents

Communication with the authors is possible via email:
Peter Foldbjerg: Peter@Foldbjerg.com
Gregers Reimann: G.Reimann@get2net.dk
Thesis web page: www.geocities.com/indoorclimate

Summary

The present Thesis investigates the impact of reduced air temperature on perceived air quality, thermal comfort, SBS symptoms and performance.

The impact was investigated in an experiment that exposed 28 thermally neutral subjects to three 3-hour exposures of typical office environments. The reference condition exposed subjects to air at 23°C. The two additional experimental conditions exposed subjects to air at 18°C; one condition with a pollution source present in the room. The ventilation rate was high at all conditions (6 h^{-1}, corresponding to 45 l/s/person).

The exposures were carried out in a real office, in which temperature, humidity and ventilation rate could be controlled. The office had four workstations where the subjects solved general office tasks with which their performance was measured. At regular intervals the subjects filled in questionnaires regarding the perceived air quality, thermal comfort, their immediate health condition and their perceptions regarding the indoor environment.

Thermal neutrality of the body was obtained by using radiant heating and by allowing the subjects to adjust their clothing. Radiant heating was used in conjunction with adjustment of clothing as a means to reduce thermal discomfort caused by clothing insulation asymmetry. Electric foils supplied the radiant heating. A set of four radiant heating panels was designed and built for each workstation as part of the Thesis.

Reducing the air temperature from 23°C to 18°C significantly decreased the number of dissatisfied with the air quality from 20% dissatisfied to 6% dissatisfied. The air at 18°C was also perceived as being fresher than the air at 23°C.

Though thermally neutral under all conditions, the thermal acceptability of the body was lower at 18°C than at 23°C, due to higher local thermal discomfort. This was caused by increased draught and clothing asymmetry at the 18°C condition. A tendency towards preferring a thermal sensation of the body higher than zero was observed at both temperature levels.

A tendency towards a lower prevalence of symptoms among subjects exposed to air at 18°C was found. The tendency was not statistically significant, but assessments of different symptoms consistently showed the same tendency. No impact on performance of changes in neither air temperature nor pollution source was found.

Reducing the air temperature thus increased the acceptability of the air quality, while decreasing the thermal acceptability. This could have had an impact on the small difference in symptom prevalence. No significant change was found in the subjects' assessments of the general indoor environment between the two temperature conditions.

Reducing the air temperature and adding a pollution source decreased the percentage dissatisfied with the air quality from 20% to 14%. The polluted air at 18°C was more satisfactory than the unpolluted air at 23°C, but less satisfactory than the unpolluted air at 18°C.

Females were more dissatisfied with the polluted air than males.

Reducing the air temperature and introducing a pollution source significantly increased the percentage dissatisfied with the general indoor environment. A tendency towards the prevalence of symptoms being highest when exposed to the polluted air was found.

Resumé

Nærværende rapport omhandler effekten af reduceret lufttemperatur på oplevet luftkvalitet, termisk komfort, SBS symptomer og produktivitet.

Effekten blev undersøgt ved at eksponere 28 termisk neutrale forsøgepersoner for tre 3-timers eksponeringer for typiske kontormiljøer. Under referencebetingelsen blev forsøgspersonerne eksponeret for luft ved 23°C.

Under de to øvrige forsøgsbetingelser blev forsøgspersonerne eksponeret for samme luft, men ved 18°C. Ved den ene forsøgebetingelse var en forureningskilde tilstede i lokalet. Ventilationsraten var høj under alle forsøgsbetingelser (6 h^{-1}, svarende til 45 l/s/person).

Eksponeringerne blev udført i et kontor, hvor temperatur, luftfugtighed og ventilationsrate kunne styres. Kontoret indeholdt fire arbejdsstationer, ved hvilke forsøgspersonerne udførte simuleret kontorarbejde til måling af deres produktivitet. Desuden udfyldte forsøgspersonerne spørgeskemaer angående deres oplevelse af luftkvaliteten, deres termiske komfort, deres helbredstilstand og deres opfattelse af indeklimaet.

Forsøgspersonerne var termisk neutrale under forsøgene, hvilket blev opnået med strålevarme samt ved justering af påklædningen. Strålevarme blev brugt for at reducere diskomfort forårsaget af asymmetrisk fordelt beklædningsisolans. Elektriske strålevarmepaneler blev benyttet. Fire strålevarmepaneler blev designet og bygget for hver arbejdsstation som en del af projektarbejdet.

Ved at reducere lufttemperaturen fra 23°C til 18°C blev procentdelen af utilfredse med luftkvaliteten reduceret fra 20% utilfredse til 6% utilfredse. Luften blev også opfattet som værende mere frisk ved 18°C end ved 23°C.

På trods af, at forsøgepersonerne var termisk neutrale ved alle forsøgsbetingelser, var den termiske acceptabilitet for hele kroppen højere ved 23°C end ved 18°C. Dette skyldtes øget træk og beklædningsisolansasymmetri ved 18°C. En tendens viste, at en termisk tilstand varmere end neutralt for kroppen blev foretrukket.

Der var tendens til lavere forekomst af symptomer blandt forsøgspersoner eksponeret for luften ved 18°C. Tendensen var ikke signifikant, men flere forskellige vurderinger pegede sammenhængende i samme retning. Det blev fundet, at hverken lufttemperaturen eller forureningskildens tilstedeværelse påvirkede produktiviteten.

Den reducerede lufttemperatur forbedrede den oplevede luftkvalitet, mens den termiske acceptabilitet blev reduceret. Dette kunne være en årsag til den lille forskel i forekomsten af symptomer mellem forsøgsbetingelser. Af samme grund kunne det tænkes at det generelle indeklima blev vurderet ens ved de to temperaturniveauer.

Reduktion af lufttemperaturen og samtidig indførelse af forureningskilde, reducerede procentdelen af utilfredse fra 20% til 14%. Den forurenede luft ved 18°C var mere acceptabel end den uforurenede luft ved 23°C, men mindre acceptabel end den uforurenede luft ved 18°C.

Procentdelen af utilfredse med luftkvaliteten var større hos kvinder end hos mænd.

Reduktion af lufttemperaturen og samtidig indførelse af forureningskilde, øgede procentdelen af utilfredse med det generelle indeklima. En tendens til højest forekomst af symptomer ved eksponering for den forurenede luft blev fundet.

Terms

A list of terms frequently used in the Thesis is presented here. The explanations are not definitions, but describe the use of each term in the Thesis.

ACC	Acceptability. Often used in conjunction with the acceptability scale for subjective assessments.
ACR	Air change rate. ACR is also referred to as ventilation rate, and is a measure of the amount of outdoor air, with which a room is ventilated.
Angle factor	Also referred to as “shape factor”. See shape factor.
Asymmetric radiation	The difference in radiant temperature “seen” by the two faces of a flat plate suspended anywhere in the room.
Clothing insulation asymmetry	Term used to describe the possible discomfort caused by a clothing ensemble that is unevenly distributed on the body.
Clo	Insulation of clothing: 1 clo = 0.155 $(m^2 K)/W$
Condition	Set of physical parameters used to describe the 3 experimental conditions.
Control room	The room next to the field laboratory, from which the experimenters monitored the experiments.
Covariate	Denotes a continuous variable used as a factor in an analysis of variance.
Effect	Measurable outputs from the results including, air quality, thermal comfort, and productivity.
Factor	Two factors were investigated in the experiments: air temperature and air quality. To this, a number of random factors were expected to have an impact on the effects: the subjects, their sex, the weekday, time of day, workstations and learning.
Field laboratory	Also referred to as “field lab”. The office space in which the experiments were carried out.
GLM	General linear model. Statistical model used for the analysis of most data.
Impact	A factor has an impact on an effect, when a statistical analysis returns a significant result.
Individual control	System for thermal control of the personal microclimate, typically at the desk.
Learning	The increase in performance expected for every time a subject performs the performance measurement tasks.
Met	Metabolism of human: 1 met = 58 W/m^2 of body area.

Occupied zone	The part of the field laboratory in which the workstations are installed.
Operative temperature	The uniform temperature of air and surfaces that would inflict the same heat loss from a human body, as the actual non-uniform environment.
Olf	Sensory pollution load (1 olf = sensory pollution from one sedentary person)
Panel	See “Radiant heating panel”
PAQ	Perceived air quality.
Performance	Efficiency at working. Workability
Personalised ventilation	Air inlet device that supplies fresh air directly to the breathing zone, typically at the desk.
Pollution	Typically pollution of indoor air by emissions from carpets, paints, humans etc.
PD	Percent Dissatisfied.
PPD	Predicted Percent Dissatisfied.
PMV	Predicted Mean Vote (scale: -3 to 3).
Questionnaire	A set of questionnaires was designed to collect the subjects’ assessments of the indoor environment, their symptoms and satisfaction.
Radiant heating panel	The system for supplying radiant heating to the subjects that was designed and built for the experiments.
SAS	Computer program used for statistical analysis.
SD	Standard deviation.
SBS symptoms	Sick Building Syndrome symptoms. A number of loosely defined symptoms related to poor indoor environment is considered the indication of the sick building syndrome.
Shape factor	The amount by which one surface “sees” another surface. The sum of shape factors for one surface is one.
Subject	A person recruited for the participation in the experiments.
Symptoms	Symptoms refer to SBS symptoms.
Task	Four tasks for measurement of the subjects’ performance were designed: Multiplication, proof reading, addition and text typing.
Technical zone	The part of the field laboratory in which the air conditioning and monitoring equipment is installed.
Thermal acceptability	Subjective measure of the acceptability of the thermal environment. Assessed on the scale from –1 to 1. The acceptability was assessed for 11 individual body parts, and the body as a whole.
Thermal sensation	Subjective measure of the perception of the thermal environments. Assessed on the 7-point scale ranging from –3 to 3. The thermal sensation was assessed for 11 individual body parts, and the body as a whole.
VA	Visual-Analogue. A scale used for subjective measurements.

1 Introduction

1.1 Background

Numerous studies have investigated the impact of individual indoor environmental parameters on human perception, satisfaction, SBS symptoms and performance, often by improving a poor indoor climate to facilitate the detection of effects. Wargocki (1998) and Lagercrantz (2000) found that removal of a pollution source improved the perceived indoor air quality, reduced the prevalence of symptoms and increased performance. Similar effects on symptoms and performance were found in a study by Witterseh (2001) for subjects exposed to decreased levels of noise levels and thermal discomfort.

The thermal properties of air and its impact on perceived air quality was investigated by Fang (1997) and Toftum et al. (1998). Both studies found that perceived air quality improved linearly with decreasing enthalpy (Figure 1.1).

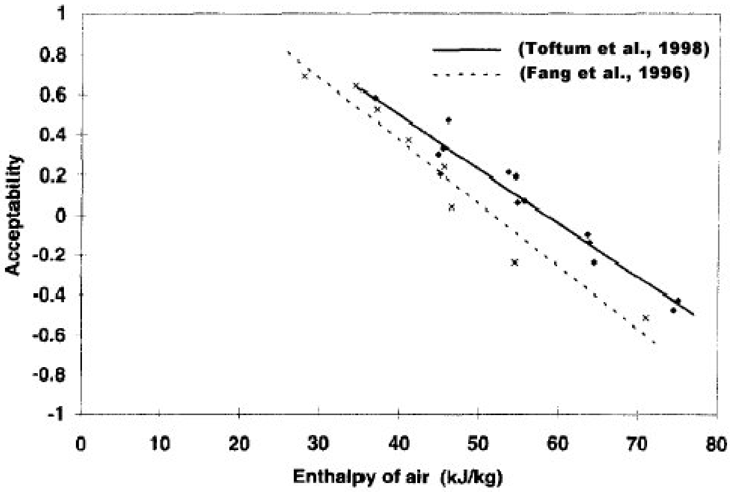


Figure 1.1 *Studies by Fang (1997) and Toftum et al. (1998) showing that perceived air quality decreases linearly with increasing enthalpy of the air. Enthalpy decreases with decreasing temperature and humidity.*

A study by Wyon et al. (1975) showed that cool air of low enthalpy had a tendency to improve health effects and performance. Only the improvement of the freshness of air was significant. The findings of Wyon et al. were similar to an unpublished study by Fang (1998), who did not observe any significant improvement in performance when exposing thermally neutral subjects to three different air enthalpies. The results of the two studies are shown at Figure 1.2 below.

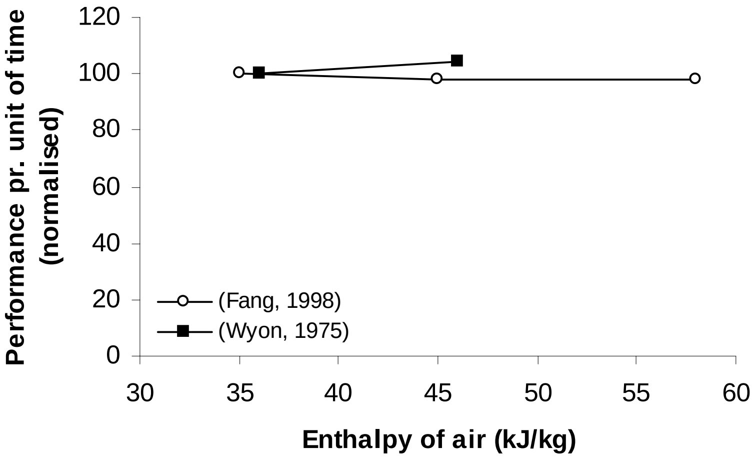


Figure 1.2 Performance as a function of enthalpy in studies by Fang (1998) and Wyon et al. (1975). No significant influence of enthalpy on performance was found.

1.1.1 Local Thermal Discomfort due to Asymmetry

Radiant heating per se is not a cause of thermal discomfort, insofar the guidelines in ISO 7730 for radiant asymmetry are followed. The guidelines are based on a study by Fanger et al. (1985), which showed that people are most sensitive to warm ceilings and least sensitive to warm walls. This study also found that radiant asymmetry does not affect the preferred operative temperature.

The draught risk was also found to be independent of radiant asymmetry at low air velocities, <0.25 m/s (Berglund and Fobelets, 1987). Subjects exposed to a number of different combinations of air and radiant temperatures showed no significant preference for predominantly radiant or convective environments (McIntyre and Griffiths, 1972).

The above studies all refer to short exposure experiments (<4 hours). In an investigation of long exposure to asymmetric radiation, muscular pains requiring medical treatment were found (McNall and Biddison, 1970). In this study, subjects were placed between a warm and a cold wall for 6-7 hours daily during 3 weeks, 6 days a week. The subjects felt thermally comfortable – similarly to people in short term experiments – but developed muscular pains at the end of the 3-week period. No other long exposure experiments have investigated the long-term effects of asymmetric radiation. However, the study mentioned by McNall and Biddison indicated that radiant asymmetry should be minimised.

Olesen et al. (1988) investigated the impact of clothing insulation asymmetry on thermal comfort, and found that subjects preferred the same operative temperature regardless of clothing insulation asymmetry level. Moreover, the study showed a tendency towards subjects preferring an increased thermal sensation when exposed to high levels of clothing insulation asymmetry.

1.1.2 Air Quality

A distinction is found between the chemical and sensory pollution load of air. The perceived air quality depends on sensory pollutants and its thermal properties, as discussed previously. The long list of air pollutants includes human bioeffluents, tobacco smoke, volatile organic compounds, particles, fibres and bacteria. The sensory pollution load is quantified by the olf unit, whereas the chemical pollution load is specified by emission rates. Standards for limitation of both the sensory and chemical pollution loads for the indoor environment are found (CEN Report CR 1752 and ASHRAE Standard 62).

Numerous studies have shown that poor indoor air quality reduces the satisfaction with the indoor environment, whereas environments of good air quality have the opposite effect. Only two studies have shown that a reduction of the air pollutants significantly increases performance (Wargocki, 1998; Lagercrantz et al., 2000). The study by Wargocki (1998) showed that performance of office workers increased by 1.5% whenever the percentage of subjects dissatisfied with the air quality decreased by 10%. Similarly, the same study showed a 1.9% increase in performance for every two-fold increase of the ventilation rate. However, the study was only valid for relatively polluted indoor environments with a percentage dissatisfied of 20-70%.

1.1.3 SBS Symptoms

Numerous studies have addressed the Sick Building Syndrome (SBS), which denotes the development of symptoms related to occupancy in buildings. A study by Menzies et al. (1996) reported several symptoms among office workers. The symptoms included fatigue, heavy-headedness, headache, nausea, difficulty in concentration, burning or irritation of the eyes, runny nose, dry facial skin and itching sensation in facial skin.

Often a bad or dysfunctional mechanical ventilation system is considered the cause of the symptoms (Mendell et al, 1996; Bholah et al., 2000).

In a study of a large office building, Jaakkola et al. (1989) found that the prevalence of SBS symptoms was higher when the temperature was considered to be too low or too high, indicating that dissatisfaction with the thermal environment could be a cause of SBS symptoms.

A study by Stenberg and Wall (1995) studied the different prevalence of symptoms among males and females. It was found that females reported more symptoms than males, and that the difference could not be attributed to known risk factors. The difference was therefore explained by an excess in psychosomatic symptoms among females. Hedge et al. (1996) and Bachman and Myers (1995) also found that sex and psychological symptoms was a risk factor.

1.1.4 Performance

Standardised tasks have been designed to quantify the performance of subjects working in the indoor environment (Langkilde, 1973; Witterseh, 2001). The tasks include text typing, proof reading, addition, multiplication, creative thinking, word memory test and cue-utilisation.

The tasks most suitable for showing small differences in performance were those that the subjects were familiar with on beforehand, so that the subjects were not required to learn something new (Wyon, 2001).

In a study simulating office work, Wargocki (1998) found the most sensitive tasks to the indoor environment to be text typing, addition and proof reading. In order to obtain the most realistic results, the subjects solving the tasks should not be over-motivated to work, but rather experience intermediate motivation characteristic of normal working environments (Wyon, 2001). Besides not resembling a typical work situation, over-motivated subjects are less sensitive to environmental effects on performance. Moderate motivation levels can be obtained by exerting the subjects to long exposures of repeated tasks (Wyon, 2001; Witterseh 2001).

1.1.5 Individual Control

Several studies have shown that people who are given individual control of their thermal microclimate become markedly more satisfied with the indoor climate (Heinemeier et al., 1990; Wyon, 1996). The reason being that people have different thermal preferences making it impossible to agree on a uniform thermal environment. Moreover, people like the psychological feeling of being “in control” of their microclimate.

In a uniform indoor climate at least 5% of the occupants will be dissatisfied with the thermal conditions due to inter-personal differences (ISO 7730). Heinemeier et al. (1990) mentions a field study of thermally uniform offices where a minimum of 40% of the occupants would prefer to feel warmer or cooler even though the offices typically were within the comfort zone. In contrast, a study by Wyon (1996) has found that individual microclimatic control systems with an adjustable air temperature of ±3ºC will satisfy 99% of the occupants. Part of the improved satisfaction arises from psychological effects of “being in control”, as people who are tricked to believe they control the indoor environment are significantly more satisfied with the indoor environment than those people who are not (Rohles, 1986). Moreover, a study showed that individual microclimatic systems improved the performance of general office work by 5.4% (Wyon, 1996).

It is arguable, however, whether individual control of the thermal climate necessarily results in maximum performance. Wyon (1996) mentioned two studies, which indicated that performance peaks when people are thermally aroused – either feeling too warm or too cold. The first study was from South Africa where factory workers performed their industrial tasks significantly better at 32°C than at 26ºC. The other study mentioned by Wyon was undertaken on young American subjects whose ability to perform mental work peaked at 20°C and reached a low at their preferred temperature of 27ºC. Heinemeier et al. (1990) stated that individual control may have negative effects on the performance because people become “too comfortable” allowing them to doze off.

1.2 Hypothesis

The main hypothesis to be investigated is that:

- A reduction of the air temperature from 23°C to 18°C will improve the perceived air quality, reduce the prevalence of symptoms and increase the performance of human subjects that remain thermally neutral.

The secondary hypothesis to be investigated is that:

- The presence of an old carpet from a building with a history of SBS symptoms will increase the dissatisfaction with the air quality of air at 18°C. And that the combined change in satisfaction due to the pollution source and the reduced air temperature will cause no change in the satisfaction with the indoor environment in general.

2 Experimental Method

2.1 Experimental Conditions

The ideal conditions for testing the hypotheses were not fully met for practical and technical reasons. The ideal conditions are presented in appendix B.

Three experimental conditions were used. One was a reference condition, the second had reduced air temperature, and the third had both reduced air temperature and increased air pollution load.

The reduced air temperature was partially compensated for by radiant heating panels and partially by allowing the subjects to modify their clothing. The aim was to keep the subjects thermally neutral. Radiant heating was used in an aim to reduce discomfort due to clothing insulation asymmetry.

The air quality was reduced by introducing a pollution source. An old carpet was used as a pollution source.

The factors that were kept constant under all conditions were:

- The air change rate: 6 h^{-1} (45 l/s/person)
- The humidity level: 0.042 kg/kg dry air

The non-constant factors are summarised in Table 2.1 below.

Table 2.1 Experimental matrix. A unique letter defines the 3 conditions. The temperatures and clo-values were not measurements but conform the ideal values.

	T_{air} = 23.0°C T_{op} = 22.0°C Radiant panels not used I_{cl} = 1.1 clo	T_{air} = 18.0°C T_{op} = 20.5°C Radiant panels used I_{cl} = 1.3 clo
Pollution source present	-	B
Pollution source absent	C	D

When referring to the "18°C condition" and the "23°C condition", the temperature denotes the air temperature in one of the three experimental conditions.

The term "reference condition" will be used to denote the 23°C condition.

2.2 Design of Radiant Heating Panels

The project diary in appendix L describes the process of designing the radiant heating panels and the reasoning behind the design that was used for the experiments. The project timeline is found in appendix A.

The main radiant heating panel design issues are described in this section.

2.2.1 Radiant Heating Panel Requirements

The requirements to be fulfilled by the radiant heating panels were:

- The mean surface temperature of the panels should be sufficiently high, in order to obtain the required operative temperature.
- The heating panels should be arranged in such a way, that unacceptable radiant asymmetry would not occur.
- The radiant temperature should be controllable for each workstation in the room.
- The heating panels should have no significant influence on the look-and-feel of the office, or on the indoor environment. The panels should not be a pollution source to the indoor air quality.
- The heat load generated by the panels should be minimised, as the heat had to be removed by cooling and the cooling capacity of the field lab was limited.

2.2.2 Radiant Heating Panel Design

The investigations led to the following conclusions regarding the number, size and location of radiant heating panels for each workstation:

- A panel to be placed on both sides of the workstation, each 0.8 x 1.0 m².
- A panel to be placed on a stand behind the workstation, sized 0.5 x 1.0 m².
- A panel to be located under the tabletop, sized 0.5 x 0.8 m².

Photos of the panels as they presented themselves in the field laboratory, are presented at Figure 2.1 and Figure 2.2 below.

The reasoning behind the design will be presented later in this chapter. Reducing the heat load was the decisive criteria for most decisions, as it will be discussed later.

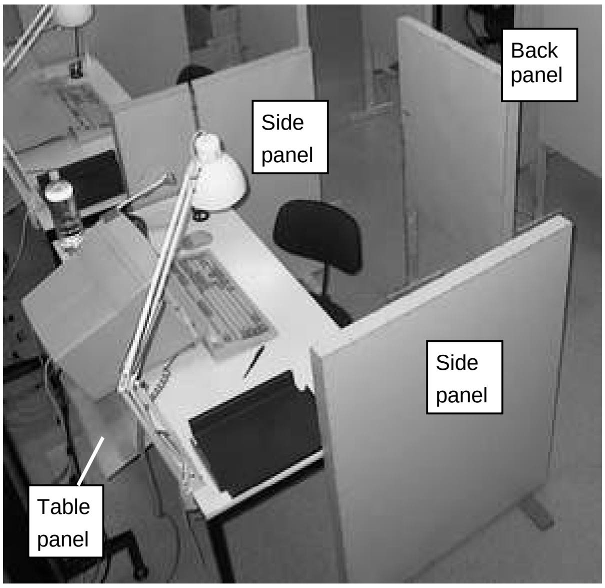


Figure 2.1 Photo of the radiant heating panels installed in a workstation.

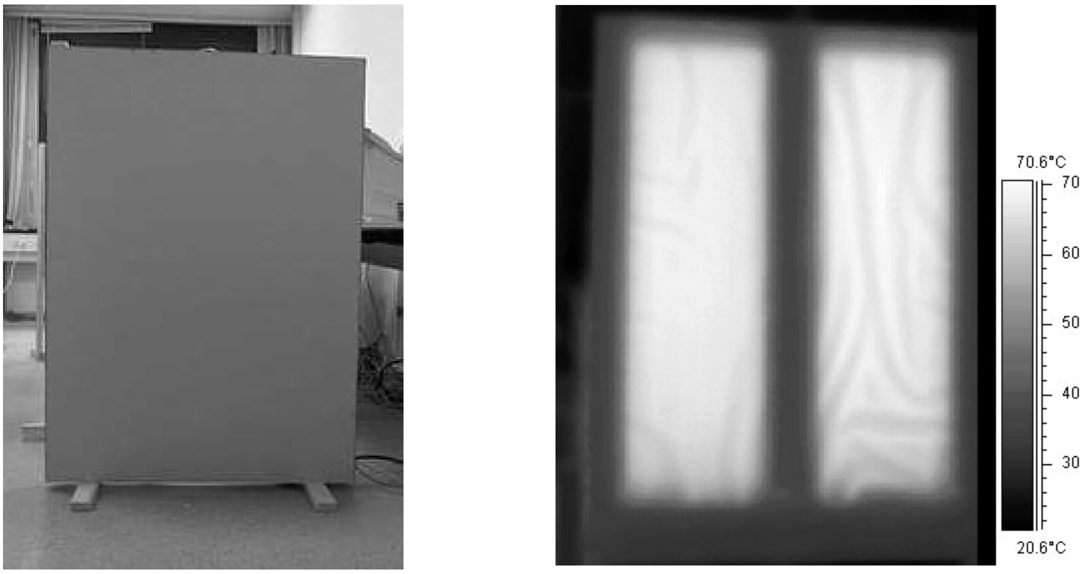


Figure 2.2 The side panel. Left a photo of the panel. To the right a photo taken with a thermographic camera. The thermographic camera was used to investigate the temperature homogeneity of the radiant panels and the room surfaces, among other things. The temperatures depicted on the photo were higher than those used during the experiments.

2.2.3 Determination of Angle Factor between Body and Radiant Panels

An investigation of the required radiant panel surface temperature was made for various sizes and locations of the radiant panels. In order to determine the required surface temperature, the angle factor between a seated person in a workstation and the radiant heating panels was determined.

The purpose of the investigation was to provide an estimate of the size, location and number of panels necessary to meet the requirements listed above.

The investigation was based on angle-factor calculations for a simplified set-up, in which the furniture was disregarded. This method was reasonably accurate, and allowed a simple approach to be applied.

The calculations were done using the Matlab-software and based on the angle factor estimates introduced by Fanger (1970). The calculations were simple and will not be described here in further detail. A total of 7 different panel locations were included in the program that calculated the angle factors. The final set-up included the 3 vertical panels, as is shown at Figure 2.3 below. A panel was located on each side of the workstation, and one was located behind the workstation. The design will be presented in further detail later.

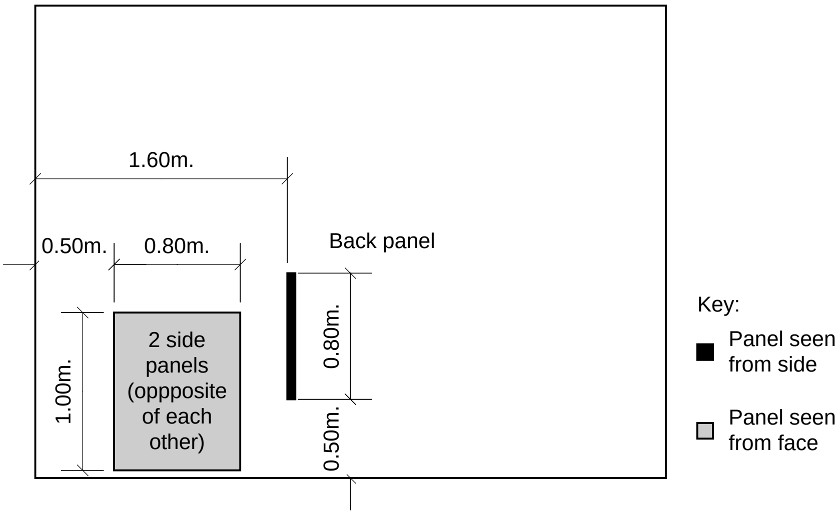


Figure 2.3 The angle factor from a seated person to each of the 3 panels and 6 walls was calculated in the Matlab program.

Using this method the angle factor from a surface to the seated body was calculated, whereas angle factors for individual body parts were not determined. This allowed the thermal environment for the entire body to be evaluated, but it was not possible to determine whether individual body parts would be uncomfortably warm or cold.

A surface temperature not higher than 50°C would be allowed, as the panels would be located within reach of the occupants. Angle factors for each panel are shown on Figure 2.4 below. The required temperatures will be discussed later.

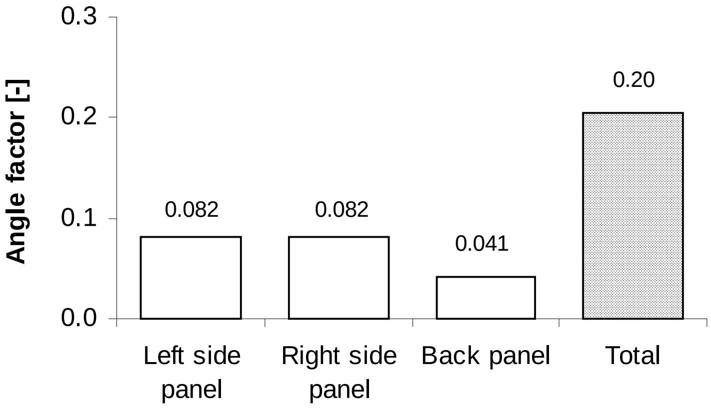


Figure 2.4 Angle factors from a seated body to the vertical radiant panels. The angle factor from the body to the room surfaces was 0.80.

The angle factor from the table panel to the lower body was not calculated. This would require detailed modelling, as no simplified methods are available. Instead it was decided to test it, and thus determine which surface temperature was required to achieve thermal comfort.

2.2.4 Materials

Side- and Back Panels

A four-piece wooden frame stabilised the panel, and surrounded the panel core, which was a thermal insulation material with a thickness of 5 cm. As insulation, mineral wool was found to be ideal. It was odourless even at high temperatures, which was a particularly important property. Heating foil was placed on one or both sides of the insulation. On the outside, the panel was covered by a thin but strong material.

Several coverings were tested, including masonite, polyethylene and a wood laminate for kitchen tables. All materials suffered in varying degrees from bending and odour emission when the temperature exceeded 40°C. For some materials – particularly the masonite – the odour emission was strong, which was unacceptable. Bending deteriorated the thermal contact between foil and covering and was unaesthetic. Particularly plastic-based materials such as the polyethylene suffered from bending, but also the masonite and the laminate were affected.

Based on the experiences from the tests, laminate was finally chosen as material for the covering. The combination of a pinewood frame and laminate had a very slight odour, but was otherwise a good solution.

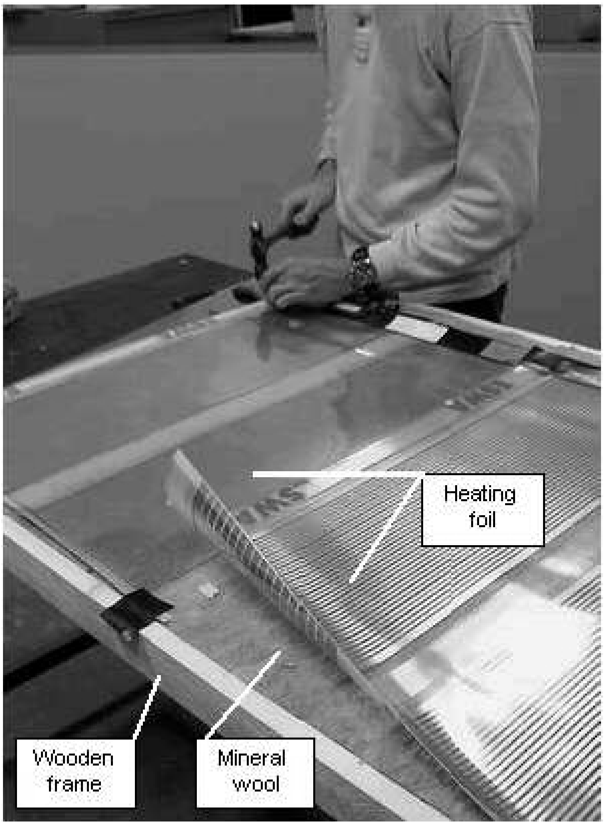


Figure 2.5 Construction of a side panel; the frame, mineral wool and heating foil is identified on the photo.

Table Panel

Mineral wool was put between the foil and the tabletop from the far edge until 20 cm from the near edge of the table. The uninsulated part caused an upward heat flow through the tabletop that would keep it above room air temperature. The foil was bend downwards in order to increase the angle factor from the foil to the feet and lower legs. The entire extent of the foil was covered with a 1 mm polyethylene sheet, so that contact between the body and the foil was hindered. As the temperature of the foil should not be as high as on the side panels, the deformation of the polyethylene was sufficiently unpronounced.

A sketch of the foil is seen on Figure 2.7, and a photo is seen below on Figure 2.6.

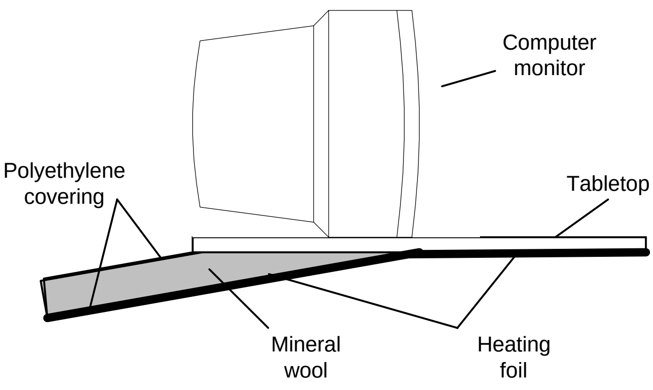


Figure 2.6 Sketch of the table foil installation. A 1 mm sheet of polyethylene covered the heating foil.

Figure 2.7 The foil installed under the table; only the polyethylene covering is visible.

2.3 Experimental Set-up

2.3.1 Resources and Facilities

The starting point of the project was that an office space should be created, in which the air temperature and radiant temperature could be controlled independently. Furthermore, the air quality should be high. Due to the heat generated by the panels, it should be possible to remove a considerable amount of heat. Also, the space was to resemble a traditional office in appearance as well as possible.

Considering that the experiments should be carried out at the Centre for Indoor Environment and Energy, two options were available: Either to use a climate chamber, or to use the field laboratory at the Centre. The field laboratory is a traditional office at DTU with equipment for temperature and humidity control plus equipment for monitoring a number of indoor environment parameters.

Using a climate chamber would allow a very accurate air temperature and humidity control. It would also allow a very substantial heat load to be removed by increasing the air change rate to the highest level of about $60h^{-1}$.

The climate chambers were unavailable for the experiments, so the field lab was used. The field lab has previously been used for indoor air quality and performance studies (Wargocki 1998, Witterseh 2001). It was well suited for studies involving air quality and temperature, given that the conditions were not extreme. Previous studies have involved air change rates of up to $6h^{-1}$ and air temperatures between 20°C and 30°C (Witterseh 2001). Humidity has been controlled by either using a 2 kW air conditioning unit for dehumidification or by using steam or ultra sonic humidifiers for humidification with up to 1.2 l/h of water. It has room for up to 6 workstations.

2.3.2 The Field Laboratory

The field laboratory is an office at the second floor of a regular office building. The room dimensions are LxWxH = 6x6x3m³ (Volume 108 m³ and floor area 36 m²). The walls are painted white. The floor covering is low-polluting polyolefine floor tiles. The wall facing east has two double-glazed windows with a total area of 6 m².

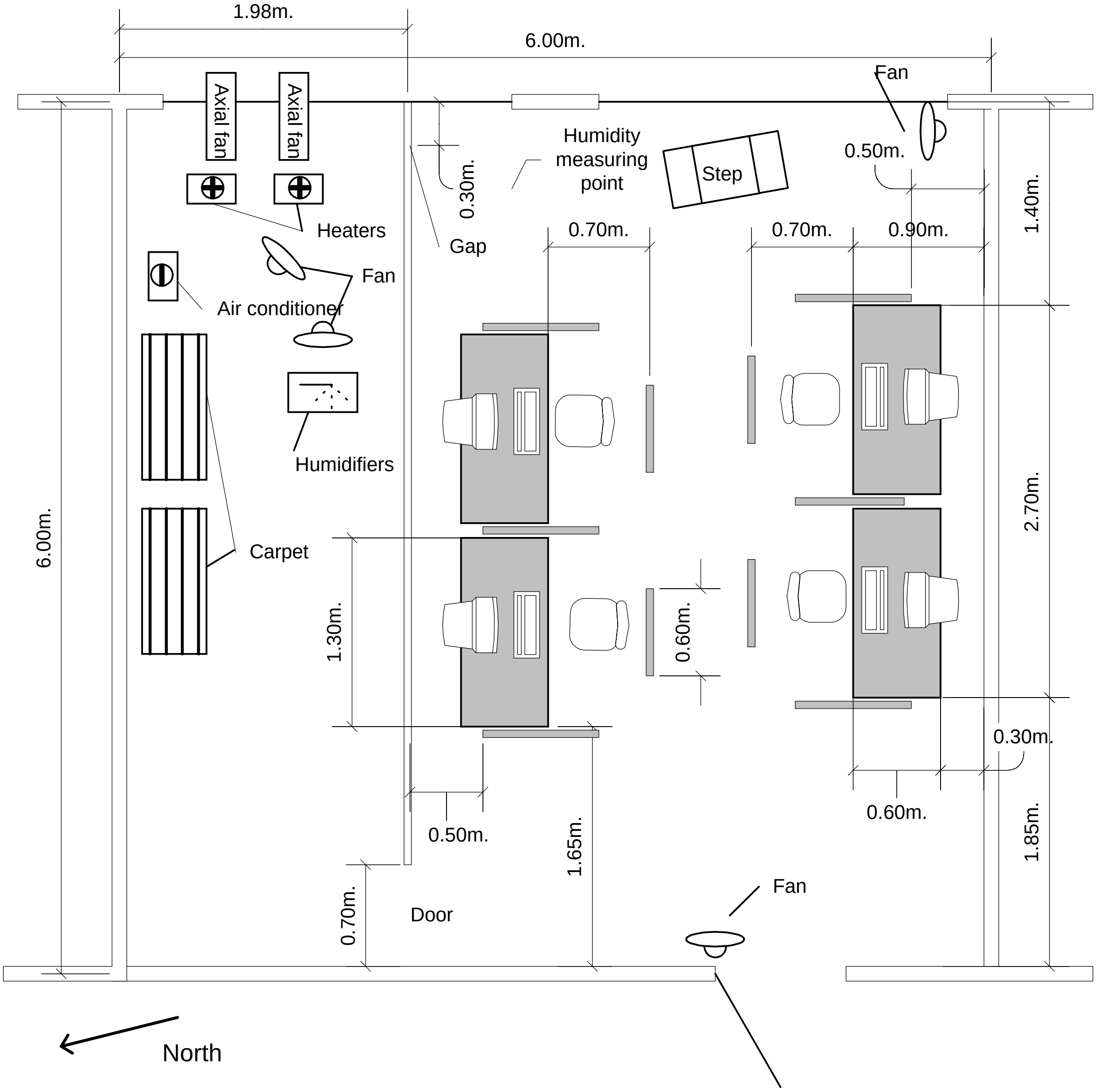


Figure 2.8 Floor plan of the field laboratory.

The room next to the field laboratory was used as a control room. The experimenters occupied this room while the experiments were carried out.

As shown on Figure 2.8, the field lab was divided into two sections: A technical zone that housed the technical equipment and air pollution source, and an occupied zone in which the workstations were installed. The partition was made using panels of laminated wood. The panels were approximately 2 m high, leaving a 1-metre gap between the panels and the ceiling. The panel towards the door-wall functioned as a door between the two zones. Conditioned air from the technical zone was mixed with the room air through the door, above the panels or through a 0.3 x 0.7 m² gap in the panel towards the window-wall. Both the door and the gap were kept open. It was not possible for the subjects to see what equipment was installed behind the partition.

Four workstations were installed in the occupied zone. Each consisted of a table, a chair, a low energy spotlight and a computer monitor. The computers were not located at the workstations, but two were stored behind the partition, while another two were stored in a closet in the corridor.

Two workstations were placed along the partition wall, and two were placed on the opposite wall. A surveillance camera was installed in the room, so that the experimenters could monitor the subjects, and so that the subjects could attract the attention of the experimenters, if required.

The occupied zone also contained a wooden step with two steps, which was used by the subjects to exercise at regular intervals to maintain a metabolic rate of 1.2 met.

Two axial fans located in the technical zone provided outdoor air to the room. The air was exhausted from the room through a slot under the door and a grill above the door. Both lead to the adjacent corridor.

An air conditioning unit was installed to cool the air, and heating was done with electrical oil heaters and convectors installed beneath the windows.

The electrical oil heaters were controlled by a PID controller (Proportional Integrated Derivative control), which was located in the control room.

A PT-100 temperature sensor used for the control was placed in the breathing zone in the workstation closest to the window on the partition side of the room.

Humidifiers controlled the humidity content of the air in the field lab. Ultrasonic humidifiers were intended for this purpose, but due to equipment failure, steam humidifiers had to be used at most sessions. A PID controller controlled both types of humidifiers. A total of 1.2 l/hour of water could be added to the air. Dehumidification was not possible in the field laboratory.

Mixing fans were installed in both the technical zone and the occupied zone to ensure that the air was mixed well, both

Figure 2.9 Overview of the field lab with workstations and radiant panels installed.

Figure 2.10 A workstation in the field lab before the radiant panels were installed. .

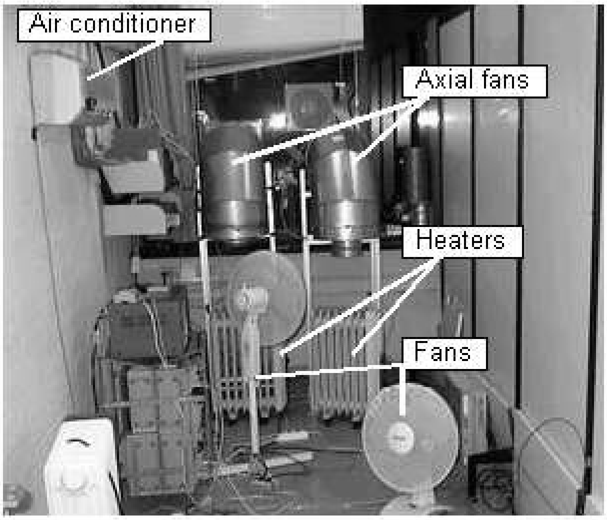


Figure 2.11 Equipment in the technical zone.

between zones and in the occupied zone. The mixing fans were also used to control the direction of the airflow.

The noise level was minimised by using noise attenuators with the inlet fans and by using small mixing fans.

When pollution sources were present in the field lab, these were placed in the technical zone, out of sight of the subjects.

2.3.3 Workstation Heat Load

The heat generated in the workstations was removed by ventilation and/or cooling in order to keep the air temperature at the desired level. An accurate estimate of the workstation heat load was therefore required. Three major sources that contributed to the heat load were a) the radiant panels b) the electrical equipment (computer monitor and spotlight) and c) the occupants. To this, a fraction of the heat generated by the electrical equipment in the field lab was added. The heat load generated by the panels was adjusted depending on the thermal sensation votes of the subjects, whereas the other heat contributions would be considered constant:

Table 2.2 Workstation heat load excluding the radiant panels.

	Heat load [W]
Occupant, 1.2 met, 1.8 m²	125
Computer monitor	70
Spotlight	7
Other equipment *	200
Total	402

* *Equipment located outside the workstations, but in the field lab. This includes humidifiers, control system, fans and others. Values are approximate.*

The heat load generated from the radiant panels was estimated as a function of the surface temperature by calculating the radiant heat exchange with the room surfaces and the convective heat exchange with the air.

The radiant exchange between panel and room surfaces was calculated as (Mills, 1992):

$$Q = \frac{\sigma \cdot (T_{panel}{}^4 - T_{room\,surfaces}{}^4)}{\frac{1}{\varepsilon_{panel}} + \frac{1}{\varepsilon_{room\ surfaces}} - 1} \quad [W/m^2]$$

Where

σ is Stefan Boltmans constant, $\sigma = 5.67 \cdot 10^{-8} \frac{W}{m^2K^4}$

ε is the emissivity [-]

The convective heat exchange was calculated by first determining the Rayleigh number (*Ra*). As this was within the range of laminar flows, the Nusselt number for the vertical panels was calculated as (Mills, 1992):

$$Nu_L = 0.68 + 0.670 \cdot (Ra_L \cdot \Psi)^{0.25} \quad [-]$$

And for the horizontal table panel, the Nusselt number was calculated as (Mills, 1992):

$$Nu_L = 0.82 \cdot (Ra_L)^{0.2} \quad [-]$$

With these input, the convective heat transfer coefficient was calculated. Repeating these calculations for a range of panel surface temperatures allowed the relationship between surface temperature and heat load to be investigated. This is depicted in Figure 2.12.

The figure also shows the operative temperature corresponding to a given radiant panel surface temperature. It assumes that the temperature of the room surfaces is 18°C, corresponding to the air temperature. The operative temperature was determined using the body-panel shape factor of 0.2:

$$T_{op} = \frac{(0.2 \cdot T_{panel} + 0.8 \cdot T_{room\,surfaces}) + T_a}{2}$$

This approach assumed the air velocity was less than 0.2 m/s.

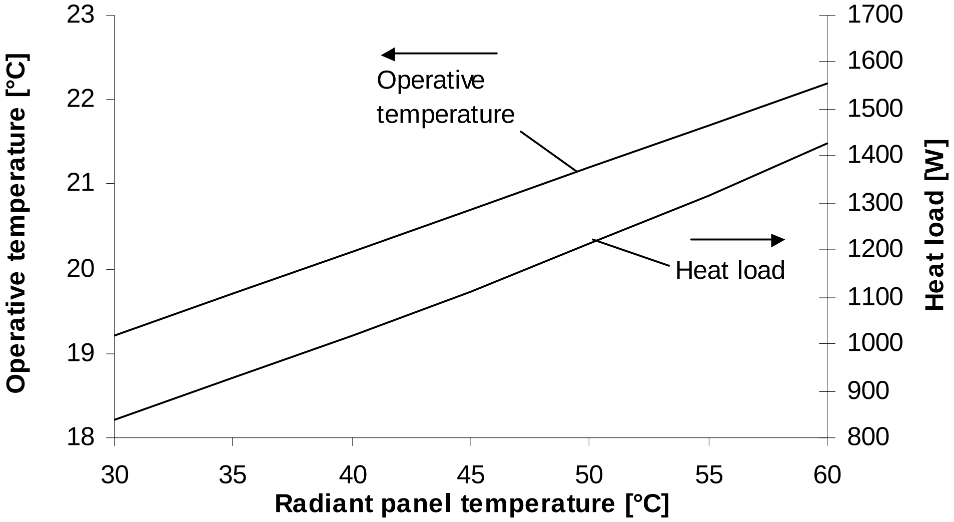


Figure 2.12 Workstation heat load and operative temperature at an air temperature of 18°C. The heat load is calculated as described in the text, and includes the 402 W heat load that is attributed to equipment in the field lab. Note that the table foil is held at a constant temperature of 40°C and contributes with 64 W. The operative temperature is calculated based on an angle factor of 0.2, and a room surface temperature of 18°C, which is the same as the room air temperature.

The calculations are discussed in further detail in appendix G. The heat load will be further discussed later.

2.3.4 Panel Surface Temperature Control

The surface temperature of the radiant panels, and thus the operative temperature, was controlled individually for each workstation. The 3 vertical panels at each workstation were controlled together, but the horizontal table panel had its own control.

The vertical panels were controlled using triac-type power regulators. The regulators had a dial that could be adjusted on a continuous scale of 1 to 10, which was proportional to the output, 10 corresponding to maximum power. The triacs could only be controlled manually and not with a regulator. The table panels were controlled by adjusting the voltage with a vario-type voltage supply.

The choice of control strategy was important, and subject to considerable attention. The overall choice was between:

1. Giving the subjects access to the dials, thus allowing them to control the temperatures themselves, or
2. Adjusting the temperatures based on the subjects' thermal sensation votes

As discussed in the literature review, individual control often has a significant positive impact on performance.

But several factors spoke against giving the subjects individual control of the temperatures:

- The surface temperatures were not allowed to exceed a given level in order to keep the heat load within the allowable range. If the subjects were given control, they might try to fully compensate for the low air temperature with radiant heating, instead of using clothing for partial compensation. Thus, risking an unwanted rise in the air temperature.
- Previous studies have shown that some subjects, who were given full individual control of radiant heating panels, have difficulty regulating the panels to their own advantage (Rasmussen, 1997). Consequently, some subjects would not experience thermal neutrality, which is unacceptable for this study.
- The panels were not used under the reference condition, wherefore the subjects would not be able to individually control the temperatures under this condition. The positive impact of individual control under the cold condition could therefore not be expected at the reference condition, thus confounding the effects of temperature and individual control.

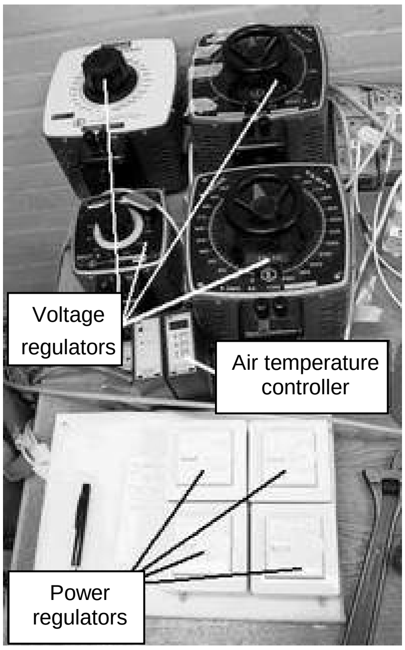


Figure 2.13 The power regulators that controlled the panel surface temperature are seen below the voltage regulators that controlled the table panels.

The surface temperature of the radiant heating panels was therefore adjusted continuously during the exposures by the experimenters based on the subjects' thermal sensation votes. The aim was a thermal sensation vote of 0 for each subject. Thermal sensation votes were given for individual body parts and for the body as a whole.

2.3.5 Field Lab Cooling Capacity

The field lab could be cooled by the air conditioning unit and by ventilation of outdoor air, which has an average temperature in January of -0.1°C (Hansen et al., 1992). Heat would also be lost by conduction through the windows and walls, and through the wall facing the staircase. The total cooling capacity depended strongly on the outside air temperature and on air change rate.

Installation of additional cooling equipment in the lab was not possible.

Using both inlet fans with noise reducing muffs but without dampers will cause an air change rate of approximately 6 h^{-1}.

The outside air temperature cannot be predicted, but based on the test reference year for Copenhagen, the fraction of a period in which the temperature will be below a given level can be determined.

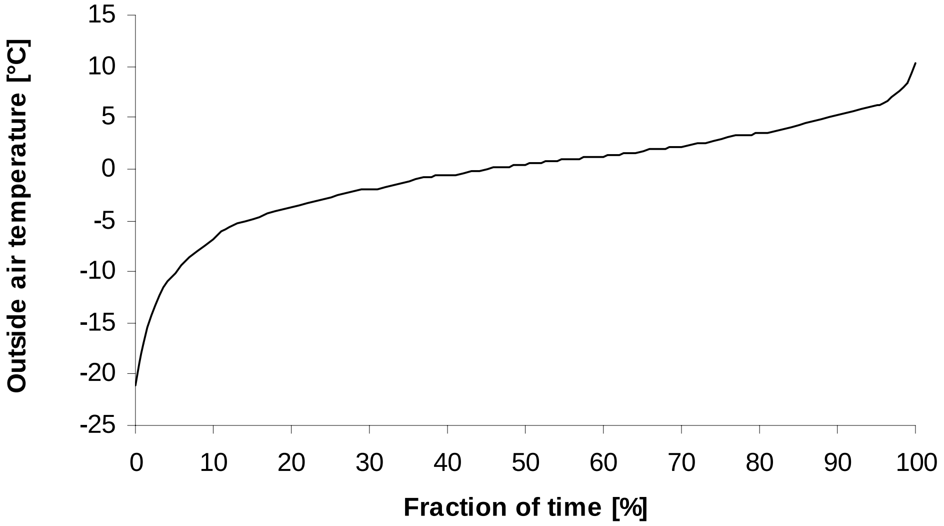


Figure 2.14 Outside air temperature distribution of the period January 15 – January 28. The values are from the Test Reference Year for Copenhagen.

It is seen from Figure 2.14 that an outside air temperature below 6°C could be expected for 95% of the time during the experimental period.

The room air temperature would not be completely uniform. An average exhaust temperature of 18°C was assumed, so that a temperature difference of 12°C could be used to determine the cooling capacity.

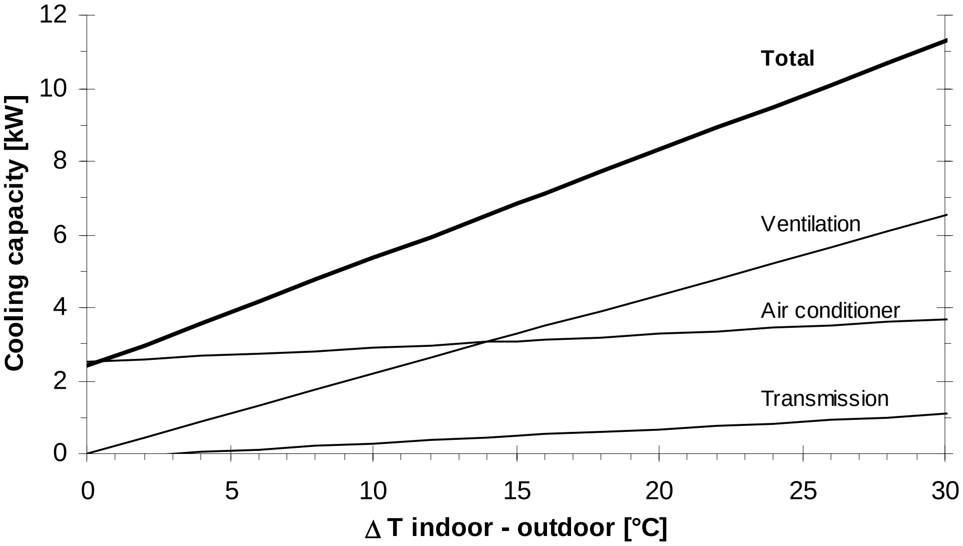


Figure 2.15 Cooling capacity of the air conditioning unit, ventilation and transmission through the building envelope as a function of temperature difference between room temperature (18°C) and outside air temperature. An air change rate of 6 h^{-1} is used for ventilation.

Figure 2.15 shows that the cooling capacity of the field lab could be assumed to be 5.9 kW when the air temperature difference between indoors and outdoors was 12°C.

The 5.9 kW was a rough estimate. It strongly depended on the temperature difference between room and outdoor air, which was assumed to be 12°C. This required a number of assumptions to hold true, including that no inlet air was exhausted without first being mixed with room air. This assumption of good mixing held true for conditions in the field lab with a lower air change rate (Wargocki, 1998).

2.3.6 Pollution Source

As the ventilation rate would have to be the same under all conditions, the air quality was controlled by adding or removing pollution sources. Wargocki (1999) successfully used this method to show a negative impact of reduced air quality on office work productivity.

The pollution source used by Wargocki was reused for the present study. It is a tufted bouclé carpet with 100% polyamide fibres and latex backing, which was removed from an office building with known indoor environment problems after 20 years of use.

The carpet was cut into 2x0.2 m^2 pieces that were attached back-to-back and hung on hangers on a mobile stainless steel rack. The rack was located behind the partition when in use, and could be removed from the field lab when it was not required. A total of 80 m^2 of carpet was available for the experiments.

2.4 Experimental Condition Details

This section describes the main indoor environmental parameters, apart from the air temperature, that made up the experimental conditions. These are the operative temperature, the air quality, the humidity level, the air velocities and the clothing insulation level.

2.4.1 Room Surface Temperatures

In order to estimate the operative temperature in the field lab, an estimate of the inside surface temperatures of the building envelope was made. Moreover, it was investigated whether the window could give rise to thermal discomfort due to radiant asymmetry. This was done based on a simple U-value calculation, as the purpose only was to produce a rough estimate of the magnitude.

For the window, a U-value of 2.0 W/m^2K was assumed, and for the inner walls, the ceiling and the floor 0.3 W/m^2K was assumed. A room air temperature of 18°C and an air temperature of 20°C in the adjacent rooms were assumed. The outdoor temperature of January would exceed –10°C approximately 95% of the time, so this value was chosen for the following calculation example.

These assumptions gave an inner window surface temperature of 12°C and a surface temperature of all other inner surfaces of 18°C.

The surface temperatures at the 23°C reference condition were not as likely to follow the air temperature. As the main concern was to keep the field lab cold, a continuous cooling strategy could be chosen. It follows, that the walls would not heat completely up to 23°C during the reference conditions. A surface temperature of 21°C was assumed without further arguments.

The maximum temperature differences between the window surface and the remaining room surfaces were computed to be 11°C and 6°C for the reference and the cold conditions, respectively. The radiant asymmetry arising from these temperature differences are roughly estimated to be no more than half these values (i.e. 5.5°C and 3°C), as the subjects did not sit very close to the window. Moreover, the side radiant panels blocked the radiation to the window for the better part of the body. Thus, the radiant temperature asymmetries that arose from the cold window temperature gave rise to minimal thermal discomfort, as the 5% discomfort level for radiant asymmetry is not reached until the radiant asymmetry is 11°C (Fanger et al., 1985).

2.4.2 Operative Temperature

In previous studies of the impact of reduced air temperature on productivity (Wyon et al., 1975; Fang, 1998) only clothing insulation levels and air temperatures were varied for attainment of thermal neutrality. In the present study radiant heating was used in addition to adjustment of clothing as means of maintaining thermal comfort.

The maximum operative temperature was limited by the heat generated by the radiant heating panels, as this heat was removed by cooling in order to maintain the air temperature.

The field laboratory cooling capacity was estimated to be 5.9 kW, or about 1.5 kW per workstation. As a margin was desired, the maximum workstation heat load was set at 1.1 kW, for the purpose of calculating the operative temperature. The relationship between operative temperature and heat load was determined earlier. Figure 2.16 shows that an operative temperature in the range of 20.5°C – 21.0°C could be obtained, whereas the heat load caused by a substantially larger value would be too high.

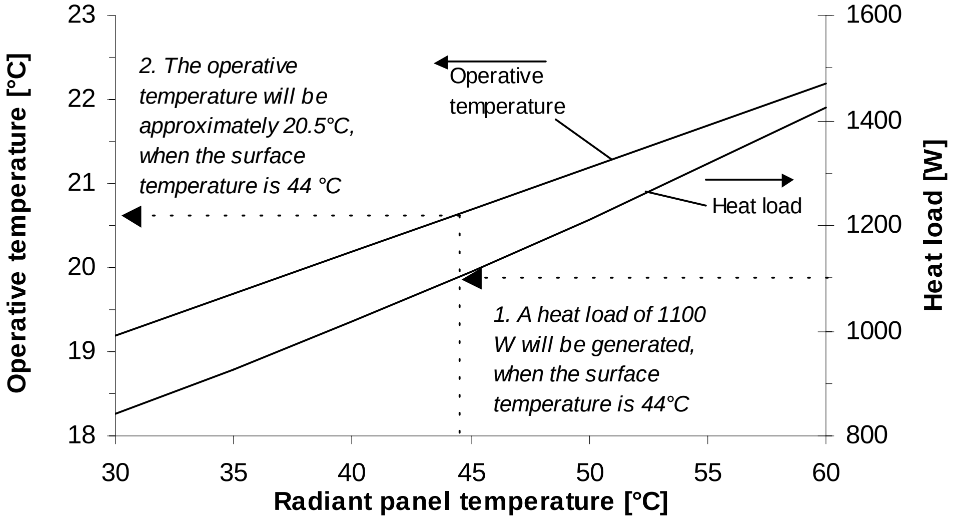


Figure 2.16 Determination of maximum operative temperature based on the 1.1 kW heat load limit. Firstly the radiant panel surface temperature is determined from the heat load. Secondly the operative temperature is determined from the radiant heating panel surface temperature.

The above considerations assumed that the surface temperature of the walls, the window, the ceiling and the floor were the same as the air temperature. This was found to be a reasonable assumption for the 18°C conditions.

The operative temperature at the 23°C reference condition was determined by assuming that the surface temperature of all surfaces had an approximate mean temperature of 21°C, as mentioned earlier. The operative temperature would therefore be approximately 22°C.

2.4.3 Air Quality

The air change rate was kept constant at 6 h^{-1} due to the cooling requirement. The air quality would therefore have to be controlled in another way. It was decided to use the previously described carpet as pollution source instead.

The chosen approach was not expected to give exactly the same effects as a change in ventilation rate would have given. In principle it would be possible to determine the amount of pollution source required to obtain a given percentage of dissatisfied, corresponding to a given ventilation rate. But because of the very high basic ventilation rate, the amount of pollution added would have to be high. The amount of pollution that could be added in practice was limited by the available space in the field lab and by the amount of pollution source available, as will be discussed below.

The volume of the field lab was 108m³, resulting in an airflow of 0.18 m³/s. The CEN Report CR 1752 (CEN, 1998) recommends a ventilation rate of 2.0 l/s/m² for a class A room with an occupancy of 0.1 person/m². The 36m² field lab had an occupancy of 4 persons, or 0.11 persons/m². The airflow of 0.18m³/s corresponded to 5.0 l/s/m², which was well above the recommendation.

The ASHRAE standard 62 (ASHRAE, 1989) states that 10 l/s/person is required for an office space. As four persons occupied the field lab, 0.18 m³/s corresponded to 45 l/s/person. It followed that an air change rate of 6 h^{-1} was well above what was considered a typical office space.

The predicted percentage of dissatisfied (PD) was predicted according to CEN (1998):

$$PD = 395 \cdot \exp(-1.83 \cdot q^{0.25})$$

where q is the ventilation rate in l/s/olf.

Wargocki (1998) found that the sensory pollution load of the field lab was 0.14 olf/m² without any added pollution sources, which corresponds to a CEN 1752 (CEN, 1998) low-polluting building. Adding the carpet caused a sensory pollution load increase of 0.09 olf/m² of carpet, which was attributed the carpet.

The total sensory pollution load was determined by adding the olfs of the room and the subjects, as found by Bluyssen and Fanger (1991) and Wargocki (1998). The total sensory pollution load of the field lab was thus 5.0 olf in total. Adding the four subjects, the total pollution load corresponded to 9.0 olf, which corresponded to a ventilation rate of

$$\frac{180 \frac{l}{s}}{9\,olf} = 20 \frac{l}{s \cdot olf}$$

The percentage dissatisfied was estimated for the room without added pollution sources:

$$PD = 395 \cdot \exp(-1.83 \cdot 20^{0.25}) = 8\%$$

Adding the carpet caused an increase of 0.09 olf/m² of carpet added. This value was used to determine the sensory pollution load in the present study, assuming that the emissions from the carpet had not deterred since the carpet was first used for experiments prior to the present study (Wargocki, 1998). As the ventilation rate was high, and as a substantial reduction in perceived air quality was desired, all available 80m² of carpet was used for the experiments. The sensory pollution load was calculated:

$$0.14 \frac{olf}{m^2 room} \cdot 36m^2 + 0.09 \frac{olf}{m^2 carpet} \cdot 80\,m^2 + 1 \frac{olf}{person} \cdot 4\,persons = 16.2\,olf$$

The ventilation rate with the pollution source added was 11 l/s/olf. This allowed the percentage dissatisfied with the pollution source present to be calculated:

$$PD = 395 \cdot \exp(-1.83 \cdot 11^{0.25}) = 14\%$$

Thus, even with a carpet twice the floor area (80m²), the room still corresponded to a CEN 1752 class A building due to the ventilation rate of 45 l/s/person.

It was decided not to use more carpet, partly because none was readily available, and partly because there was no more room in the technical zone to store it during the experiments.

The above considerations assumed that the emissions from the carpet and the room were independent of the air temperature and ventilation rate. Fang (1997) found that temperature changes in the range of 18°C – 28°C did not give rise to a substantial increase in VOC emissions from five tested building materials. He found that relative humidity only had an impact on waterborne materials such as paint or floor varnish. It was therefore assumed that the sensory pollution load from the carpet was influenced by neither temperature nor humidity.

2.4.4 Humidity Level

The humidity level was meant to have minimal influence on the results of the experiments. The air used at the different conditions should have the same absolute humidity content for the two different temperature conditions. Since the absolute humidity level of the outdoor air changes from day to day, it was necessary to humidify the air, as dehumidifiers were unavailable.

The nasal thermal perception of air is determined partly by convective and partly by evaporative heat loss of the mucous membranes in the upper respiratory tract. The equation below shows that the evaporative heat loss solely depends on the vapor pressure (p_a), while the convective loss solely depends on the air temperature (t_a) (Toftum et al., 1998). The vapor pressure is proportional to the absolute humidity, so when the absolute humidity level is fixed, the air acceptability (ACC) is affected only by changes in air temperature.

$$ACC = -1.06 + \underbrace{0.046 \cdot (30 - t_a)}_{\text{convective loss}} + \underbrace{0.038 \cdot (42.5 - 0.01 \cdot p_a)}_{\text{evaporative loss}}$$

The absolute humidity in the field lab was controlled using three humidifiers; dehumidification was not technically possible. Given the high ventilation rate of the field lab, the absolute humidity level of the field lab was approximately the same indoors as outdoors, because the only moisture load was that coming from the 4 subjects (0.24 kg/h). The level of absolute humidity was therefore chosen according to the climatic data for January, as it was necessary to find a level, which was not exceeded too often by the outdoor climate, yet, was not so high that the humidifiers could not supply the necessary moisture. A target value of 0.0042 kg/kg was chosen for the absolute humidity, as seen on Figure 2.17 below.

The high air change rate of 6 h^{-1} limited the range of humidity control to 0.0015 kg/kg, as it was not practically possible to humidify with more than 1.2 kg/h using three ultrasonic humidifiers. The moisture control of the three ultrasonic humidifiers was determined as:

$$Moisture\ \ control = \frac{humidification\left(\frac{kgH_2O}{h}\right)}{air\,change\left(\frac{m^3}{h}\right) \cdot density\left(\frac{kg\,air}{m^3}\right)} = \frac{1.2}{648 \cdot 1.2} = 0.0015\left(\frac{kg\,H_2O}{kg\,air}\right)$$

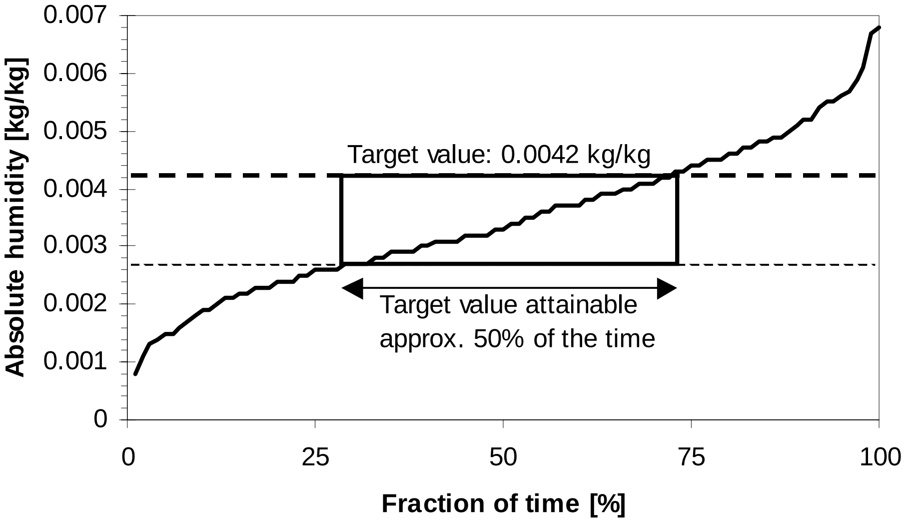


Figure 2.17 Absolute humidity level distribution of outdoor air in January (Denmark). The three humidifiers could add 1.2 kg/h corresponding to a moisturising control of 0.0015 kg/kg as indicated by the interval between the dotted lines. The shaded box shows the time interval within which the target value of 0.0042 kg/kg absolute humidity can be attained, namely approximately 50% of the time. The high air change of 6 h^{-1} makes it impossible to attain better humidity control, but this is not considered critical for the experiments, as the humidity deviations will be relatively small (flat curve).

Applying the target value to the conditions, gave the relative humidities shown below in Table 2.3.

Table 2.3 Relative and absolute humidities at the temperature conditions of 18°C and 23°C.

Temperature condition	23°C	18°C
Absolute humidity	0.0042 kg/kg	0.0042 kg/kg
Relative humidity	24%	34%
Enthalpy	33 J/kg	29 J/kg

These values were low, when referring to for example ISO 7730, which recommends a relative humidity in the range of 30% - 70%. Studies presently taking place at the International Centre for Indoor Environment and Energy will investigate the impact on health and acceptability of dry air.

2.4.5 Air Velocities

As air velocity was not a factor to be investigated, it was desired to keep this low, so that dissatisfaction due to draught was kept at least below 15 percent dissatisfied, as required for a category A room according to CEN 1752.

But as the air change rate was high, 6 h^{-1}, and the air temperature 18°C under the cold conditions, this would be difficult to obtain. The radiant panels would also give rise to convective airflows, thus further increasing the air movements close to the occupants.

The room was used by Wargocki (1998) with an air change rate of 2 h^{-1}. The air velocities measured in this experiment were approximately 0.15 m/s.

Therefore, dissatisfaction due to air movement was anticipated to possibly reach an unacceptably high level. Several measures were taken to reduce the air velocities in the room. The main concern was to mix the cool inlet air from the technical zone with the air in the occupied zone. This should be done so that the air temperatures at each workstation were the same.

The door between the technical zone and the occupied zone was kept open during the experiments, to increase mixing and reduce the air velocity. The gap in the partition below the window was made for the same reason. Both smoke and velocity measurements were used to locate and quantify the airflows. Figure 2.18 shows a rough outline of the airflows in the field lab.

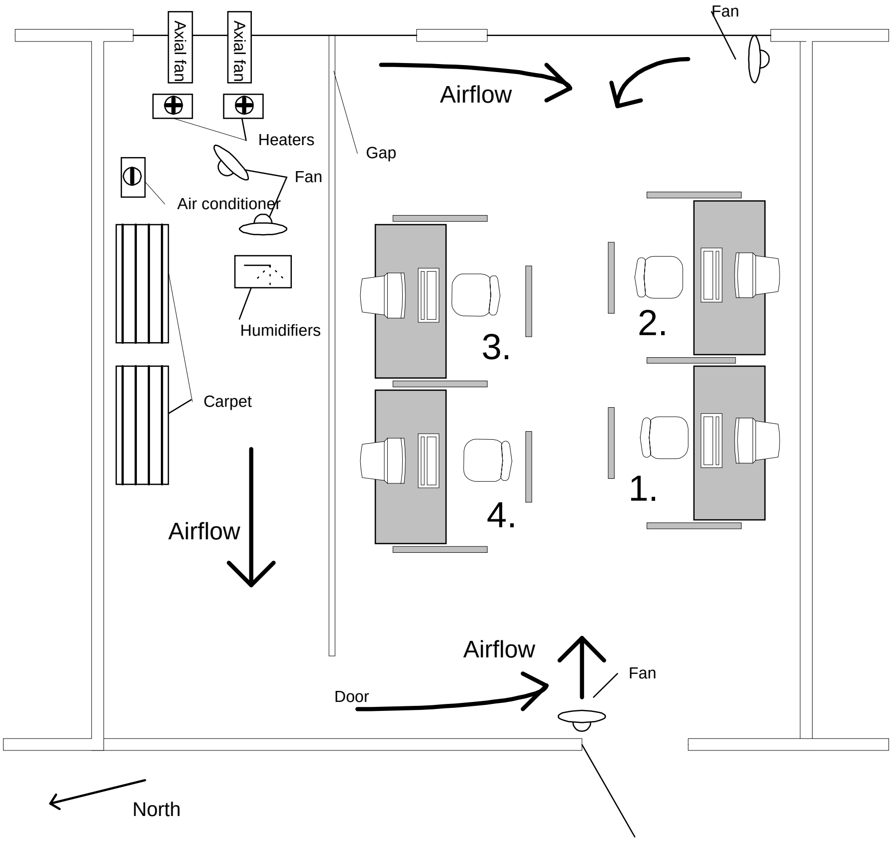


Figure 2.18 Airflow outline. The air was exhausted through a slot under the door, and through a grille above the door. The workstations were numbered 1 through 4.

Small fans were necessary in the field lab to direct the airflows. The main flow of air followed a path from the inlet fans, through the door into the occupied zone. A smaller flow entered the occupied zone through the gap in the partition. Without the fans, these flows would cause draught in workstations 1 and 2, and the air temperature in these workstations would be 1°C – 2°C lower.

Two fans were used to counteract the draught, one located near the door, and one near the window. A number of locations and directions were tried. The one sketched caused the lowest air velocities while temperature uniformity between the workstations were maintained to an acceptable extent. Using fans in the occupied zone had two disadvantages. They attracted the subjects' attention and thoughts to air movement and possibly to draught. And they also made an audible noise, even though they were ran at minimum position and selected as the least noisy fans available.

Still, draught ratings were expected to reach levels beyond the acceptable for a category A room. As the high air change rate was required to cool the room air, no solution was found to this problem.

2.4.6 Clothing Insulation Level

The optimal level of clothing insulation was defined as the level causing thermal neutrality, i.e. a PMV of zero.

The ASHRAE Thermal Comfort computer program was used to calculate the clothing insulation level.

For the calculations, a metabolic rate of 1.2 met and an air velocity of 0.15 m/s were used. The operative temperature and relative humidity used for each temperature condition was based on the previously established levels:

- 18°C air temperature: 33% RH and T_{op} = 20.5°C
- 23°C air temperature: 25% RH and T_{op} = 22.0°C

Equal air and mean radiant temperatures were assumed, which was an assumption that facilitated the calculations.

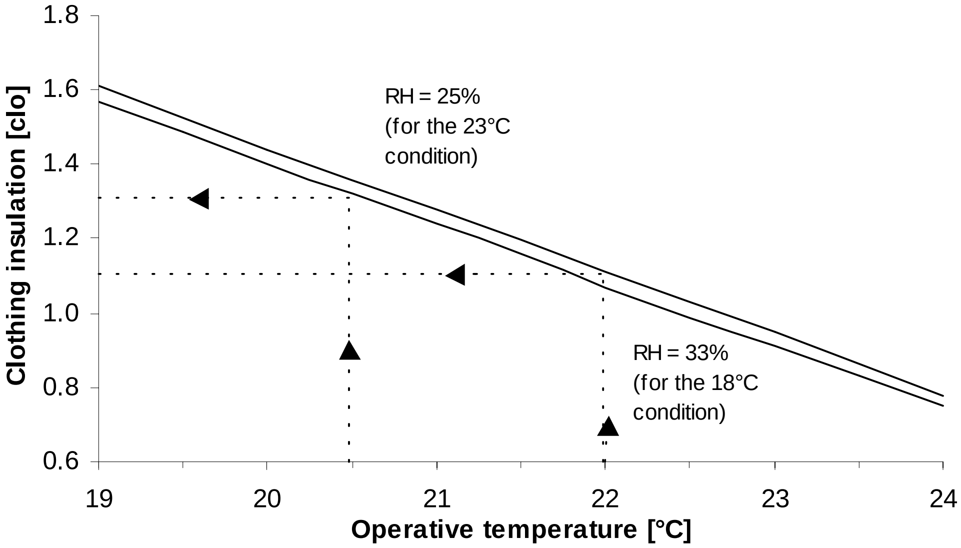


Figure 2.19 The clothing insulation that gives a PMV of 0.0 for 2 relative humidity levels and a range of operative temperatures.

The calculations were carried out for both temperature conditions. Figure 2.19 shows the results, which are summarised in Table 2.4 below. Appendix H contains clo-value estimates for a wider range of air velocities.

Table 2.4 Optimal clothing insulation levels for the two conditions, summarised from Figure 2.19.

	Condition - air temperature	
	18°C	23°C
Operative temperature	20.5°C	22°C
Optimal clothing insulation level	1.32 clo	1.11 clo

1.32 clo was above the level for typical winter clothing, which was what the subjects were expected to wear when participating in the experiments. Additional clothing was required. This was chosen while bearing in mind the risk of local discomfort at feet, legs and neck.

A fleece jacket insulates well, and has a collar that can be adjusted to reduce draught at the neck, should the subjects experience this.

Leg warmers keep the lower legs warm, while adding some insulation to the ensemble. They are fairly large, and do not feel constraining while worn.

The fleece jacket and leg warmers were added to the ensemble. Photos of subjects wearing the fleece jackets and leg warmers are found in appendix J. With the added clothing, an ensemble of winter clothing could comprise the items in Table 2.5.

Table 2.5 Ensemble of winter clothing. The values were taken from ISO 9920 and ASHRAE 55, as neither standard comprises clo-values for all of the clothing items used. Instead a table has been compiled, based on the two standards as described in appendix I.

Item	I_{cl} [clo]
Shoes, heavy	0.04
Socks	0.02
Men's briefs	0.04
T-shirt	0.10
Heavy sweater	0.36
Jeans	0.18
Chair †	0.15
Fleece ‡	0.36
Legwarmers ‡	0.07
Total	1.32

† The chair is included, as the subjects will be sitting in a chair during the exposures.

‡ Additional clothing provided to the subjects.

1.32 clo was considered the limit of what the subjects could be asked to wear without making them feel too uncomfortable. 1.32 clo was also the target value determined in Table 2.4 as the optimal clothing insulation for an operative temperature of 20.5°C.

2.5 Experimental Plan

2.5.1 Sample Size

A power analysis was used to estimate the sample size needed for attainment of significant results. The larger the sample size the smaller effects can be detected.

A significant impact on performance was expected to require the largest sample size, compared to impacts on perceived air quality, thermal comfort and symptoms. Thus, the sample size required to detect a significant impact on performance was determined.

A repeated-measures design was chosen to strengthen the experiment. For a repeated-measurement the same subjects participate in all of the exposures instead of having new subjects participating each time. This way the large variations between people balanced out, as it was only the relative intra-personal differences that matter. A suitable test for determining the sample size for a repeated-measures experiment is the paired t-test, which required the following input.

a. The mean values of both data sets to be tested against each other
b. The standard deviation of the intra-personal difference between data sets
c. Power of the test (typically value is 0.95, which corresponds to $p<0.05$)

Expected mean (8000) and standard deviation (800) values were obtained from an unpublished study by Fang (1998), where 23 persons completed a text-typing task in a repeated-measures design. The statistical computer program SAS was used to determine the needed number of subjects for different levels of increased performance (Figure 2.20).

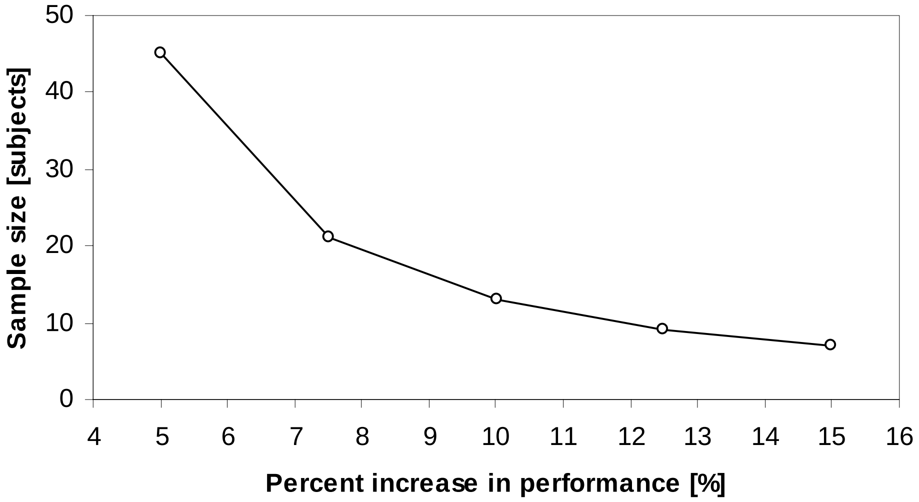


Figure 2.20 Sample size determination with a one-tailed paired t-test at a power of 0.95 ($p<0.05$). The analysis was based on text typing data from a previous study (Fang, 1998).

The figure shows that the required number of subjects rises steeply for small improvements of performance. It was decided to use 28 subjects for the experiments assuming an increase in performance of 5-10%.

2.5.2 Experimental Plan

It was decided to perform 2 experimental conditions 7 days a week for 2 weeks. The experiments were thus conducted in a satisfactory manner, and in a minimum amount of time. A power analysis based on previous experiments was performed, which indicated that 28 subjects would be a reasonable amount. 4 subjects could be exposed in the field lab simultaneously, so the experiments comprised 7 groups of 4 subjects.

The exposure time was set to 3 hours. Based on the experiences from previous experiments, this was a reasonable compromise between the odds of obtaining significant results and economy. Moreover, it allowed two sessions to be performed per day; one in the afternoon at 15:00 – 18:00 and one in the evening at 19:00 – 22:00.

All groups were thus exposed to 2 conditions during one week, and 4 conditions in total. One condition was used as a training session, from which no results were obtained. Each subject was therefore exposed to 3 conditions.

The 3 experimental conditions were denoted as shown in Table 2.6 below. The denotations were used during the experiments, but have not been used in the report.

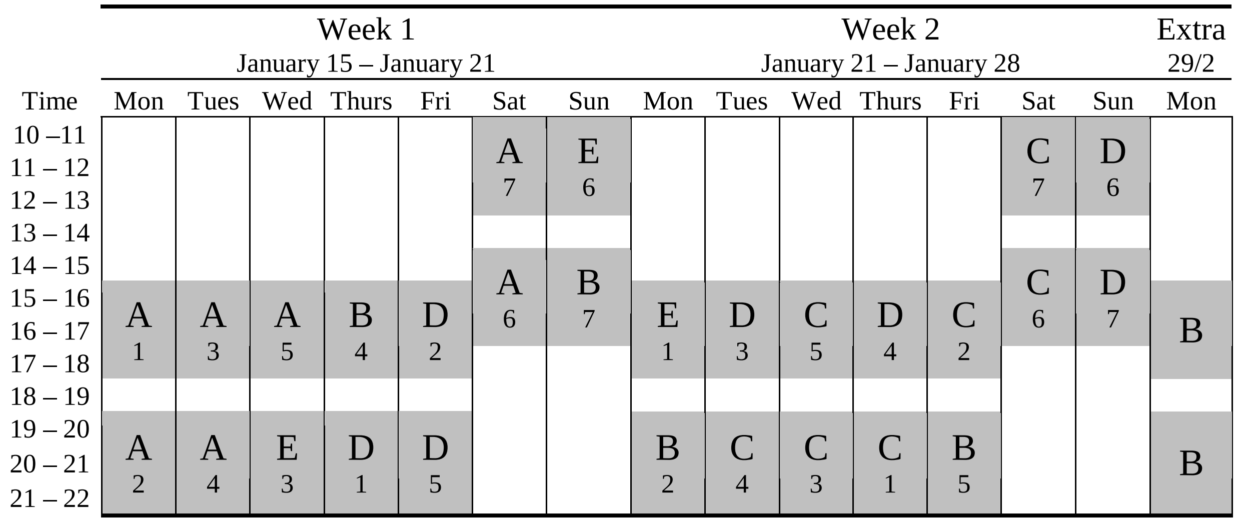
Table 2.6 The experimental conditions for the two-factor incomplete design.

	23°C	18°C
Pollution source present	*	B
Pollution source absent	C	D

** This condition was used for training.*

The course of experiments is sketched below. For practical reasons the exposures in the weekends were scheduled earlier than those of weekdays. This was done solely to facilitate the recruitment of subjects. The effect of not conducting all experiments on the same time of day was unknown, but expected to be very small.

The design was balanced, while offering a plan that was as simple as possible for the subjects. It was decided that each subject would appear on the same weekdays and times both weeks. The confounding thus introduced to the model was assumed negligible.



	Week 1							Week 2							Extra
	January 15 – January 21							January 21 – January 28							29/2
Time	Mon	Tues	Wed	Thurs	Fri	Sat	Sun	Mon	Tues	Wed	Thurs	Fri	Sat	Sun	Mon
10 –11						A 7	E 6						C 7	D 6	
11 – 12															
12 – 13															
13 – 14															
14 – 15						A 6	B 7						C 6	D 7	
15 – 16	A 1	A 3	A 5	B 4	D 2			E 1	D 3	C 5	D 4	C 2			B
16 – 17															
17 – 18															
18 – 19															
19 – 20	A 2	A 4	E 3	D 1	D 5			B 2	C 4	C 3	C 1	B 5			B
20 – 21															
21 – 22															

Figure 2.21 Outline of the experiments. Each grey area is a 3-hour exposure. Letters refer to experimental conditions, and numbers to groups. The exposures denoted "A" were used for training. The subjects that participated in the "Extra" sessions were mixed between groups.

The plan contained 4 conditions instead of 3. A change in the plan was made while the experiments were being conducted. As it became clear that the temperature initially chosen for the reference temperature condition (20.5°C) was not sufficiently high to detect any impact of air temperature on performance, the temperature was raised.

The change was made so that it inflicted a minimum of consequences on the plan. For the groups that had not yet been exposed to the reference condition, the temperature was simply increased. Of the 3 groups that already had been exposed to the reference condition, none had been exposed to the reduced air quality condition. It was therefore decided to change this condition to a reference condition for the 3 affected groups.

As a consequence of this, 3 groups were not exposed to the reduced air quality condition. Extra sessions were therefore run the day after the end of the scheduled experiments, and the subjects of the affected groups were invited to join. Of the 12 subjects, 7 accepted to join so that a total of 5 subjects were not exposed to the reduced air quality condition.

The number of subjects exposed to each condition is seen in Table 2.7 below.

Table 2.7 Number of subjects that were exposed to each experimental condition.

	Training	23°C No source	18°C No source	18°C Source
Number of subjects	28	28	28	23

On one occasion it was decided to switch conditions based on the weather forecast, namely in the second weekend of the experiments. A warm Saturday and a colder Sunday was expected, which is why two reference temperature conditions were conducted Saturday, and two 18°C conditions were conducted Sunday. The benefit of upholding the target air temperature was considered greater than the disadvantage of a design that was not perfectly balanced.

In addition to balancing the time of day and weekday, workstations and set of problems for the performance tasks were assigned so that each subject was exposed to four different “levels” of the factors.

Though no differences in time of day, weekday, set of problems or workstation were expected, the balanced design allowed any differences in the impact of these factors to be detected with analyses of variance.

2.6 Subjects

28 subjects were recruited for the experiments, 14 women and 14 men. Posters were put up at DTU and universities in the vicinity of Lyngby and an email was sent to participants in another indoor climate experiment that was carried out in December 2000 at the Centre. Those that responded to the postings were asked to answer a questionnaire regarding their general health status. This included questions regarding occupation, general health status, smoking habits, allergies, etc. The subjects were selected upon a set of criteria: they should be healthy, neither under- or overweight, non-smokers and not suffer from chronic diseases, asthma or allergy. They were informed about the type of experiment (indoor environment) that they participated in, and were allowed to drop out of the experiments at any time. Anthropological data are found in the table below.

Table 2.8 Anthropological data of the 14 male and 14 female subjects participating in the experiments. The data is formatted as the mean value ± the standard deviation.

	Males	Females
Age [years]	21.9 ± 2.4	20.9 ± 1.5
Height [cm]	183.5 ± 7.9	168.7 ± 6.1
Weight [kg]	73.6 ± 6.9	60.9 ± 6.8

It was decided to use both male and female subjects to reflect the population. Studies showed that females report more symptoms than males (Witterseh, 2001). As the present study comprises effects on more issues, using both males and females was considered reasonable.

The subjects' olfactory sense was tested through a ranking test. In the ranking test, each subject ranked four concentrations of 1-butanol in order of odour strength. The concentrations used were 10, 80, 320 and 1280 ppm. All subjects passed the ranking test.

Due to the importance of each subject appearing at all four experimental sessions, a bonus of 200 kroner was introduced. The subjects were told, that they would receive the bonus if they appeared at all four sessions, and if they completed the tasks in a satisfactory manner. As all subjects did appear at all sessions, and everyone also completed the tasks satisfyingly, they were all paid the bonus.

At the end of the training session an individual interview was made with every subject. This was done with two purposes. Firstly, to find out if the subjects had ideas or suggestions that could improve the conduction of the experiments.

And secondly, the interview was made to make a more personal contact with each subject. The importance of appearing to every session was pointed out, and this increased the feeling of responsibility that the subjects felt for the experiments.

2.7 Measurements

2.7.1 Physical Measurements During the Experiments

All temperatures were measured by thermistors of the brand Astra Meditec. The thermistors were calibrated prior to the experiments.

At each workstation, thermistors were used to measure the air temperature in the breathing zone, and the surface temperature of both the 3 vertical radiant panels, and the foil installed under the table. The thermistor measuring the air temperature was fastened to the monitor on a 20 cm plastic arm, so that it was raised 40 cm above table level. It was shielded from irradiance by a cylindrical piece of aluminium foil. The thermistors measuring surface temperature were fastened to the radiant panels using transparent tape.

The accuracy and validity of the surface temperature were investigated in detail. It was checked, that the temperature measured by the thermistors was the true surface temperature.

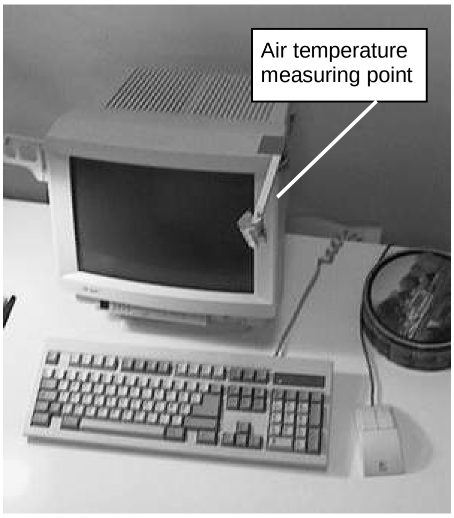


Figure 2.22 The air temperature was measured with a thermistor placed on an arm.

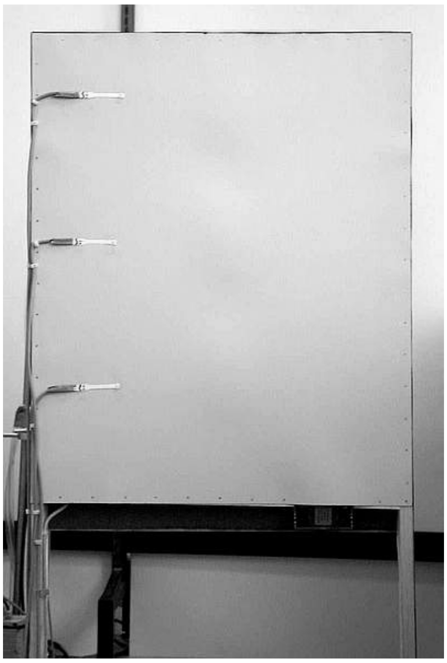


Figure 2.23 Surface temperature measurement with thermistors on the back panel of workstation 3.

It was further checked that the temperature measured by the thermistors represented the mean surface temperature of the panels. These investigations are found in appendix E.

The surface temperature of the floor, ceiling and the four walls were also measured using thermistors fastened by transparent tape.

Outside air temperature was measured.

At the workstation closest to the window on the partition-side of the room, additional thermistors were installed in order to allow detailed analyses.

Thermistors were placed at 3 different heights on the radiant panels, and a thermistor was placed on top of the tabletop. Two thermistors were placed on the far right table leg 10 and 60 cm above the floor.

Relative humidity was measured along with air temperature at a stand located in the southeast part of the occupied zone, using Vaisala HMP 133Y sensors. A list of temperature and humidity measurements is found in appendix C.

Both temperature and relative humidity were recorded on a computer using a HP data acquisition unit and a computer equipped with HP VEE software. Measurements were taken every 30 seconds. The HP VEE software was also used to continuously monitor data measured during the experiments.

The dial positions of the radiant heating panel power controllers were recorded regularly.

Gas sample tubes were placed on the right side of each workstation. These were used to measure the CO_2 level in the field lab during the experiments, and to measure the air change rate by means of tracer gas. A Brüel & Kjær 1302 Multigas Monitor and a Brüel & Kjær 1303 Multipoint sampler were used for this. The concentration decay method was used by dosing once with SF_6 and subsequently measuring the gas concentration. As the gas concentration was measured at all workstations, it was possible to verify that the air was fully mixed. The equipment was also used to measure the background concentration of CO_2 though a tube located outside the window by the air intake. Air change rate was measured without subjects present in the room.

The noise level in the field lab was measured on several occasions during the experiments using a Brüel & Kjær 2218 Sound Level meter.

2.7.2 Fingertip Temperature Measurements

The temperature of the subjects’ fingertips was measured three times during each exposure. The temperature was measured in two ways.

The first with the Astra Meditec thermistors, which the subject held for at least 30 seconds between thumb and index finger. Thus, it was not the surface temperature of the fingertips that was measured, but a temperature between surface temperature and core temperature of the finger.

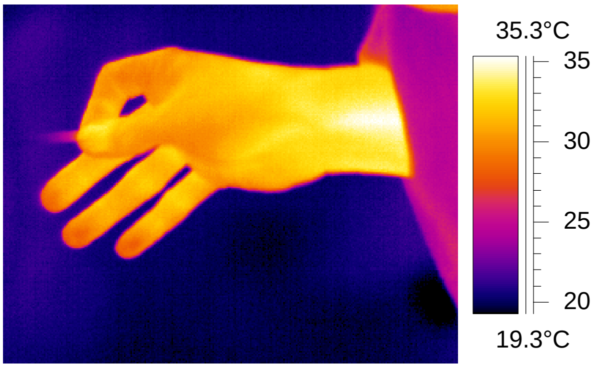


Figure 2.24 Thermographic image of a hand.

The second method used a thermographic camera to take a photo of each subjects' hand. The temperature recorded with this method was the true surface temperature. Further, the temperature distribution across the hand could be evaluated. The camera used was a Agema 570, PAL version. No filters were used with the camera.

The purpose of measuring the fingertip temperature was correlating the temperature with the performance. As has been established by Wyon (1996), the fingertip temperature can be used as an indication of the thermal sensation. It also has a direct impact on the dexterity of the fingers, which in turn has an impact on the performance in such tasks as text typing (Imamura 1998).

2.7.3 Subjective Measurements

During the experiments, the subjects filled in a number of questionnaires. All questionnaires can be seen in appendix M. The questionnaires were in Danish, and have not been translated.

The scales used for the assessments are seen at Figure 2.25.

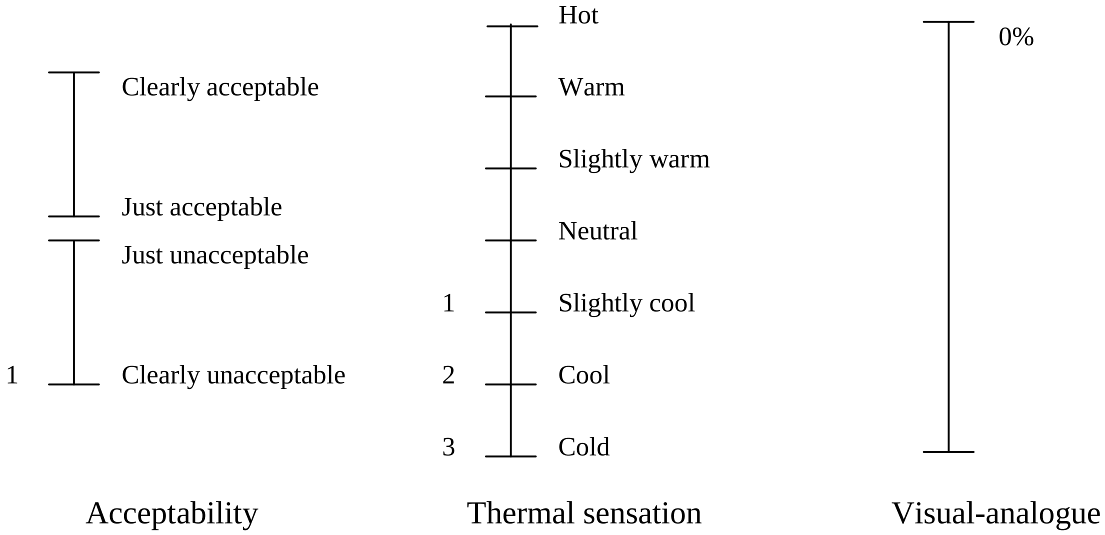


Figure 2.25 The scales used for acceptability, thermal sensation and visual-analogue votes.

The coding of the scales is seen at the figure.

From the mean acceptability score, the percentage dissatisfied (PD) was calculated (Gunnarsen and Fanger, 1992):

$$PD = \frac{\exp(-0.18 - 5.28 \cdot ACC)}{1 + \exp(-0.18 - 5.28 \cdot ACC)} \cdot 100\%$$

The correlation between acceptability and percentage dissatisfied was based on data from air quality assessments. When calculating the percentage dissatisfied from mean acceptabilities of other parameters, the above correlation was not used. Instead the percentage of the votes in the range of –1 to 0 was determined; this percentage was used as the percentage dissatisfied with all other parameters than air quality.

The visual-analogue scale is a horizontal line 105 mm long with no other marks but the two end points. Each end of the line contains a statement. The subject indicates to which extent he agrees to the statement.

Entrance Questionnaire

The subjects filled out the entrance questionnaire while they were waiting to enter the office. It contained questions about their hygiene and activities prior to arriving at the Centre. It also had a section regarding the subjects clothing, in which they made a detailed description of the clothes they wore upon arrival. The subjects were told to wear winter clothes, and to wear similar clothes at every appearance.

Air Quality Assessment Questionnaire

As the first thing upon entering the office in the beginning of the exposure, the subjects assessed the air quality using the acceptability scale. Before entering the office they spent approximately one minute in the corridor outside the office to refresh their senses.

At the end of the exposure, the subjects assessed the air quality again. They first left the office, and spent approximately 2 minutes in the corridor to refresh their senses, upon which they re-entered the office and assessed the air quality.

Air quality was also assessed on the questionnaires regarding thermal sensation, as will be described below.

Thermal Comfort Questionnaire

The thermal sensation, acceptability of thermal sensation and air quality were assessed six times during the exposure. The air quality was assessed using the same scale as for the dedicated air quality assessments.

The thermal sensation was rated on the thermal sensation scale. An assessment was made for 11 individual body parts, and for the body as a whole. The 11 body parts were: Head, neck, face, shoulders, arms, hands, back, loin, thighs, shins and feet.

Thermal acceptability was assessed on the acceptability scale, which rates the sensation as being either between clearly acceptable and just acceptable or between clearly unacceptable and just unacceptable. The thermal acceptability was assessed for the same 11 body parts as the thermal sensation, and for the body as a whole.

Comfort Questionnaire

After approximately an hour and a half the subjects filled in a 3-page questionnaire covering several aspects of the indoor environment.

The intensity of the smell in the room was assessed, as well as the irritation of eyes, nose and throat. Visual-analogue scales (VA-scales) were used to assess four general indoor environment parameters: dryness of the air, stuffyness of the air, lighting level and noise level.

Visual-analogue scales were also used to assess the following symptoms or perceptions: nose dryness, throat dryness, eye dryness, headache, difficulty in thinking, dizziness, tiredness, difficulty in concentration and sleepiness. A VA-scale was also used to assess the immediate work ability.

The subjects indicated if they felt any air movement. In case they did, they would rate the air movement on an acceptability scale.

The subjects were asked to imagine that they in their daily work were exposed to a noise level corresponding to the one in the office, and to rate this on the acceptability scale.

Similarly, they were asked to imagine that they in their daily work were exposed to an indoor environment corresponding to the one in the office, and to rate this on the acceptability scale.

Exit Questionnaire

The last questionnaire contained questions regarding the additional clothes supplied to the subjects. These were a fleece jacket, leg warmers and socks.

The subjects first indicated for how much of the time they had used the additional clothing. If they were wearing the fleece jacket at the time they filled in the questionnaire, they were asked to indicate if it was open or closed and whether the collar was up or down. They would similarly indicate how much of their legs were covered by the leg warmers, if they were wearing these.

During the exposure, the subjects estimated their performance on a VA-scale, and they could give their comments on any aspect regarding the office or the indoor environment that had influenced their performance or health during the exposure, either positively or negatively.

Post Experimental Questionnaire

After the end of the experiments, a questionnaire was sent to the subjects by email. They evaluated the experiments, and in particular how they had perceived the different temperature conditions in relation to their comfort and performance. The email is not found among the other questionnaires. The results from the questionnaire are found in appendix K.8.

2.7.4 Measurements of Performance

The performance of office workers doing their daily work is difficult to measure, as it is comprised of various individual tasks. A number of representative tasks were selected for use in the study, based on the experiences from earlier studies (Wyon et al., 1975; Langkilde, 1973; Witterseh, 2001).

Four versions of each task were prepared, and the tasks were randomised so that each subject only solved each task once, and so that all four tasks were used during each exposure. The tasks were of equal length and difficulty. The tasks were not made for this study, as tasks from a previous study were available (Witterseh, 2001). It was checked, that the subjects participating in the present study had not participated in the study by Witterseh.

The tasks were presented to the subjects on paper with print on both sides. On the first page, each subject filled in their name, unique test person number, date and a code identifying the task they were solving. The experimenter gave the code to the subjects prior to starting the task. The following page contained an instruction on how to solve the task, with examples where appropriate.

Multiplication

The objective of the multiplication task was multiplying two 3-digit numbers. The numbers were generated at random and contained no zeros. The numbers were printed in two columns, with sufficient room below each problem for the subjects to solve the problem.

Two measures of performance were derived: number of problems solved per unit of time and the number of errors divided by the number of problems solved (the error ratio).

$$\begin{array}{rr} & 475 \\ \text{X} & 987 \\ \hline \end{array}$$

Figure 2.26 Example of multiplication task

Subjects were expected to be unaccustomed with solving multiplication problems by hand, as the use of electronic calculators was becoming common practice. It was therefore expected that the subjects improved their performance from one exposure to the next, but that they would only solve a modest number of problems. The multiplication task was therefore used as the first task during the exposures, and mainly intended to tire the subjects in order to moderate their motivation level (Wyon, 2001).

Proof Reading

Four texts were selected from a Danish popular science magazine, and retyped. They were printed on paper using double line spacing for increased ease of reading. Four categories of errors were inserted in the texts, averaging one error per four lines. The errors were evenly distributed among the following four categories:

Type 1: Misspellings. The errors occurred as single words in ways that often occur. The errors and misspellings were obvious and did not require the subjects to be good at spelling.

Type 2: Grammatical errors that in the context of the phrase were obvious – e.g. verbs conjugated incorrectly.

Type 3: Grammatical errors which could be correct in the immediate phrase, but wrong in the wider context of the text that preceded – e.g. verbs in the wrong tense or incorrect personal pronouns, for example he for she.

Type 4: Contextual errors, grammatically correct but factually or logically wrong in the context of the preceding text.

The subjects were asked to highlight the words that were wrong, but not to enter the correct spelling or conjugation. Two measures of performance were derived: number of lines read, and the fraction of errors found in the part of text that had been read (the error ratio).

Addition

The objective was to add five 2-digit numbers. Again, random numbers without zeros were used. The numbers were printed in columns, and the subjects would add the numbers and print the answer below each column.

Two measures of performance were derived: number of problems solved per unit of time and the number of errors divided by the number of problems solved (the error ratio).

$$\begin{array}{rr} & 45 \\ & 65 \\ & 83 \\ & 25 \\ + & 54 \\ \hline \end{array}$$

Figure 2.27 Example of addition problem

Text Typing

The texts were selected among articles from a Danish popular science magazine. The texts were printed using triple line spacing for increased ease of reading. The subjects would type the texts into a word processor on a PC exactly as it appeared on paper. The text was not formatted in any way, only typed. The word processor used was MS Word version 6 without the spell checking feature.

Two measures of performance were derived: number of characters typed per unit of time, and number of errors made per unit typed (the error ratio).

2.8 Procedure

The subjects were exposed four times each, according to the experimental plan presented earlier. The first exposure functioned as a training session, during which the subjects became acquainted with the procedure, the tasks and questionnaires, the experimenters and the field laboratory.

2.8.1 Training Session

The purpose of the training session was to familiarise the subjects with the questionnaires and tasks, and the procedure in general. Several studies have shown significant adaptation and learning to occur during the first exposure (Wargocki 1998, Witterseh 2001). The training session was basically an ordinary session from which the results from tasks and questionnaires were not be included in the analyses. The subjects were not informed about this, and believed it was an ordinary session.

The procedure of the training session was identical to that of the ordinary session, except that the length of each task was reduced. This was done so that there was time to make a general presentation in the beginning of the session, and to make an individual interview at the end of the session.

The first half hour of the training session was used to give the subjects a presentation of the Centre, the experiments and the subjects’ role in them. They had already received an email covering many of the issues, that were repeated in the introduction. The purpose of the experiments was not explained to the subjects, but they were of course aware that they participated in indoor environment experiments and could only be exposed to conditions as could be found in a real building.

They were also made aware that the output of the tasks they were going to solve would be measured in some way, and they were encouraged to perform the tasks to the best of their abilities; for this a bonus of 200 kr. was offered to those of the subjects that also participated in all four exposures. The importance of participating in all exposures was explained. It was made clear that the experiments played an important role in the authors’ Master Thesis project. This was done to instil a sense of responsibility in the subjects.

The subjects were instructed to do their normal routines in the day prior to the exposures, but to rest well the night before and to have eaten before arriving to the experiments. They were encouraged not to wear strong perfume, because perfume could have an impact on the air quality evaluations.

The importance of clothing was explained, and it was made clear that the experiments would be conducted in a typical office environment, but that it would be cooler than in a typical office. It was stressed that they should appear wearing a heavy clothing ensemble suited for winter use. Such an ensemble was presented in Table 2.5. They were asked to wear the same clothes at all exposures, and if impossible, to wear similar clothes. At each exposure they would fill in a questionnaire describing their clothing. A photo was also taken of each group before each exposure, so that the experimenters could check the questionnaires with the photos, if a misunderstanding or neglection was suspected.

At the end of the training session, during the text typing task, an interview was made with each subject. The interview concerned the session and the physical environment. The conditions were not discussed, and it was made sure that the subjects were not aware to which conditions they were exposed. The interviews revealed, among other things, that one of the keyboards used was very poor. The interviews were recorded with the acceptance of the subjects.

2.8.2 Experimental session

The time-course of the experimental sessions is shown at Figure 2.28.

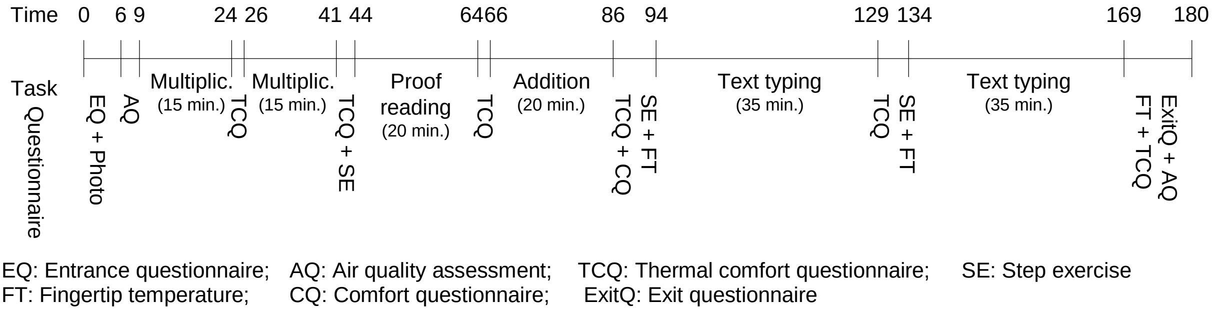


Figure 2.28 The schedule for the experimental session.

As the subjects arrived for the experiments, they would wait for the start in a meeting room. While waiting in the meeting room, they filled in the entrance questionnaire.

When all subjects had arrived, the 3-hour exposure started by taking a group photo, whereupon the group of four subjects proceeded to the field laboratory. Upon entering, they assessed the air quality. This was done after they had inhaled a few times, and before they seated themselves.

During the exposures they solved the performance tasks, and filled in questionnaires at given intervals. Each task was timed, so that it would last the designated time, and no longer. The subjects would start on the signal of the experimenter, and end likewise. The questionnaires were not timed, but sufficient time was allocated for a thorough completion.

The tasks were completed in the following order: multiplication, proof reading, addition and text typing, so that arithmetic and word-related tasks were mixed. At six points in time, the subjects filled in the thermal comfort questionnaire, which was used to adjust the radiant panel temperature for each subject.

Approximately halfway through the session, the comfort questionnaire was filled in. Three times during an exposure, the subjects walked across 2 steps. This simulated the walks to the coffee machine or photocopier, which are typical for the office worker. It had the purpose of increasing the subjects’ activity level to match the 1.2 met assumed for office work.

Fingertip temperatures were measured three times during the exposure, before, during and after the task typing task.

At the beginning of sessions under the cold conditions, the subjects were asked to put on the fleece jacket and leg warmers. They were instructed to keep on these additional pieces of clothing for at least half an hour; after half an hour, their level of activity was expected to have stabilised and they were adapted to the thermal environment. They were encouraged to adjust their clothing throughout the exposures, with the purpose of obtaining thermal comfort.

Biscuits and water were available for the subjects during the experiments. No other food or beverages were allowed, as it could influence the air quality assessments.

The subjects were not allowed to leave the office during the experiments, unless they needed to go to the restroom. They were not allowed to talk during the exposures, and were encouraged not to discuss the experiments before or after the exposures.

At the end of the exposures, the subjects left the field laboratory and stayed in the corridor for approximately 2 minutes to refresh their senses. They re-entered the office, and assessed the air quality immediately thereafter. The air would now be polluted with bioeffluents, as opposed to the first air quality assessment.

2.9 Statistical Analysis

The method of statistical data analysis of experimental data will be described and discussed. The discussion is based on concrete statistical problems encountered in this study.

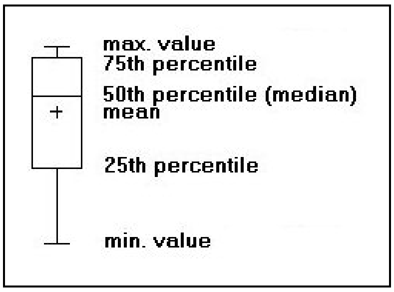
The data collection methods and their constraining effect on the use of statistical analysis will be briefly described. The choice of analytical method is very important to prevent incorrect conclusions to be drawn. This applies both to the strength of the statistical test and to the fulfilment of its requirements. The following questions must be addressed to perform a statistical analysis.

1. Are the data independent or dependent?
2. What type of data (nominal, ordinal etc.)?
3. What type of scale (open-end or closed-end)?
4. What type of distribution (normal, binomial etc.)?
5. Is the variance homogenous between data sets?

When these questions have been answered, a proper statistical analysis can be chosen. Statistical tests are typically grouped in two main categories, namely parametric and non-parametric. Parametric tests are generally stronger than non-parametric tests, but do also pose more strict requirements to the data than non-parametric tests.

In the following each of the above questions will be addressed, and at the end a flow chart will summarise the statistical data analysis used for this study. The appropriate statistical tests will be introduced along the way.

To get an overview of data sets it is often helpful to graph with so-called box plots, which contain information of the mean and the distribution (see box plot legend on the right).



2.9.1 Independent Data

A fundamental requirement for statistical analyses is stochastic variables, i.e. independent data. Some of the data was collected with questionnaires used several times during the 3-hour exposure. Collectively the data are not stochastic, because the subjects may remember and vote according to the preceding questionnaire of the same type. This applies to the thermal comfort questionnaire, which was given six times during the exposure. Thus, only data obtained within each questionnaire can be classified as stochastic.

2.9.2 Data Type

Different types of data require different statistical treatment, as shown in the table below.

Table 2.9 The four main classifications of data types with specification of appropriate statistical test type.

	Data types	Description	Appropriate statistical test
1.	Nominal	Data falling in categories, e.g. “male” and “female”	non-parametric
2.	Ordinal	Data falling in inter-related categories, e.g. “slightly hot” < “very hot”	non-parametric
3.	Interval	Data with distances between them, i.e. data on a continuous scale	parametric
4.	Ratio	Data with distances between them and with a true zero point, so the ratio can be calculated	parametric

The numbered order of the data types in Table 2.9 follows the increasing strength of the statistical test that can be applied to them The strongest statistical tests are thus found for ratio data, but interval data can also fulfil the requirements for parametric tests. It is often self-evident what classification the data belong to. The majority of the data coming from the questionnaires has been marked on continuous scales spanning between two extreme values, e.g. “too noisy” and “too quiet”. The data from these closed-end scales have been statistically treated as interval measurements despite the confined scale (see Scales for Data Collection, below). The scale for thermal sensation belongs to the group of closed-end scales, which are classified as interval measurements. However, unlike the other scales, the thermal sensation scale has been sub-divided with markers of ordinal character. The ordinal character of the scale is reflected in the data, which showed a slight tendency to collect around the markers (for scales, see Figure 2.25). The tendency of ordinal distribution was small enough not to affect the analysis significantly, so the data kept their interval classification.

2.9.3 Scales for Data Collection

The data relating to air quality, comfort and health symptoms were all collected on closed scales. Statistic treatment of data collected from closed-end scales can be troublesome if a) the data collects in the far end or if b) the scale is not perceived to be increasing linearly. For example, votes cast on a 0-100% scale are likely to follow a binomial distribution and not an expected normal distribution – especially in the regions 0-30% and 70-100% (Zar, 1999). A normal distribution can be obtained through data transformation, as will be discussed.

Comparison of data, which is constrained by the scale, is troublesome. To give an example, imagine a subject, who evaluates an air quality to be “clearly acceptable” (the highest score on the acceptability scale) and later is exposed to an even better air quality. The scale refrains the subject from giving a better air quality vote the second time. Thus, comparison of data from closed scales like the acceptability scale may be untruthful. Moreover, statistical analysis of constrained data is troublesome but can be accomplished with proper data transformations (see page 38).

2.9.4 Normal Distribution

Many statistical tests require that the data follow a specific distribution or that the distribution of two data sets is identical. The likely distribution for the data is most often self-evident. For this study, it was expected that all interval measurements (scale voting, performance, error rate etc.) would follow a normal distribution, since the data was expected to be distributed evenly around a mean value.

The test for normality is done with Shapiro-Wilk's *w*-test. For this study the statistical software SAS is used to perform Shapiro-Wilk's *w*-test on the residuals generated by a general linear model (GLM). Further discussions of checking the residuals instead of the data for the normal distribution is found in appendix D.

When using a GLM, the requirement for normal distribution is not so strict. Thus, the test criterion for Shapiro-Wilk's *w*-test is set to the 10%-level ($p<0.10$) and not to the conventional 5%-level. In supplement to Shapiro-Wilk's *w*-test, the data was examined for normal distribution by visual evaluations of residual and quantile plots. The quantile plot also helped to identify abnormal data (outliers). See appendix D for details. However, the objective Shapiro-Wilk's *w*-test was used as the principal indicator for normal distribution. Though identified, no outliers were removed.

2.9.5 Homogeneous Variance

Many statistical tests – and especially the GLM – require that the data sets be of homogenous variance. Bartlett's test is used at the 10%-level to test for homogeneous variance. The test is very sensitive to data that diverge from the normal distribution, wherefore Bartlett's test may reject homogeneous data on the basis of approximate normal distribution (Conradsen, 1995). No better alternative test to Bartlett's test was found.

In the present Thesis, Bartlett's test was performed with SAS, in such a way that the result of the test is 1-p. Thus, $p<0.90$ indicates that homogenous variance is found at the 10%-level.

2.9.6 Transformations

Insofar data does not fulfil the requirements for normal distribution and/or homogeneous variance it can sometimes help to transform the data. If the transformed data met the requirements the subsequent statistical analysis must be carried out on the transformed data. The most common transformations used for this study were log and reciprocal transformations. Data with binomial tendencies or collecting in the far end of a scale were in some cases subjected to an arcsine transformation (Zar, 1999).

2.9.7 Parametric Test

It was initially tried to analyse the data with a strong parametric test, namely with a general linear model (GLM). The GLM requires data to be normally distributed and to have homogeneous variance. Further requirements are that arithmetic rules can be applied to the data and that the observed effects are additive.

The input to the GLM consists of one or more explanatory variables and one or more response variable, as discussed in appendix D. The GLM takes missing data and unbalanced designs into account, and can also handle blocked data and nested variables. In supplement to the main effects, the GLM is able to compute all the inter-factorial interactions on two or higher levels.

2.9.8 Non-Parametric Test

Data, which could not fulfil the GLM-requirements of normal distribution and homogeneous variance, were subjected to non-parametric t-testing of lesser statistical strength. The reason being that a t-test analysis does not account for all the inter-factorial variations, as only two data sets are compared. The t-test utilises the plain observations from two data sets. Both simple and paired t-tests require data sets of homogeneous variance. Most often this is not fulfilled, as the data would otherwise have to be tested with a GLM. Thus, the data was tested with an estimated t-test, which is based on a Satterthwaite estimation of the degrees of freedom. The estimated t-test was chosen, as it generally is stronger than other non-parametric tests.

Further discussions of non-parametric tests are found in appendix D. The estimated t-test is computed with the SAS-software.

2.9.9 Flow Chart

The statistical tests and their respective requirements have been accounted for above. Data that fulfil both the homogeneity of variance criterion and the normal distribution criterion can be tested using a GLM, whereas data without homogeneity of variance must be analysed with an estimated t-test. A graphic illustration of the decision process for the statistically data analysis of this study is found in the flow chart below.

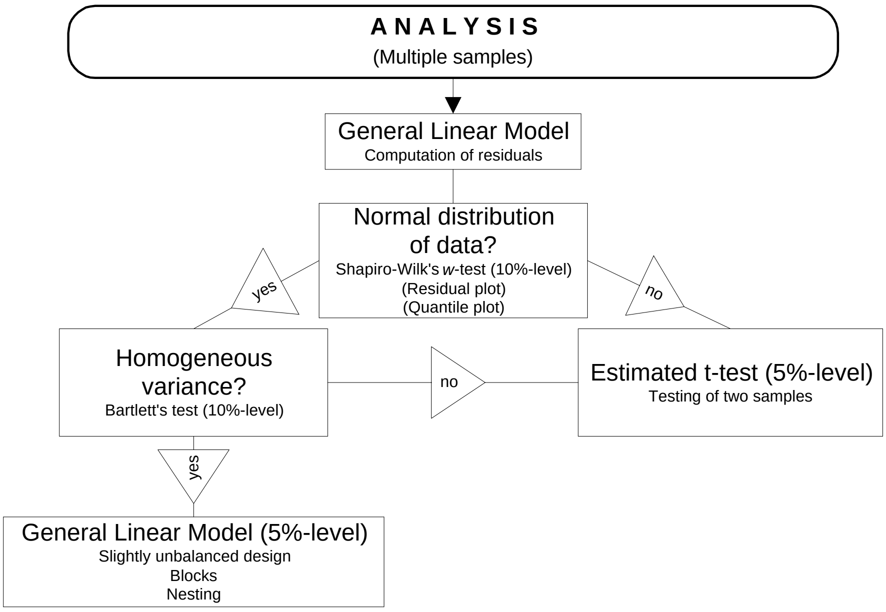


Figure 2.29 Flow chart of statistical test procedure for experimental data. The test types, names and significance levels are given.

The empiric statistical principles have been presented above. In practise, statistical data treatment is a dynamic process rather than a strict objective methodology. For example, determination of the data distribution demands a visual interpretation of residual and quantile plots, an identification and elimination of outliers and/or suggestions for appropriate data transformations. For this study, however, the data analysis was primarily based on the use of objective tests.

3 Results

Each of the 28 subjects participated in the 4 scheduled exposures. The experiments were conducted successfully.

The results from the experiments were collected from the questionnaires and tasks filled in by the subjects. All results were manually typed into an Access database for data treatment in, primarily, the SAS system for statistical analyses. A check was made of all questionnaires and tasks, to ensure that no mistakes had been made when typing in the results. A sample SAS program used for the analysis is found in appendix D.

The data have been analysed for effects of the main parameters: thermal comfort, air quality and air temperature. The three experimental conditions conformed and two-factor incomplete factorial design. Thus, combined effects of temperature and air quality could not be found.

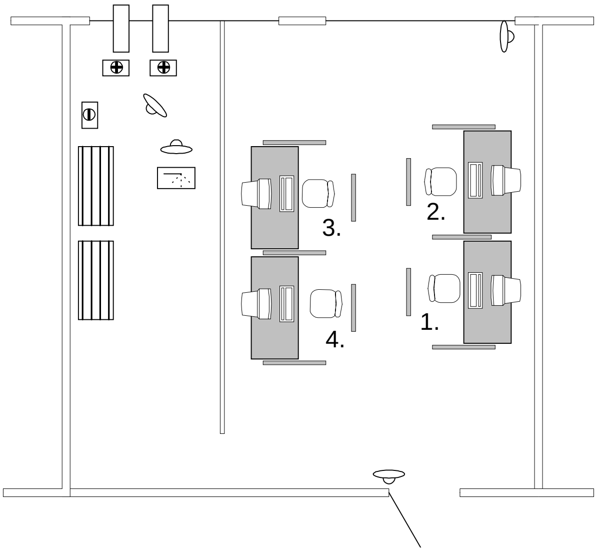


Figure 3.1 *Physical layout of the field laboratory. The workstations were numbered 1 to 4 anticlockwise from the workstation on the right from the door.*

The field laboratory as it appeared to the subjects is shown at Figure 3.2 below.

Figure 3.2 Photo from an experimental session.

More photos from the experiments are found in appendix J.

3.1 Physical Measurements

This section presents the physical measurements made during the experiments. These include temperature, humidity, air change rate, air velocities, noise and fingertip temperature.

References to the field laboratory are made throughout the section. Figure 3.1 below shows the field lab with dimensions and the numbering of workstations from 1 to 4.

Table 3.1 below contains a summary of the physical measurements that will be described in further detail in this section.

Table 3.1 Physical measurements for each of the three experimental conditions.

		23°C, no source	18°C, no source	18°C, source
Air temperature	[°C]	23.1 ± 0.42	18.0 ± 0.47	18.0 ± 0.51
Absolute humidity	[kg/kg]	0.0052 ± 0.00044	0.0043 ± 0.00026	0.0040 ± 0.00027
Relative humidity	[%]	30 ± 2	34 ± 2	31 ± 2
Enthalpy	[J/kg]	36 ± 1	29 ± 1	28 ± 1
Ventilation rate†	[l/s/person] [h^{-1}]	44 ± 4 5.8 ± 0.5	42 ± 2 5.6 ± 0.3	43 ± 2 5.8 ± 0.3
CO_2‡	[ppm]	568 ± 25 (426 ± 6)	550 ± 25 (458 ± 26)	546 ± 28 (482 ± 39)
Air velocity ††	[m/s]	0.10 ± 0.04	0.22 ± 0.12	0.22 ± 0.12

† Measured either before or after the experimental session, using the concentration decay method with SF_6 as the tracer gas.

‡ Supply air CO_2- concentrations in parentheses. Data unavailable from a minority of sessions.

†† Air velocities measured once at the reference condition, and once at the 18°C condition.

3.1.1 Temperatures

Air temperatures were measured close to the breathing zone of the subjects at 30-second intervals during the experiments. Table 3.2 below provides an overview of the temperatures at each condition and workstation. The values in the table exclude both the first and the last quarter of an hour of the exposure, as the subjects were not sedentary in the workstations at these times, but moving in and out of the room.

Table 3.2 Air temperatures measured in the breathing zone of each workstation. The values are mean values of the continuous temperature measurements starting from 15 minutes after the formal start of the exposures, and ending 15 minutes before the formal end of the exposures.

Air temperature ± SD [°C]	23°C, source absent	18°C, source absent	18°C, source present
Workstation 1	22.8 ± 0.4	17.7 ± 0.4	17.7 ± 0.5
Workstation 2	22.9 ± 0.3	17.8 ± 0.4	17.9 ± 0.5
Workstation 3	23.3 ± 0.3	18.3 ± 0.3	18.3 ± 0.4
Workstation 4	23.4 ± 0.3	18.3 ± 0.4	18.3 ± 0.4
Average	23.1 ± 0.4	18.0 ± 0.5	18.0 ± 0.5

The target temperatures were held at all conditions for the field lab as a whole. A systematic difference in temperatures between workstations is noticed; the mean temperature is lowest in workstation 1 and highest in workstation 4.

The standard deviations indicate that the temperatures were not kept completely constant through the exposures. The target temperatures were, however, representable of the actual conditions, as the deviations represent mainly fluctuations rather than trends toward rising or falling temperatures during the exposures. A small rise, however, was observed towards the end of the 18°C conditions. Figure 3.3 below shows mean air temperatures from all workstations at each of the three conditions. Appendix K.1.1 contains figures showing the time-course at each workstation.

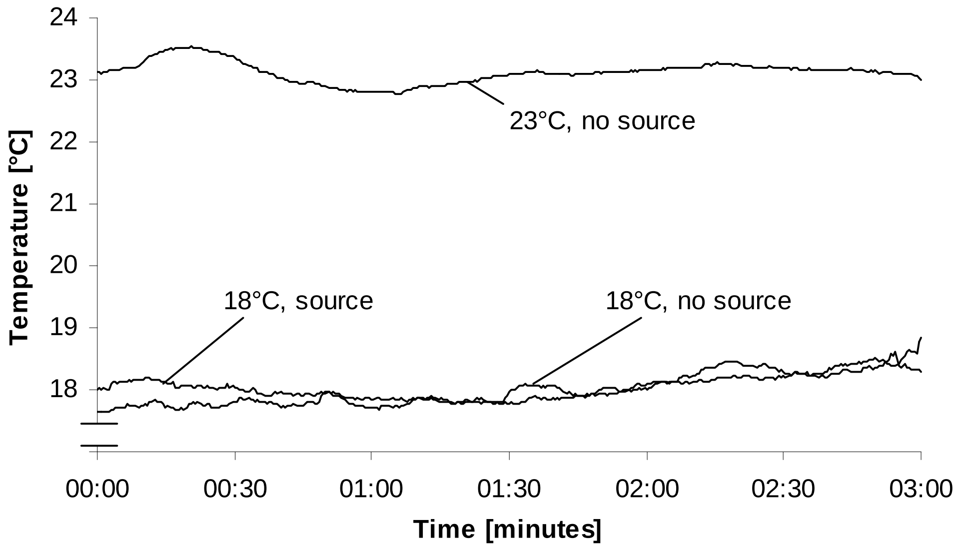


Figure 3.3 Average air temperatures for all workstations at each condition.

Operative temperature was calculated with the HP-Vee data logging software continuously during the experiments, based on the surface temperature of the panels and the room surfaces.

No target value was used with the operative temperatures, as these were adjusted according to the preferences of the subjects. Personal preferences differed as expected, so little homogeneity in the operative temperatures was observed.

The temperature of the radiant heating panel installed under the table was also adjusted in order to achieve thermal comfort for the subjects. The preferred temperature varied considerably between occupants. The table panel surface temperature was not included in the calculation of the operative temperature.

Table 3.3 below summarises the average operative temperatures and the average temperature of the table panel at each condition.

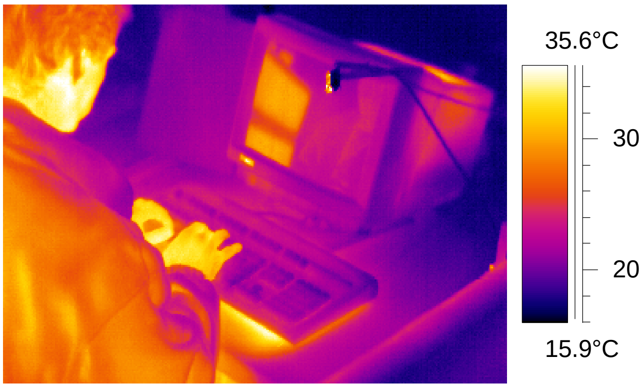


Figure 3.4 Thermographic image of subject performing the text typing task. The heated tabletop below the keyboard is seen.

Table 3.3 Average operative temperature and average table panel surface temperature, as measured during each condition.

	23°C, source absent[†]	18°C, source absent	18°C, source present
Operative temperature ± SD [°C]	22.4 ± 0.4	20.9 ± 0.6	20.6 ± 0.8
Table panel surface temperature ± SD [°C]	26 ± 1	44 ± 5	42 ± 4

[†] The table panel was not used at the reference condition.

At the reference condition (23°C, no source) the temperature of the table panel was 26°C at average, which was about 3°C higher than the air temperature at this condition. The difference was explained by the plume of warm air that rose from the legs of the sedentary subject. The thermistor that measured the table panel temperature was located below the panel, where a thin layer of warmer air could be upheld.

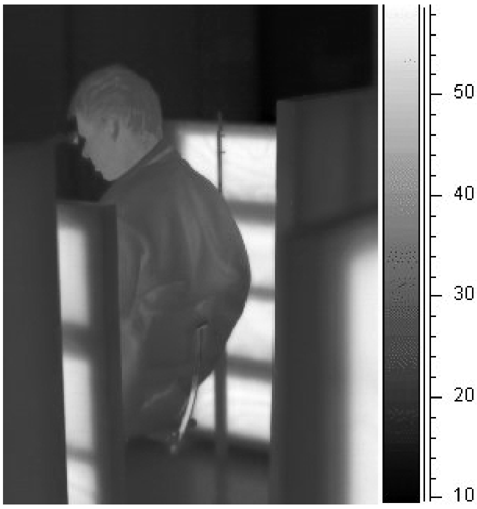


Figure 3.5 Subject at work. The radiant panels are clearly visible.

3.1.2 Humidity

The relative humidity and temperature of the room air was measured at one central point in the room. Only small differences in the humidity level throughout the room can occur as a result of non-perfect mixing. The absolute humidity level was therefore calculated based on this measurement.

Table 3.1 above summarised the absolute humidity levels for each condition, along with the workstation average relative humidity. The relative humidity was calculated using the average air temperature in the workstations (Table 3.2).

The target absolute humidity level was 0.0042 kg/kg. It is noted, that the humidity level at the 23°C condition was somewhat higher than the target. This was a result of the warm weather during the experiments, which caused the supply air to exceed the target humidity level.

3.1.3 Air Change Rate

The air change rate was measured using the concentration decay method with SF_6 as the tracer gas. Measurements were made before, between or after a set of two sessions. Measurements were made on most, but not all days. Little deviation was expected between sessions. As SF_6 is a strong greenhouse gas, it was decided to limit its use. Table 3.4 below shows all measured air change rates during the experimental period.

Table 3.4 All measured air change rates. "Before" indicates a measurement before the first session on a day, and "After" indicates a measurement performed after the last session on a day.

Air change rates [h^{-1}]											
Session	3 & 4	9 & 10	11 & 12	13 & 14	15 & 16	19 & 20	21 & 22	23 & 24	25 & 26	27 & 28	Mean
Before	5.7	4.8		5.7							5.4
Between			5.8			5.8	5.8	5.6		5.7	5.7
After	5.8	5.5			6.0				5.9		5.8
Mean											5.7

It is seen that there were little deviations between the measured air change rates. The mean value was 5.7 h^{-1}.

3.1.4 Air Velocities

The same ventilation rate, fans and other relevant equipment were used at all conditions. The air velocities were measured once at the 23°C condition, and once at the 18°C condition. Air velocities and standard deviations were measured in each workstation, and at 0.2 m, 0.6m and 1.1m above the floor. The measurement at ankle height was incorrectly made at 0.2m instead of 0.1m as prescribed by the standards. The measurements were made 15 cm from the table, as shown on Figure 3.6 below.

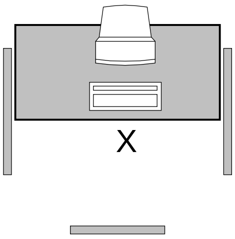


Figure 3.6 The measuring point for the velocity measurements.

The measured air velocities are shown for each temperature condition at Figure 3.7 below. Values are found in Appendix K.1.2.

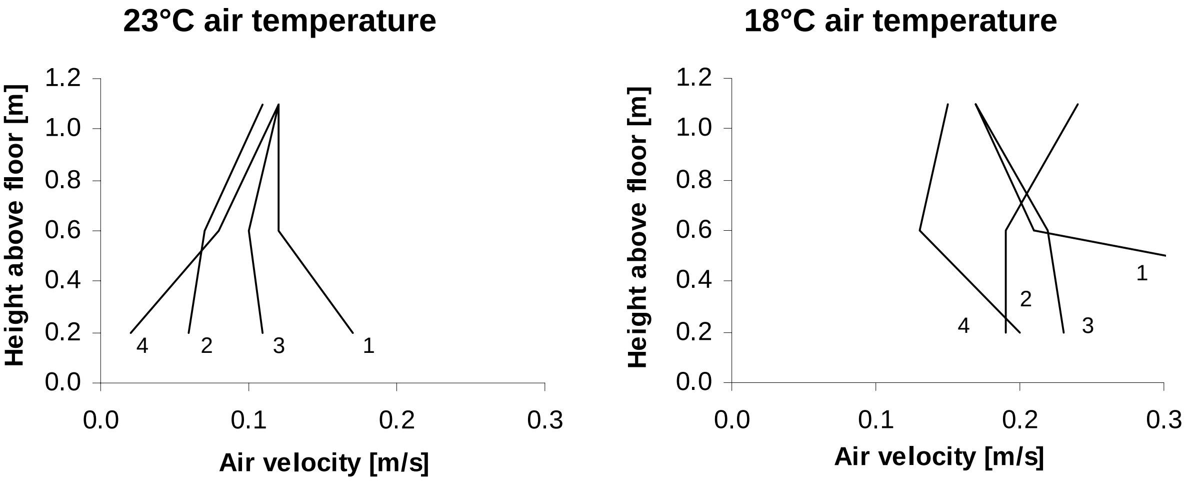


Figure 3.7 *Velocities measured in each workstation, and at three different heights. The numbers refer to the workstations.*

It is noted that the air velocity at 0.6m and 1.1m was similar in the different workstations, but that the velocity at 0.2m varied greatly, and that it at particularly station 1 and 3 was very high. Average velocities, standard deviations and calculated draught ratings are shown at Table 3.5 below.

Table 3.5 *Measured air velocities, standard deviations and draught ratings. Velocities and standard deviations were measured with the B&K 1213 over a 3-minute interval.*

	23°C			18°C		
Workstation	Air velocity [m/s]	St. dev. [m/s]	DR† [%]	Air velocity [m/s]	St. dev. [m/s]	DR† [%]
1	0.14	0.03	15%	0.32	0.23	69%
2	0.08	0.03	6%	0.21	0.03	34%
3	0.11	0.01	10%	0.21	0.03	32%
4	0.07	0.05	9%	0.16	0.04	26%
Average	0.10	0.04	10%	0.22	0.12	40%

† *Calculated as* $DR = (34 - T_a)(v - 0.05)^{0.62}(0.37 \cdot v \cdot Tu + 3.14)$ *as prescribed by ISO 7730. Tu is the turbulence intensity of the air, which is the standard deviation of the air velocity divided by the air velocity.*

A difference in magnitude of the air velocity is noted between the conditions. The velocity was considerably higher at the 18°C conditions than at the 23°C condition. The draught ratings indicated that a high percentage of the subjects would be dissatisfied due to draught: 40% at the 18°C conditions, and 10% at the 23°C condition.

3.1.5 Noise

The sound pressure level was measured at several occasions in the field lab. It was found, that the background level was constant through the exposure and independent of all such factors as temperature, pollution source and time of day.

The sound pressure background level was primarily comprised of the noise from the axial fans installed in the technical zone. Also the mixing fans in the technical zone contributed to the background level, as did the mixing fans in the occupied zone. The individual contribution of these factors was not investigated, as they were in constant operation at all conditions.

The measured sound pressure during an exposure is shown at Figure 3.8 below.

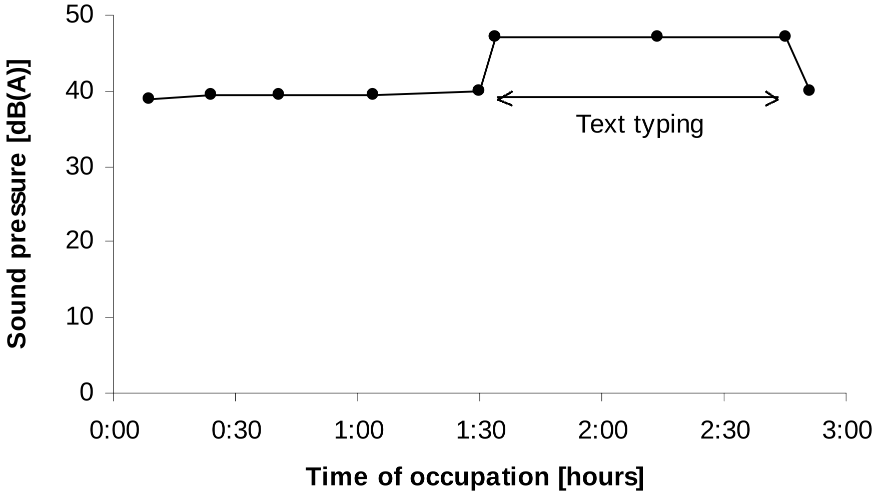


Figure 3.8 Measured sound pressure level in the field lab during exposure. The markers on the plot indicates measurements, as the sound pressure level was not measured continuously.

The sound pressure was approximately 39 dB(A) through the first part of the exposure, during which the subjects solved tasks or filled in questionnaires using pen and paper. The subjects themselves did not cause a significant rise in the sound pressure level.

As the subjects commenced the text typing task, the noise level was raised to approximately 46 dB(A). The rise was attributed the noisy keyboards.

It is noted that the design criteria stated in CEN CR 1752 is 40 dB(A) for a type “B” classification, and 45 dB(A) for a type “C” classification.

3.1.6 Fingertip Temperature

Table 3.6 below presents the mean measured fingertip temperatures for each condition.

Table 3.6 Measured fingertip temperatures for each condition.

	Fingertip temperature ± SD [°C]		
Time [min]	23°C, no source	18°C, no source	18°C, source
86	27 ± 6	27 ± 5	25 ± 5
129	28 ± 5	27 ± 5	26 ± 6
169	28 ± 5	28 ± 5	26 ± 5

Substantial differences between subjects were noticed, which is reflected by the standard deviations.

A statistical analysis was made to investigate whether the air temperature had had a significant impact on the temperature of the fingertip. The requirements for using a general linear model were not met, and an estimated t-test was used. This showed a significant difference between the reference condition and the 18°C condition without a source ($p<0.04$).

No difference was found between the reference condition and the 18°C condition with a source.

Though the mean values rose with time, no significant change of fingertip temperature was found with time. The fingertip temperature of the individual subject often changed between measurements. The rise or fall in temperature seemed not to follow any pattern.

Validation of Thermistor Measurements

The thermographic camera was used to verify the validity of the thermistor measurements. The thermographic camera presents a detailed image of the hand, from which temperatures in points, on lines or in areas can be returned. Figure 3.9 presents sample photos.

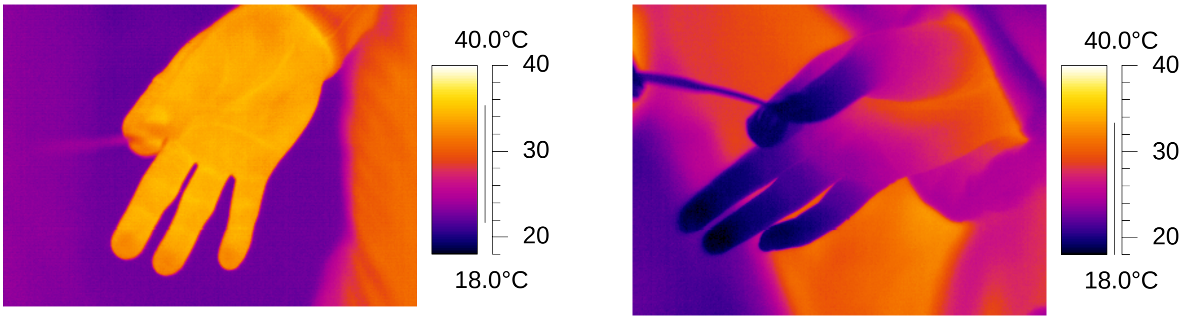


Figure 3.9 Sample photos of hands taken with the thermographic camera. The photos illustrate the wide range of temperatures observed during the experiments.

The images indicated that the temperature distribution varied between hands. The palm temperature was within the range of 25°C to 35°C, but the temperature of the fingers, and particularly the fingertips, was as low as 18°C for some subjects.

The images were taken of the palm of the hand of each subject, while the subject held the thermistor for the fingertip measurement. For the thermographic photos, the subjects presented their hands differently. For this reason, a systematic analysis of the photos was not possible; the same location for measuring the temperature was not available on all hands.

Instead the temperature closets to the point of the fingers holding the thermistor was read for a random selection of hands. Two groups were selected, and temperatures from both an 18°C condition and a 23°C condition were read. The detailed results are found in appendix K.1.3. They showed a fair correspondence between the two fingertip measurements, as seen in Table 3.7. .

Table 3.7 Difference between fingertip temperatures measured with thermistor and thermography. A positive number indicates that the thermographic camera returned a higher value.

Condition	18°C air temperature	23°C air temperature
Temperature difference [°C]	-0.29 ± 1	1.9 ± 3

The difference in fingertip temperature was smaller for the 18°C conditions, whereas the results from the 23°C condition showed a larger difference. The thermographically obtained results for the 23°C condition were systematically higher than those obtained with thermistor, which could be explained by a bad thermal contact between the fingers and the thermistor.

The fingertip measurements were done with a handheld, battery-powered meter that was validated several times during the experiments.

Temperature Distribution of Hand

It was investigated whether the temperature distribution was comparable between hands; this would indicate whether the fingertip temperature measured with the thermistor was a representative measure for the temperature of the entire hand, or whether the fingertips had a significantly different temperature than the rest of the hand.

This was done with the line analysis tool of the thermographic camera software. A line was drawn on the photo of the hand, and the software returned a temperature distribution. Figure 3.10 shows an example.

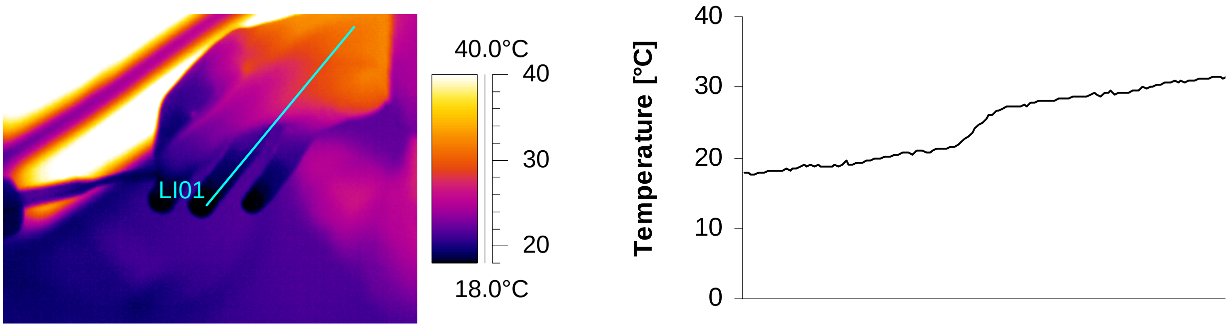


Figure 3.10 Temperature distribution of a hand at the 18°C condition. The graph to the right shows the temperature distribution of the line (LI01) shown at the hand to the left. Notice that the fingertip temperature practically equalled the air temperature; the temperature measured with the thermistor was 18.1°C.

The subjectively placed line at Table 3.9 gives a good impression of the temperature level across the hand. A group of 4 subjects was selected randomly for analysis; the results from 18°C and 23°C conditions were used. The distributions are seen on Figure 3.11.

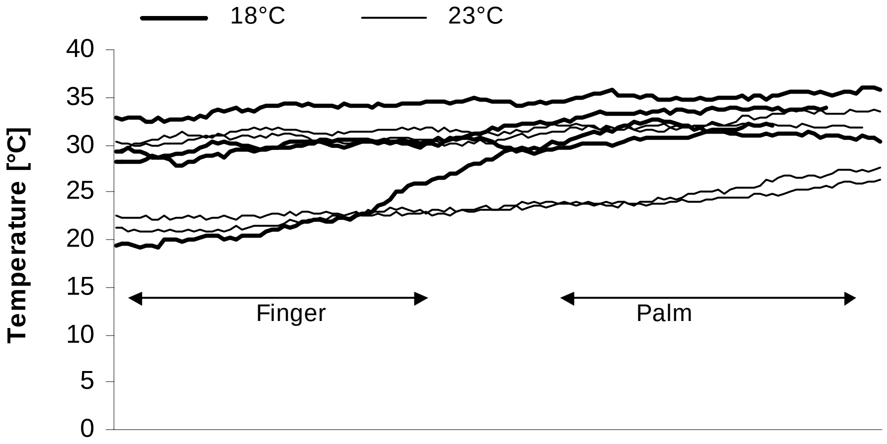


Figure 3.11 Temperature distribution of the hand temperature for a group of subjects. Results from two conditions are presented.

It was found, that the fingertip temperature in most cases followed that of the hand. In one of eight cases, the temperature of the finger was considerably lower than that of the hand. These findings corresponded well with a visual check of all thermographic photos. The finger temperature was generally lower than that of the hand. Roughly estimated, the palm temperature was 1-2°C higher than the fingertip temperature.

3.1.7 Summary of Physical Measurements

- The target air temperatures of 18°C and 23°C were obtained in a satisfactory manner. The temperature varied with time and between workstations, but not unacceptably.
- The humidity level was higher at the 23°C condition (0.0052 kg/kg) than the target level of 0.0042 kg/kg. The difference was caused by unexpectedly warm weather. The target humidity level at both 18°C conditions was obtained.
- The mean ventilation rate was $5.7h^{-1}$. As a consequence, the CO_2 level was low (550 ppm).
- The air velocities were different between the two conditions. On average 0.10 m/s at the 23°C condition, and 0.22 m/s at the 18°C conditions.

3.2 Clothing Insulation and Radiant Heating Panel Shape Factors Measured with Thermal Manikin

A thermal manikin was used to determine the clo-value of the office chair and the shape factors of the radiant panels. Moreover, the clo-value of a typical clothing ensemble for the 18°C condition was found. The clothing ensemble included the fleece jacket and the leg warmers, which were provided to the subjects during the experiments.

The clo-value computation required knowledge of the operative temperature, which required knowledge of the shape factors, which again required knowledge of the clo-value. Thus, the clo-values and shape factors had to be determined iteratively.

3.2.1 Clothing Insulation

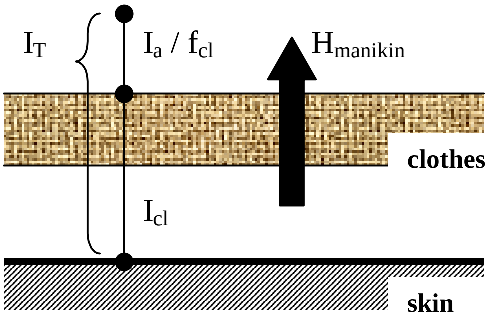
The clo-value was calculated according to Annex C of ISO 9920. In order to determine the clo-value of the chair, the measurements were performed on a seated manikin in one of the workstations, even though the standard suggests using a standing thermal manikin. The shape factor computation also required a seated manikin.

The clo-value was computed from the stabilised heat loss of a thermal manikin at steady-state conditions. The physical environment in the field lab could not be fully controlled (e.g. the temperature of the walls), thus reducing the accuracy of the results.

An air temperature of 22°C was chosen as this was most easily achieved and maintained. Air and surface temperatures in the room were recorded, and air velocities around the manikin were measured. The manikin software recorded the skin temperature and heat loss from each of the 16 body parts. Each body part of the manikin was controlled to obtain optimal thermal comfort in accordance with Fanger's comfort equation relating skin temperature (t_{skin}) to dry heat loss ($H_{manikin}$) from the skin (Melikov, 1999).

$$t_{skin} = 36.4 - 0.054 \cdot H_{manikin}$$

Different definitions of clo-values exist. The clo-value used here is I_{cl}, which accounts for the thermal resistance from the skin surface to the outside surface of the clothing. Figure 3.12 illustrates the relationship between the I_{cl} and the total thermal resistance (I_T), which includes the contribution from the surface resistance (I_a) corrected by a clothing factor (f_{cl}).



$$I_{cl} = I_T - \frac{I_a}{f_{cl}}$$

Figure 3.12 Thermal resistance values for clothed body. $H_{manikin}$ is the dry heat loss measured by the manikin, and f_{cl} is a clothing correction factor for the surface area (ISO 9920).

To determine separate clo-values for the clothing ensemble and the chair it was necessary to perform three steady-state measurements of the dry heat loss from the manikin.

a. Seated nude manikin for determination of the surface resistance (I_a). A wire chair was used not to affect the thermal resistance around the nude manikin body.
b. Seated clothed manikin in wire chair for determination of the thermal resistance of the clothing ensemble (I_{cl}).
c. Seated clothed manikin in office chair for determination of thermal resistance of the chair.

The total thermal resistance (I_T) and the surface resistance (I_a) are determined from the operative temperature (t_o) and from the manikin measurements of dry heat loss ($H_{manikin}$) and mean skin temperature ($\bar{t}_{skin}$). The operative temperature (t_o) was calculated on the assumption of a 0.2 shape factor between the manikin and radiant panels. The iterative process for determination of the shape factors and thus the operative temperature is described in appendix F. Even though the radiant panels were turned off for the clo-experiments, the table panel still had an effect on the operative temperature, as its temperature was approximately 7°C higher than the ambient temperature due to convective heat from the thighs (Table 3.12). Below are the equations for the total thermal resistance (I_T) and the surface resistance (I_a) (ISO 9920).

Figure 3.13 Thermal manikin in wire chair

$$I_T = \left. \frac{\bar{t}_{skin} - t_o}{H_{manikin}} \right|_{clothed} \qquad I_a = \left. \frac{\bar{t}_{skin} - t_o}{H_{manikin}} \right|_{nude}$$

The I_{cl} was calculated with the introduction of a clothing correction factor (f_{cl}), which accounts for the larger surface area for increased clothing levels. ISO 9920 estimates a clothing correction factor (f_{cl}) based on I_{cl}. Thus, f_{cl} must be determined iteratively.

$$I_{cl} = I_T - \frac{I_a}{f_{cl}} \qquad\qquad f_{cl} = 1.00 + 1.97 \cdot I_{cl}$$

The surface resistance (I_a) is assumed to be temperature independent. Measurements obtained at each of the three manikin sequences are given in the table below.

Table 3.8 Thermal manikin data for determination of I_{cl} of clothing ensemble and chair. Note that the operative temperature was iterated to yield the correct value (bold font).

	Manikin data		Iteration →		
	$\bar{t}_{skin}$ [°C]	$H_{manikin}$ [W/m²]	v_{air} [m/s]	t_o [°C]	**t_o [°C]**
a. Nude manikin (wire chair)	31.7	86.4	0.15	22.5	**22.8**
b. Clothed manikin (wire chair)	34.1	42.9	0.15	22.5	**22.7**
c. Clothed manikin (office chair)	34.2	40.0	0.15	22.5	**22.7**

The data in Table 3.8 were inserted in the equations presented above and yielded the I_{cl} values contained in the table below. The clothing factor (f_{cl}) was found to equal 1.37.

*Table 3.9 The clothing insulation values of clothing ensemble and chair were found according to the ISO 9920 after determining the operative temperature through iteration (**bold** font).*

	Iteration →			
	I_{cl} [m²K/W]	I_{cl} [clo]	**I_{cl} [m²K/W]**	**I_{cl} [clo]**
Clothing ensemble	0.192	1.24	**0.190**	**1.23**
Chair	0.024	0.15	**0.022**	**0.14**
Total (clothing and chair)	0.216	1.39	**0.212**	**1.37**

I_{cl} for the clothing ensemble and the chair was determined to be 1.23 clo and 0.14 clo, respectively, yielding a total I_{cl} of 1.37 clo. For the sake of comparison, the measured clothing insulation levels were compared to the tabulated clothing insulation levels in appendix I, as seen in Table 3.10 below.

Table 3.10 Comparison of measured clothing insulation levels with table look-up values in appendix I.

	I_{cl} [clo] (tabulated values)	I_{cl} [clo] (measured values)	Difference
Briefs	0.04	-	
T-shirt	0.10	-	
Jogging pants	0.18	-	
Socks	0.05	-	
Shoes	0.05	-	
Sweat shirt	0.30	-	
Fleece jacket	0.36	-	
Leg warmers	0.07	-	
TOTAL (clothing ensemble)	1.15	1.23	+ 7%
Chair	0.15	0.14	- 7%
TOTAL (clothing ensemble + chair)	1.30	1.37	+ 5%

The measured and tabulated values of I_{cl} corresponded well to one another with an overall divergence of 5%.

3.2.2 Shape Factor of Radiant Panels

In order to determine the operative temperature in the workstations, the shape factor of the radiant panels had to be determined. The radiant panels were grouped according to their controls mechanisms.

Table 3.11 Overview of the three groups of surfaces for the subsequent shape factor calculations of the radiant panels. The three shape factors included all surfaces visible from the body: $F_1 + F_2 + F_3 = 1$.

Grouping of radiant surfaces and room surfaces	Shape factor [-]	Average temperature [°C]
Radiant table panel	F_1	t_1
Radiant back and side panels	F_2	t_2
Ceiling, floor and room walls (incl. window)	F_3	t_3

Temperature data recording took place for all the surfaces listed in Table 3.11. Thus, the mean radiant temperature in each workstation (t_r) could be determined with the following equation.

$$t_r = F_1 \cdot t_1 + F_2 \cdot t_2 + F_3 \cdot t_3 = F_1 \cdot t_1 + F_2 \cdot t_2 - (1 - F_1 - F_2) \cdot t_3$$

The shape factors were based on the dry heat loss from the thermal manikin. The data from the three steady-state measurements are shown below (Table 3.12).

Table 3.12 Heat loss measurements from thermal manikin and surface temperature of radiant panels. The air velocity was at all times 0.15 m/s.

	$H_{manikin}$ [W/m²]	Table panel t_1 [°C]	Back + side panels t_2 [°C]	Room surfaces t_3 [°C]	t_{air} [°C]
a. No radiant panels turned on	48.8	25.2	18.2	17.9	17.9
b. Table panel turned on	46.9	43.9	18.7	18.0	17.9
c. Table panel + back and side panels turned on	40.7	43.9	51.7	18.2	18.3

In order to compute the shape factors of the radiant panels, Fanger's comfort equation was used to correlate the heat loss of the manikin ($H_{manikin}$) to the mean radiant temperature (t_r). Only the results will be brought here (Table 3.13); the calculations are found in appendix I.

Table 3.13 The shape factors between the radiant panels and a seated body.

F_1 (table panel)	F_2 (back and wall panels)	Total (all radiant panels)
0.08	0.1	0.18

The total shape factor of all the radiant panels was 0.18, which was close to the original estimate of 0.2 (see section 2.2.3). The shape factor of the table panel (F_1) nearly accounted for half of the total shape factor, even though the area of the table panel was approximately five times smaller than the collective area of the back and side panels. The comparatively high impact of the table panel was explained by its close proximity to the body. Moreover, the table panel may have created a hot air pocket under the table, which could have caused an additional heating of the thighs, thus, increasing the calculated shape factor.

3.3 Thermal Comfort

3.3.1 Clothing Insulation Levels During the Experiments

The clothing ensemble worn by the subjects was determined through the use of questionnaires. Each clothing ensemble was checked visually using frontal and profile pictures that were taken of the subjects prior to each experiment. The clo-values of the garments were taken from Ashrae55 and ISO9920; the list of garments and their clo-values are found in appendix I.

The mean clothing insulation level for each condition is found in Table 3.14.

Table 3.14 Average clothing insulation at each workstation and at each condition. The clothing insulation levels (I_{cl}) are based on questionnaires containing garment tables that were check marked by the subjects. The values include the contribution from the chair (I_{cl} = 0.15 clo).

Condition	23°C no source	18°C no source	18°C source
I_{cl} ± SD [clo]	0.89±0.10	1.24±0.15	1.22±0.14

The clothing insulation level at the 18°C and 23°C conditions were 1.2 clo and 0.9 clo, respectively. The values differed a little from the computed optimum clothing insulation values, 1.3 clo (18°C) and 1.1 clo (23°C). The variation was a function of personal preference, workstation differences and different use of radiant panels.

Subjects were encouraged to adjust their clothing throughout the experiments, but for the 18°C condition each subject was asked to wear the fleece jacket and the legwarmers for the first half hour. The adjustment of the clothing during the 3-hour experiment is displayed below.

Figure 3.14 The development in clothing insulation level (clo) for temperature conditions 18°C and 23°C. The clothing level drops after the first hour and increases again towards the end of the experiments.

The clothing level was practically constant during the course of the experiments.

3.3.2 Thermal Sensation and Thermal Acceptability

The subjects were asked to evaluate their thermal sensation and thermal acceptability for 11 body parts and for the body as a whole. The questionnaire was filled in six times during the 3-hour experiment. Subjects were encouraged to adjust their clothing to attain thermal neutrality; the radiant panels were meanwhile regulated to help each subject attain thermal neutrality globally (for the entire body) and locally (for each of the body parts). A graphical presentation of their thermal sensation and thermal acceptability votes of the body over the course of the 3-hour exposure is found below.

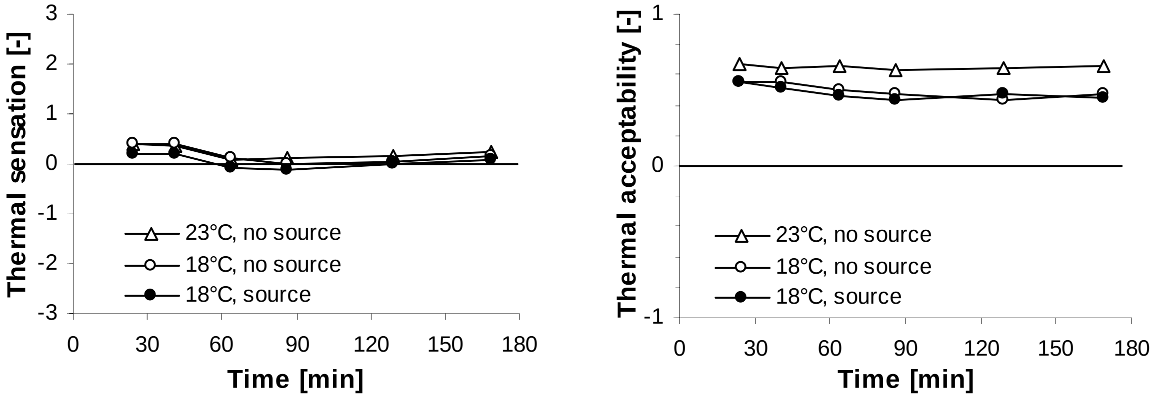


Figure 3.15 Time-course of thermal sensation votes and thermal acceptability votes for the entire body during the 3-hour exposures. The thermal sensation votes were grouped around zero for each of the three conditions, whereas the thermal acceptability votes were grouped according to temperature.

The thermal sensation graph in Figure 3.15 shows that the subjects spent the first hour of the 3-hour exposure to stabilise themselves thermally. The thermal acceptability graph shows higher value for the 23°C condition than for the two coinciding 18°C conditions. The mean and standard deviations are given below for the thermally stabile part of the experiments, i.e. the 2nd and 3rd hour.

Table 3.15 Thermal sensation and acceptability votes for the body for the 2nd and 3rd hour of the experiments. The mean values and standard deviations for each condition were comparable to one another. The sensation votes were cast on a scale ranging from –3 to 3; the acceptability scale ranges from –1 to 1.The percentages dissatisfied were a count of the votes marked as "unacceptable" on the acceptability scale divided by the total number of votes.

Condition	23°C no source	18°C no source	18°C source
Thermal sensation ± SD [-]	0.15±0.5	0.08±0.5	-0.03±0.6
Thermal acceptability ± SD [-]	0.65 ± 0.3	0.47 ± 0.4	0.45 ± 0.4
Percentage dissatisfied [%]	5	13	13

The table shows that thermal neutrality was obtained at all conditions, and that the standard deviations of the thermal sensation votes were of an equal magnitude.

In contrast, the thermal acceptability was higher at the 23°C condition than at the two other conditions. When subjecting the data to statistical analysis, the thermal sensitivity votes of the body were shown to be uniform between conditions – both with regard to their fluctuations and their mean values (see Table 3.16 below). The thermal acceptability votes were also examined and were found to be significantly dependant on temperature (see Table 3.17 below).

Table 3.16 Significance of factors on the thermal sensation votes for the body. The table contains the GLM-requirement checks for normal distributed data (Bartlett's test) and homogenous variance between data sets (Shapiro Wilks' w-test). Insofar GLM-requirements were not met, an estimated t-test was used for the analysis.

	Effects on thermal sensation of body						
	Time [min]	24	41	64	86	129	169
	Transformation	-	-	-	-	-	log
Assumption checks (GLM)	Shapiro Wilks' ($p<0.1$)	0.32	0.84	0.0001	0.0008	0.0001	0.056
	Bartlett's[†] ($p<0.9$)	0.08	0.093	0.78	0.63	0.15	0.009
Results: **Estimated t-tests**	Temperature	-	0.83	-	-	-	-
	Pollution	-	0.22	-	-	-	-
Results: **GLM**	Temperature	0.801	-	0.717	0.304	0.156	0.465
	Pollution	0.119	-	0.053	0.537	0.887	0.195
	Appearance	-	-	-	0.034	0.076	-
	Group	0.098	-	0.012	-	0.197	0.017
	Sex	0.215	-	0.017	0.029	0.071	<0.0001
	Subject	0.062	-	0.025	0.122	0.023	0.049

[†] Check between conditions

No significant impact was detected on the thermal sensation of the body between conditions, as the p-values for temperature and pollution exceeded the 5%-level.

Table 3.17 Significance of factors on the thermal acceptability votes for the body. The table contains the GLM-requirement checks for normal distributed data (Bartlett's test) and homogenous variance between data sets (Shapiro Wilks' w-test). Insofar GLM-requirements were not met, an estimated t-test was used for the analysis.

	Effects on thermal acceptability of body						
	Time [min]	24	41	64	86	129	169
	Transformation	-	-	-	-	-	log
Assumption checks (GLM)	Shapiro Wilks' ($p<0.1$)	0.08	0.81	0.57	0.0005	0.08	0.09
	Bartlett's[†] ($p<0.9$)	0.82	0.72	0.57	0.69	0.38	0.12
Results: **Estimated t-tests**	Temperature	-	0.16	0.037	-	-	-
	Pollution	-	0.43	0.23	-	-	-
Results: **GLM**	Temperature	0.139	-	-	0.018	0.001	0.030
	Pollution	0.677	-	-	0.497	0.681	0.448
	Appearance	0.090	-	-	-	-	0.192
	Group	<0.0001	-	-	<0.0001	<0.0001	<0.0001
	Sex	0.130	-	-	-	-	-
	Subject	0.004	-	-	<0.0001	<0.0001	<0.0001

[†] Check between conditions

Table 3.16 and Table 3.17 show no significant effect of pollution on the perceived thermal environment of the body. With regard to the impact of air temperature, a significant effect was observed for the thermal acceptability of the body, whereas no impact was observed on the thermal sensation of the body. These findings were investigated further with plots of thermal sensation votes versus thermal acceptability votes for each temperature condition (Figure 3.16).

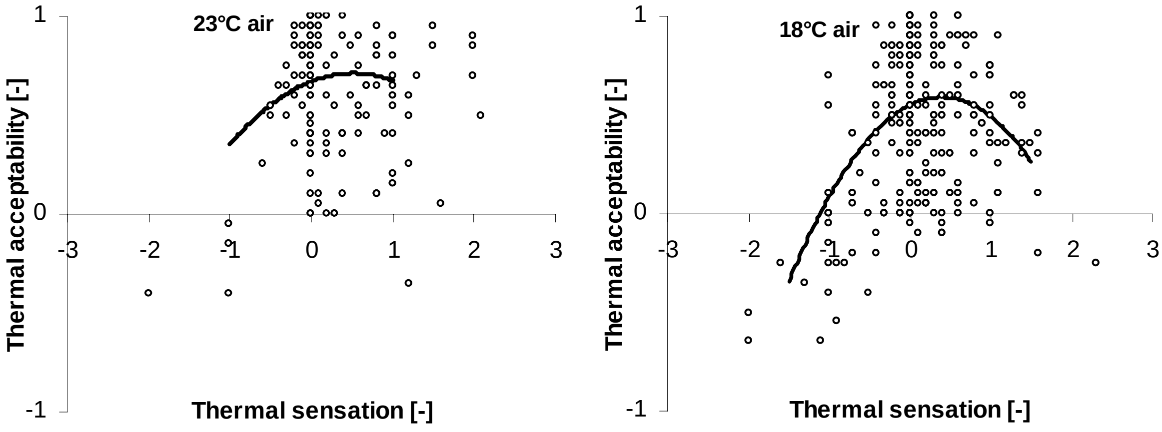


Figure 3.16 Thermal acceptability votes of the body plotted against the thermal sensation votes of the body at both temperature levels. Many data points coincide and are thus not visible - especially for thermal sensation equalling zero; the number of data points are 168 (23°C) and 336 (18°C).

Figure 3.16 yielded two scattered sets of data points. Parabolic regression lines were added, as these represented the expected relationship between thermal sensation and acceptability. Judging from these regression lines, the thermal acceptability curve of the 23°C condition seems to be higher and flatter than the curve for the 18°C condition. The observations were confirmed by plotting the regression curves in the same co-ordinate system, as seen on Figure 3.22.

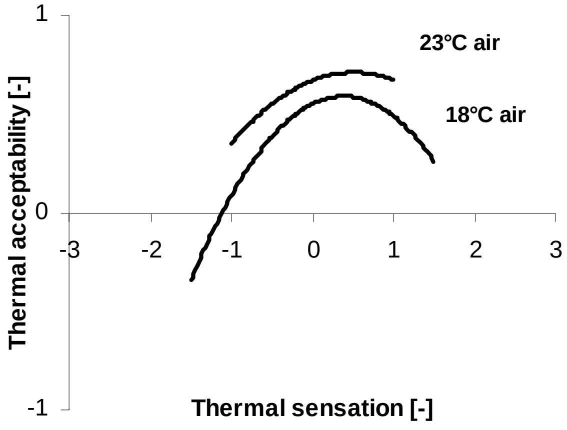


Figure 3.17 Comparison of thermal acceptability votes for the body at 18°C and 23°C. The parabolic regression line for the 23°C condition is shorter than for the 18°C condition, as it is based on half the amount of data and because the data covers a shorter range of thermal sensation votes.

Figure 3.17 shows that the average thermal acceptability was highest at the 23°C condition for the entire range of thermal sensation votes. The elevated thermal acceptability at the 23°C conditions was shown to be statistically significant (Table 3.17); local thermal discomfort may explain the observed difference and will be treated later.

Interestingly, both regression lines (Figure 3.17), and thus the thermal acceptability, peak at similar values of thermal sensation different from zero, namely at 0.4 (18°C) and at 0.5 (23°C). This shift away from thermal sensation of zero for the body is a tendency rather than a result.

3.3.3 Local Thermal Discomfort

Local thermal discomfort could have caused the thermal acceptability of the body to be higher at the 23°C condition than at the 18°C condition. Deviations from thermal neutrality of body parts are assumed to cause local thermal discomfort. As an indicator for local thermal discomfort, the histogram below was made of the standard deviations of each individual body part. For reference the figure also included the mean thermal sensation.

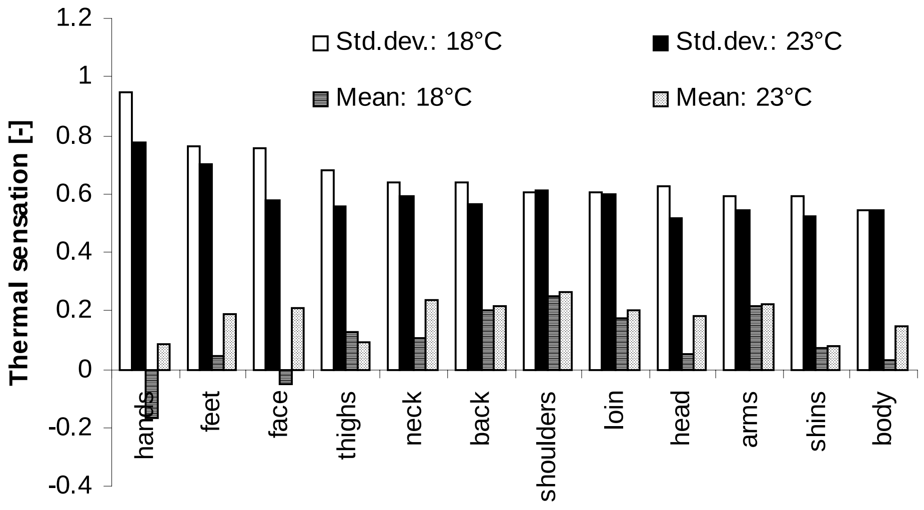


Figure 3.18 The mean thermal sensation votes (scale –3 to 3) for all experiments and the standard deviation of the votes in descending order. The figure includes the data from the 2nd and 3rd hour of the experiments after thermal stabilisation had taken place. As expected the standard deviation of the body attained the smallest value.

Figure 3.18 shows that the standard deviation of the body parts generally was higher for the 18°C conditions than for the 23°C condition, which indicated higher local thermal discomfort at the 18°C conditions. Higher air velocities and draught at the 18°C conditions also pointed towards higher levels of local thermal discomfort at the 18°C conditions.

A factor analysis was made to investigate which body parts had the greatest impact on the thermal sensation and thermal acceptability of the body. The factor analysis was supportive of the finding that a higher level of local thermal discomfort was found at the 18°C condition. The factor analysis is found in appendix K.3.

3.3.4 Quantification of Compensation by Clothing and Radiant Heating

The subjects had been thermally neutral at both the 23°C condition and the 18°C conditions. It was quantified how the subjects had used clothing and radiant heating panels to compensate for the reduced air temperature of 18°C.

The measured values of air temperature, operative temperature and clothing insulation level are found in Table 3.18.

Table 3.18 Air temperature, operative temperature and clothing insulation levels for the two temperature conditions. The values for 18°C are mean values of both 18°C conditions. The clothing insulation means in the tables are for the last 2 hours of exposure, where the thermal sensation had stabilised.

	18°C	23°C
Air temperature [°C]	18.0	23.1
Operative temperature [°C]	20.8	22.5
I_{cl} [clo]	1.2	0.89

Thus, the difference between operative temperature at the 23°C condition and air temperature at the 18°C condition was 4.4°C. This difference was compensated for with clothing and radiant panels; these contributions were quantified.

The difference in clothing insulation level was converted to a difference in operative temperature. This was done using the corresponding values of clothing insulation level and operative temperature that yield a PMV of zero. See appendix H for details.

Values based on a relative humidity of 33% and an air velocity of 0.20 m/s, corresponding to the 18°C conditions, were used to obtain the following correlation between operative temperature and clothing insulation (in clo):

$$T_{op} = 28.86 - 6.10 \cdot I_{cl}$$

The difference in clothing insulation between the two conditions was 0.33 clo. The 0.33 clo difference corresponded to a 2.0°C increase in operative temperature, referring to the above correlation.

The remaining difference of 2.4°C between the two conditions was compensated for with radiant heating, as seen on Figure 3.19.

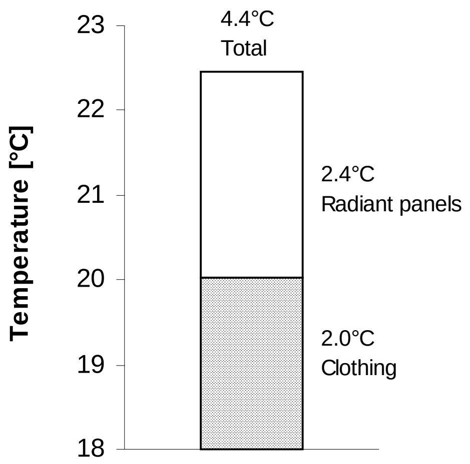


Figure 3.19 Difference in air temperature (18°C) at the 18°C conditions, and operative temperature (22.5°C) at the 23°C condition explained by a difference in clothing and the use of radiant panels.

The figure shows that a slightly larger part of the compensation was done with the radiant panels: 2.4°C, corresponding to 55% of the 4.4°C difference.

3.3.5 Equivalent Operative Temperature

An equivalent operative temperature for the 18°C condition was determined, with the purpose of comparing it with the operative temperature of the 23°C condition.

A simple estimate was made, disregarding the minor differences in air velocity and relative humidity at the two conditions. An increase in operative temperature corresponding to the difference in clothing insulation between the two conditions was found above; the value was 2.0°C. The 2.0°C difference was added to the measured operative temperature at the 18°C condition, thus yielding a measure of the operative temperature that would have caused a thermal sensation identical to that of the 23°C condition, had the subjects worn the same clothes.

The result is on Figure 3.20.

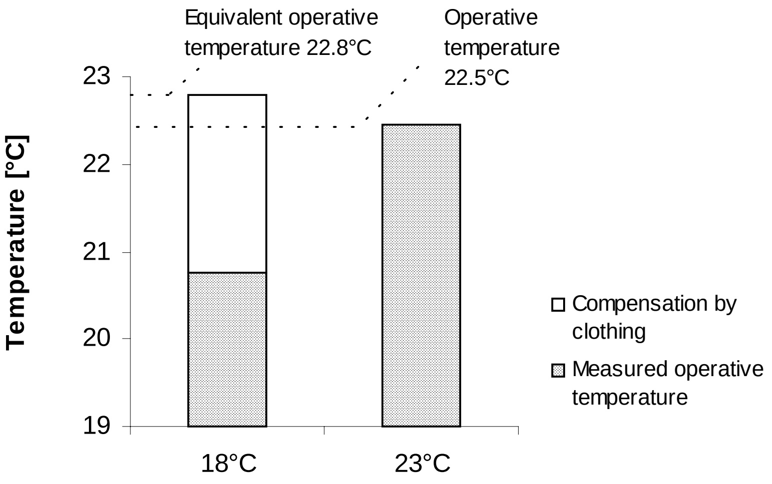


Figure 3.20 The equivalent operative temperature, that would have given the subjects at the 18°C condition the same thermal sensation as they had at the 23°C condition; the difference in clothing was converted to an increase in operative temperature, and added to the measured operative temperature.

It is seen that the equivalent operative temperature at the 18°C condition was higher than that of the 23°C condition, but that the difference was small.

Both air velocity and relative humidity were higher at the 18°C condition than at the 23°C condition. These differences have a minor impact on the result, but cause the equivalent operative temperature of 22.8°C to be slightly overestimated. The equivalent operative temperatures at the two conditions were therefore practically identical.

3.3.6 Summary of Thermal Comfort Results

- Thermal neutrality was obtained at all conditions.
- Thermal acceptability was higher at the 23°C condition than at the 18°C conditions, in spite of thermal neutrality at both levels.
- Local thermal discomfort was more pronounced at the 18°C conditions.
- An equivalent operative temperature based on compensation with clothing and radiant heating was determined for the 18°C conditions. The equivalent operative temperature at the 18°C conditions was practically equal to the measured operative temperature at the 23°C.

3.4 Perceived Air Quality

The air quality was assessed on the acceptability scale a total of 8 times during each exposure. Each of these 8 sets of assessments will be referred to as a completion at a given time.

It was expected that the air temperature and presence of the pollution source would have an impact on perceived air quality (PAQ).

The mean acceptability votes for the 3 experimental conditions have been compiled at Figure 3.21 below. The figure indicates the impact of temperature and pollution as a function of time. The acceptability votes are found in Table 3.19 below, and in appendix K.5.

The first assessment and the last assessment were made after entering (or re-entering) the field laboratory from the corridor. The remaining six evaluations were made while sedentary in the field laboratory, as part of the thermal comfort questionnaire. This should be kept in mind, when interpreting the figure.

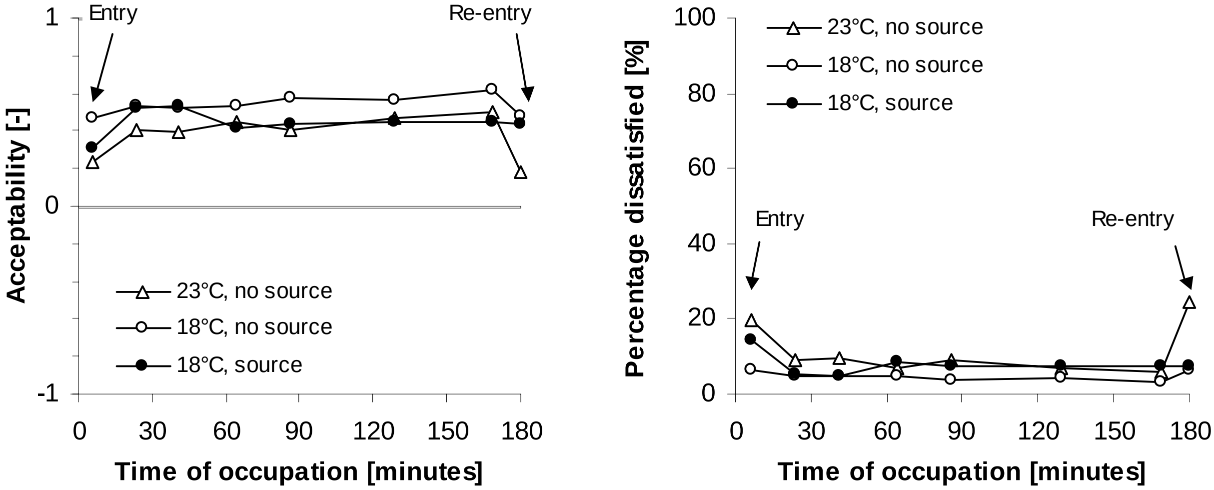


Figure 3.21 Acceptability of the air (left) and percentage dissatisfied (right) as a function of time of occupation.

Table 3.19 Acceptability and percentage dissatisfied with the air." Entry" is the first assessment; "Re-entry" is the last. "Continuous" is the mean value of the 6 assessments made while sedentary in the field laboratory.

	Acceptability ± SD [-]			Percentage dissatisfied [%]		
Condition	Entry	Continuous	Re-entry	Entry	Continuous	Re-entry
23°C, no source	0.21 ± 0.4	0.43 ± 0.3	0.18 ± 0.4	20	8	25
18°C, no source	0.47 ± 0.5	0.56 ± 0.3	0.48 ± 0.4	6	4	6
18°C, source	0.31 ± 0.4	0.46 ± 0.4	0.39 ± 0.5	14	7	8

The air was perceived as least acceptable when the subjects had refreshed their senses in the corridor, which they did prior to the first and the last assessments. During occupation of the field lab, the air was perceived as being gradually more acceptable, even though it became increasingly polluted with bioeffluents.

Each of the 8 completions was investigated individually for significant differences between conditions.

The experiments were designed in such a way, that it would be the most advantageous to use a general linear model for analyses. The factors included in the general linear model were: Temperature, pollution source, subject, sex, group, weekday and time of day.

The requirements of normally distributed data with homogeneous variance between conditions were investigated, as seen in Table 3.20. No transformation of data was used.

Figure 3.22 Air quality assessment upon entering the field laboratory.

It was found, that all data met the homogeneity of variance test, when tested with Bartlett's test. Only 4 of the 8 sets met the requirement of normal distribution, when tested with Shapiro-Wilk's *w*-test. Investigation of the quantile plots for data sets that did not meet the requirement of the *w*-test indicated, that lone outliers could have caused the non-fulfilment.

Table 3.20 Assumption checks and p-values from the statistical analysis of the acceptability of the air. Questionnaires filled in at the same time form a set of observations; these sets were investigated individually. The general linear model was used when the requirements were met; otherwise an estimated t-test was used between reference and test conditions. Bartlett's test was used to test for homogenous variance and Shapiro Wilks' w-test was used to test for normal distribution. Insofar GLM-requirements were not met, an estimated t-test was used for the analysis.

Statistical analysis for acceptability of air data

	Time [min]	6	24	41	64	86	129	169	180
Assumption checks	Shapiro-Wilk's ($p<0.10$)	0.25	0.0058	0.39	0.26	0.90	0.0002	0.060	0.034
	Bartlett's ($p<0.90$)	0.38	0.29	0.33	0.79	0.86	0.86	0.87	0.57
Results: **Estimated t-tests**[†]	Temperature	0.027	-	0.071	0.34	0.056	-	-	-
	Pollution	0.38	-	0.097	0.72	0.74	-	-	-
Results: **GLM**	Temperature	-	0.025	-	-	-	0.31	0.050	0.0005
	Pollution	-	0.81	-	-	-	0.29	0.024	0.37
	Sex	-	0.026	-	-	-	0.047	0.19	0.016
	Group	-	0.0001	-	-	-	0.021	0.0020	0.0001
	Time of day	-	-	-	-	-	-	0.049	-
	Subject	-	<0.0001	-	-	-	0.041	0.0004	0.0011

[†] Estimated t-test used between conditions: 18°C (no source) vs. 23°C (no source) for temperature; source present (18°C) vs. source absent (18°C) for pollution source.

It was found that 4 of 8 sets of data met the requirements for using the GLM.

It was found that weekday had no impact on any set of observations, and it was therefore removed from the model. The time of day had a significant effect on one observation only, namely that at 169 minutes.

The temperature had a significant impact on 4 of the 8 sets of observations. A strong tendency was seen for another two sets (41 and 86 minutes). This indicated that the difference between the mean acceptabilities of the reference condition and the 18°C condition without source depicted at Figure 3.21 was significant. The unpolluted air at 18°C was generally perceived as being the most acceptable.

The presence of the pollution source only had a significant impact on the acceptability of the air at the completion at 169 minutes. Figure 3.21 indicates that the 18°C condition with source was different from the 18°C condition without source, but this is not a significant difference.

The polluted air at 18°C was perceived more acceptable as the unpolluted reference air at 23°C. This was not the case for the first 3 assessments, where the polluted air was perceived as better than the reference air, and almost as good as the unpolluted 18°C air. This trend was not significant.

Subject was significant at all 4 of the 8 sets of observations, for which the GLM was applicable. Group of subjects was similarly significant at all 4 sets, for which the GLM was applicable. Sex was significant at 3 of the 4; males assessed the air as being more acceptable than females. This will be investigated further in the following sub-section.

An additional analysis was made, which is described in Appendix K.5.2. The analysis was not statistically valid, as it used all 8 sets of questionnaires in one analysis, thus disregarding the basic requirement of independent samples. But due to the considerable amount of data, it was possible to get indications of the impact of each factor on the effects. The analysis showed that all model factors (Temperature, pollution source, subject, sex, group, weekday time of day and appearance) had a significant impact on the effects, with the exception of appearance. This indicated that the subjects did not change their assessment of a given air quality, as they were exposed more times.

3.4.1 Impact of Sex on Perceived Air Quality

The statistical analysis showed that the subjects' sex had a significant impact at six completions, namely those at 24, 41, 64, 129 and 180 minutes. A figure showing the time-course of the votes for each sex and at each condition is found in appendix K.5.1. The two sexes voted similarly when exposed to unpolluted air (though males tended to find the air more acceptable), but that a large difference was seen in the assessments of the polluted air.

The impact of sex on the perceived air quality is shown at Figure 3.23 below. It was found that the polluted air was perceived considerably more acceptable by males than females. The unpolluted air was also perceived as more acceptable by the males, but the difference was less profound than with the polluted air.

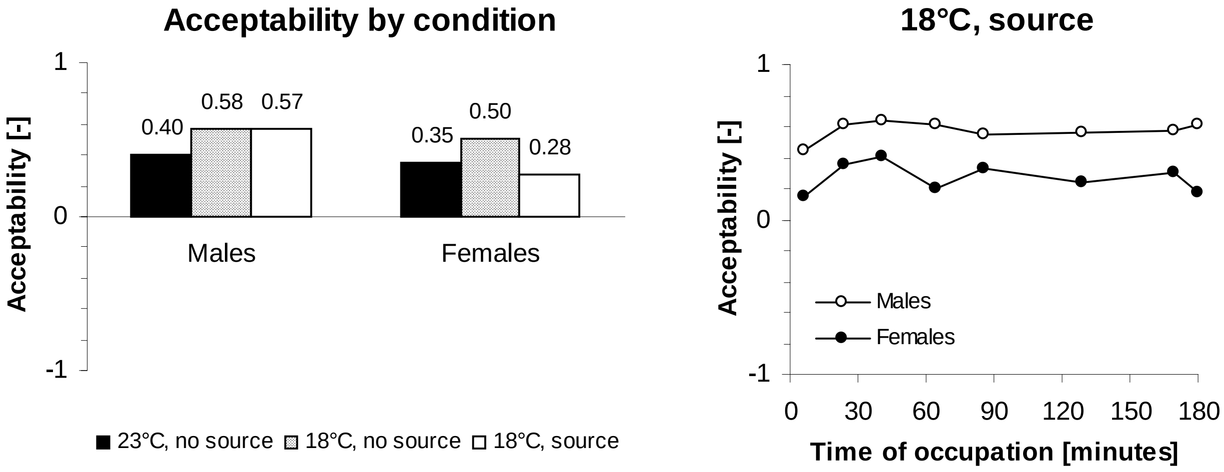


Figure 3.23 Mean acceptability of the air by each condition and sex (left). The mean comprises all 8 sets of observations. A difference in acceptability of the polluted air is observed; a plot of the time-course of the acceptability of the polluted air is presented (right).

Estimated t-tests were used to test whether the observed difference in the assessments by the two sexes were the same for each condition, or different as Figure 3.23 indicated. The tests are found in appendix K.5.1. The tests were made within conditions, with sex being the test statistic. Despite the small number of subjects of each sex exposed to each condition, one of the tests was significant; that of 24 minutes ($p<0.03$). Thus, a trend was found towards the difference between the sexes being greater for the polluted air, than for the unpolluted air (Figure 3.23).

The acceptability votes by time, condition and sex are found in appendix K.5.1.

3.4.2 Summary of Perceived Air Quality Results

- The unpolluted air at 18°C was in 4 of 8 assessments perceived as being significantly more acceptable than the reference air at 23°C.
- The polluted air at 18°C was in 1 of 8 assessments perceived significantly less acceptable than the unpolluted air at 18°C. The polluted air at 18°C was perceived approximately as acceptable as the unpolluted air at 23°C.

- The acceptability of the air did not change markedly with time of occupation. It was, however, lower when assessed after the subjects had refreshed their senses, which they did twice during the exposure.
- Males assessed the air as being significantly more acceptable than females, particularly the polluted air.

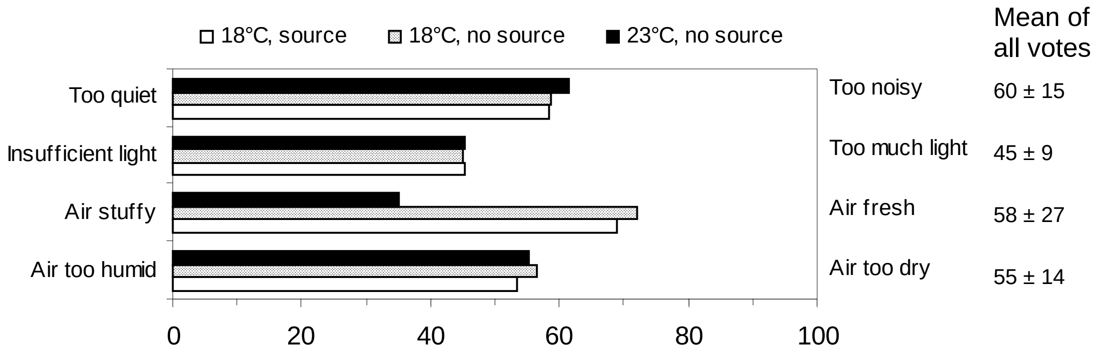
3.5 Perceptions and Symptoms

After 90 minutes of exposure the subjects filled in the Comfort Questionnaire, which comprised 22 questions or statements relating to the indoor environment and the health condition of the subjects.

The mean votes for each statement and condition are shown on the following figures. 8 statements met the requirements for analysis with a GLM. The remaining 14 statements were investigated with estimated t-tests between conditions.

The statistical analysis is found in Appendix K.7, along with tabulated mean votes by condition.

On the figures below, significant impacts are indicated with an “ * ”.



* A significant impact of the time of day was found on the lighting level. An estimated t-test between the “Early” and “Late” times of day returned a p-value of p<0.02.

** A significant difference was found between the reference condition and the 18°C, source-condition (p<0.001) and between the reference condition and the 18°C, no source-condition (p<0.001). Both tests were estimated t-tests.

Figure 3.24 Mean votes for statements regarding the indoor environment. Votes were made on the visual-analogue scale.

Figure 3.24 presents the statements relating to the indoor environment.

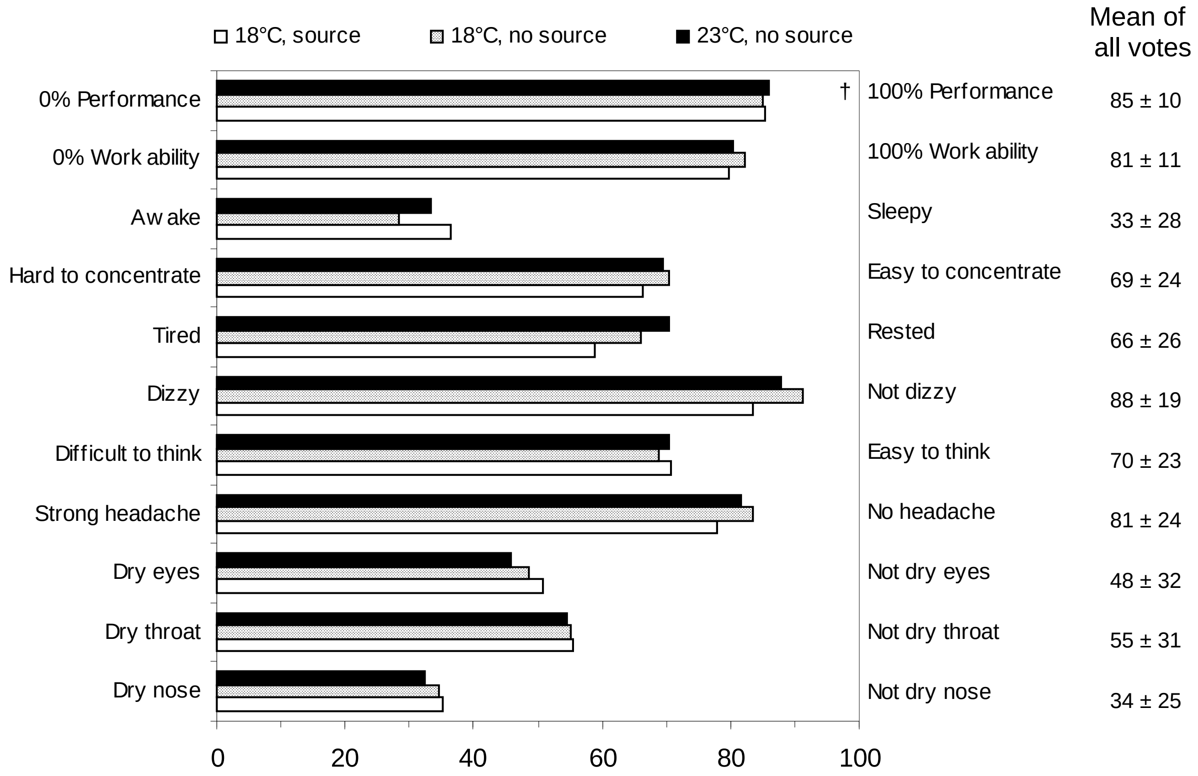
No significant difference between conditions was found for the statements concerning noise, lighting level and humidity. The mean votes for these 3 statements were between 40 and 60, which could be considered within the neutral range.

A significant impact on the lighting level of time of day was found, as will be presented later.

A significant difference between conditions was found for the votes concerning the freshness of the air, as estimated t-tests showed significant differences at the $p<0.0001$ level between the reference condition and both of the two other conditions. This indicates that temperature had a substantial impact on the perceived freshness of the air, and that the presence of the pollution source had an unsubstantial impact.

Figure 3.25 below presents the statements relating to the subjects’ health condition. For none of the statements significant differences between conditions were found. No other significant effects were found, unless mentioned in the following.

The “Performance” is included at the figure; the “Performance” vote was a self-evaluation of performance that was not cast on the Comfort questionnaire, but on the Exit questionnaire. It is brought here for increased clarity.



† The “Performance” vote was cast on the exit questionnaire, and was an estimate of the performance for the entire session. In contrast, “Work ability” was the immediate impression at the time of the Comfort questionnaire.

Figure 3.25 Mean votes for statements regarding the subjects’ health condition. Votes were made on the visual-analogue scale.

The mean values for all perceptions on Figure 3.25 are found to the right on the figure, as no significant difference was found between conditions for any of the statements.

Figure 3.26 below shows results from statements regarding odour intensity and irritation.

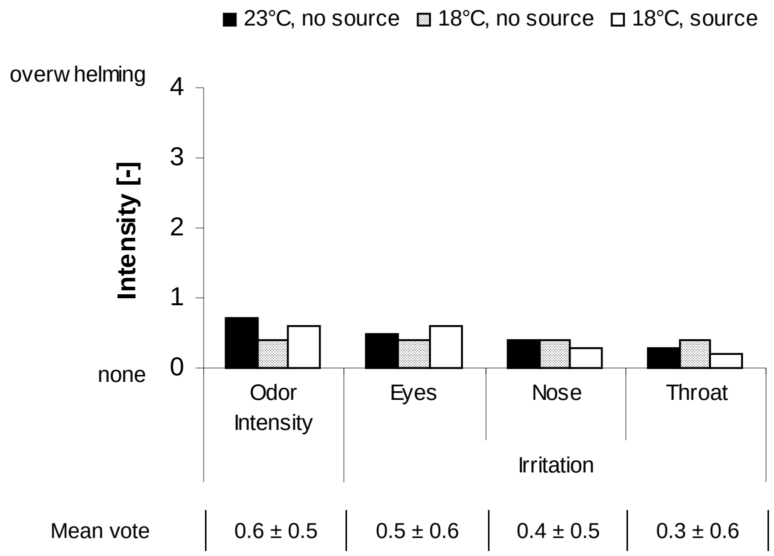
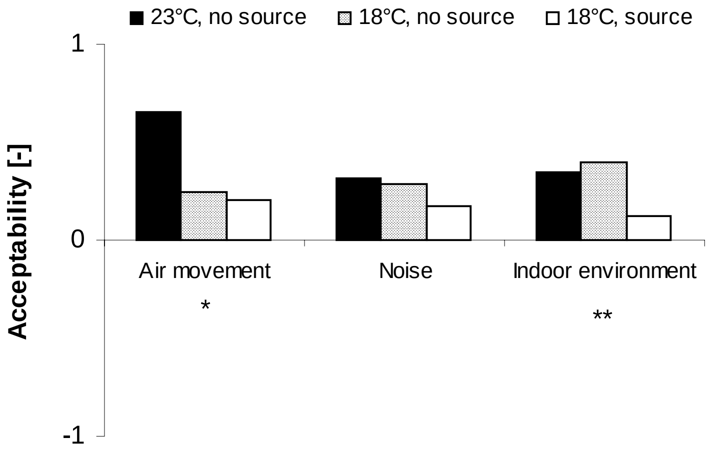


Figure 3.26 Mean votes for statements regarding intensity of odour and irritation.

Figure 3.26 shows that a low odour intensity was perceived. The level of irritation of eyes, nose and throat was perceived as being low, as well. No significant difference between conditions was noted.

Figure 3.27 below shows results from statements regarding air movement, noise and the general indoor environment.



* A significant difference was found between the reference condition and the 18°C, source-condition (p<0.004) and between the reference condition and the 18°C, no source-condition (p<0.008). Both tests were estimated t-tests.

** A significant impact of the pollution source was found on the assessment of the indoor environment (GLM, p<0.007).

Figure 3.27 Mean acceptabilities of air movement, noise level and a general assessment of the indoor environment.

The air movement was perceived as being significantly more acceptable at the reference condition, than at the two other conditions, as seen on Figure 3.27.

The noise level was assessed as being the same for all conditions at a mean acceptability of 0.26.

The presence of the pollution source had a significant impact (GLM: p<0.007) on the assessment of the general indoor environment.

Estimated t-tests showed the same effect, as the general indoor environment was perceived as being most acceptable at the 18°C, no source-condition (ACC = 0.4). The difference between the 18°C, no source-condition and the 18°C, source-condition was significant at (estimated t-test: $p<0.03$). The 18°C, source-condition was the least acceptable (ACC = 0.12), but not significantly different from the reference condition (estimated t-test: $p<0.08$).

The results from the post experimental questionnaire that was filled in by the subjects via email after the end of the experiments are found in appendix K.8. The main results are presented here. The subjects found that the 23°C was the most comfortable, but that they were more productive at 18°C. The answers indicated that local thermal discomfort had been prevalent. In particular, the subjects reported that their performance in the text typing task had been hindered by cold fingers.

3.5.1 Assessment of Lighting Level

A significant impact of the time of day was found on the assessment of the lighting level (estimated t-test, $p<0.02$). The levels used for the factor "time of day" were "early" and "late". Sessions on weekdays and weekends were performed on different times of day, but due to the limited amount of subjects participating on weekends, only two levels were used.

No significant difference between conditions was found. The mean values for the two levels of time of day are seen at Figure 3.28.

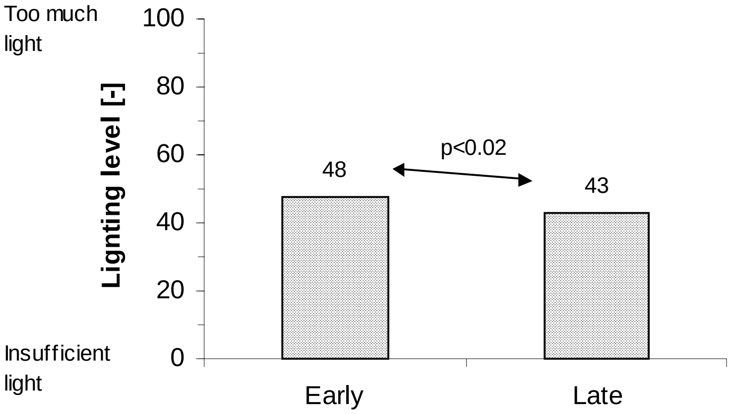


Figure 3.28 Subjective measurement of the field laboratory lighting level. "Early" denotes the first exposure on a day, and "Late" is the last exposure.

It is seen, that the lighting level at both levels were within the neutral range, but that the lighting level was significantly lower in the evenings of weekdays, and afternoons of the weekends.

3.5.2 Assessment of Air Freshness

The freshness of the air was assessed differently for the different conditions, as seen on Figure 3.29 below.

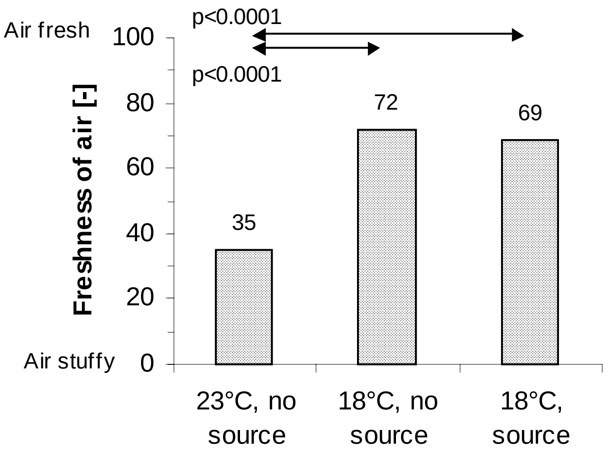


Figure 3.29 Subjective measurement of the freshness of the air that the subjects were exposed to.

It was found that the air was the freshest at both conditions at 18°C, regardless of the presence of the pollution source. The requirements for using a GLM were not fulfilled, thus an estimated t-test was done between conditions. The difference was significant between the reference condition and both 18°C conditions (estimated t-test, $p<0.0001$).

The mean values indicated that the unpolluted air at 18°C was perceived as being fresher than the polluted air, but the difference was not significant.

3.5.3 Assessment of Air Movement

As air movement might have caused discomfort, the assessment will be presented. Two linked questions were related to air movement. Firstly, the subjects stated whether they felt air movement, by checking either a “yes”-box or a “no”-box. If “yes” was checked, the subjects were asked to indicate the acceptability of the air movement on the acceptability scale.

A summary of these votes is brought on Figure 3.30 below, along with the previously determined draught rating and the mean acceptabilities. Appendix K.7.1 contains the data.

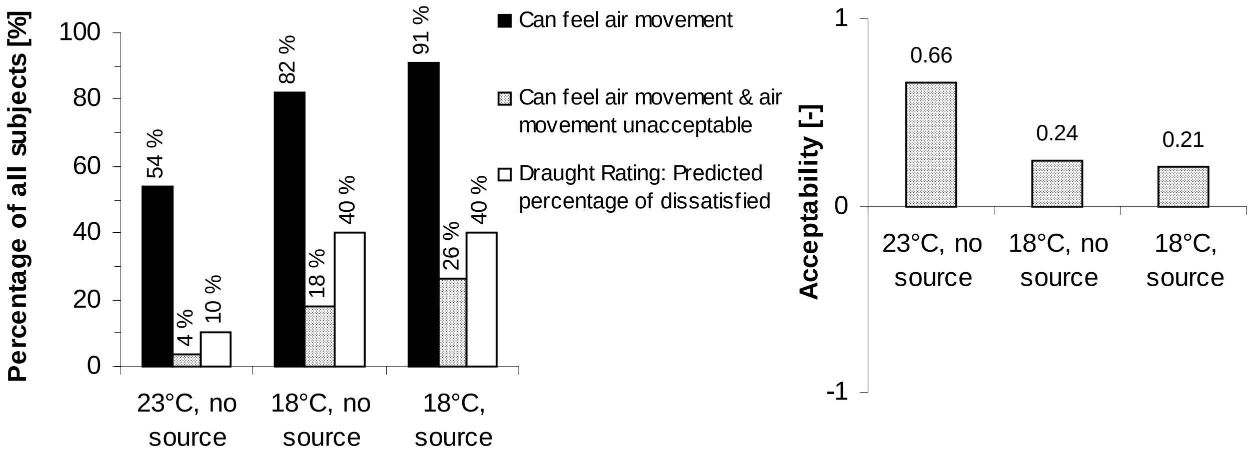


Figure 3.30 Left: Percentage of all subjects who felt air movement, and the percentage of all subjects who felt air movement and rated the air movement as unacceptable. The draught rating (see Table 3.5) was calculated based on the air velocity measurements.

Right: Mean acceptability of the air movement, for those subjects who felt air movement. The difference between the reference condition and both of the two other conditions was significant at p<0.0079 and p<0.0037, respectively.

It is noted, that several subjects assessed the acceptability of the air movement, even though they also stated that they did not feel any air movement. The questionnaire specifically stated, that the acceptability should be assessed only if air movement was felt. The subjective indications of unacceptable air movement on Figure 3.30 thus only include the response from those subjects who felt air movement.

3.5.4 Assessment of Noise

The sound pressure level was measured as 40 dB(A) generally, and 45 dB(A) during the text typing task, corresponding to a room of category B and C, respectively (CR 1752).

The percentage of subjects dissatisfied with the noise level was calculated as the percentage of subjects assessing the noise level on the negative part of the acceptability scale. The percentage is found on Figure 3.31 below, along with mean acceptabilities for each condition. The data are found in appendix K.7.2.

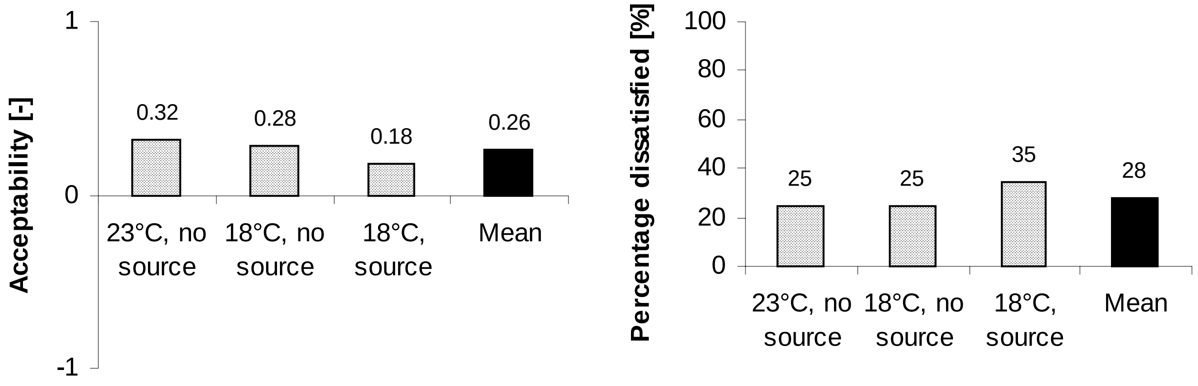


Figure 3.31 The mean acceptability of the noise level (left) and the percentage of subjects dissatisfied with the noise level (right).

No significant difference between conditions was found. Thus, the noise level was not perceived differently at any conditions.

3.5.5 Assessment of the Indoor Environment

A significant difference between conditions was found for the acceptability of the indoor environment. The statement to which the subjects responded, was: “Imagine that you in your daily work is exposed to the indoor environment you are experiencing now”. The acceptability scale was used for their responses.

The requirements for using a GLM were fulfilled. It showed a significant impact of pollution source on the acceptability ($p<0.007$). Further, an estimated t-test between the 18°C conditions was also significant ($p<0.03$).

Mean values for the votes with and without the presence of the pollution source are found in appendix K.7.3.

The mean values for each condition are seen at Figure 3.32.

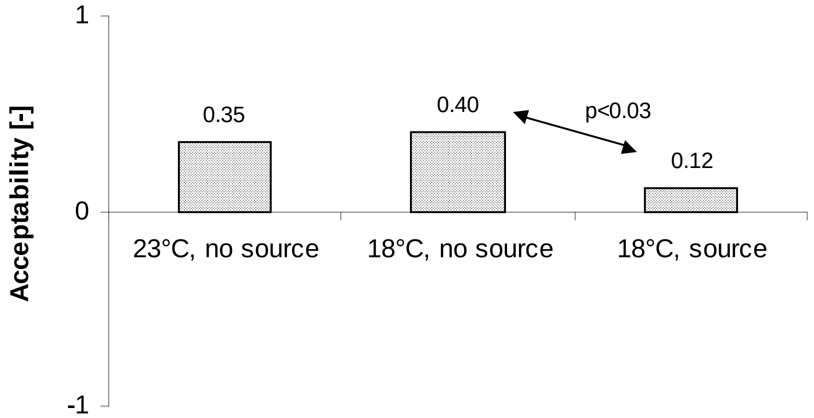


Figure 3.32 Acceptability of the indoor environment at each condition. The percentage dissatisfied was 14, 11 and 35, respectively. The percentages were a count of the votes marked as “unacceptable” on the acceptability scale divided by the total number of votes.

The 18°C condition without source was evaluated as the most acceptable, and significantly more acceptable than the 18°C condition with a source present.

No significant difference was found between the two conditions without a pollution source present (18°C and 23°C).

3.5.6 Summary of Perceptions and Symptoms Results

- The indoor environment was most acceptable at 18°C and without the presence of a pollution source. The presence of a pollution source significantly reduced the acceptability.
- The air was perceived as being significantly fresher at 18°C than at 23°C. The presence of a pollution source had no significant impact on the freshness.
- The air movement was found to be significantly less acceptable at both 18°C conditions, than at the reference conditions.

- A tendency towards a lower prevalence of symptoms was found when exposed to unpolluted air at 18°C compared to the air at 23°C. The highest prevalence of symptoms was found when exposed to the polluted air at 18°C.

3.6 Performance

Four tasks were used to measure the performance of the subjects: Multiplication, proof reading, addition and text typing.

If a subject had ended the addition or multiplication task while working on a problem, this would count as half a unit, regardless of how much of the problem was actually solved. The time spent on each task was measured using a clock. The subjects spent an equal amount of time on the same task at each session.

In a few cases a subject completed the task before the time was up. In these cases, the time actually spent on a task was recorded based on the information provided by the subject.

Figure 3.33 Subject performing the text typing task in workstation number 3.

The error ratio was the number of falsely completed problems divided by the total number of completed problems. A high error ratio indicated that many errors were made. For the proof reading task, 4 different types of errors were used.

The speed and error ratio of each task thus forms 8 measures of performance. The mean performance of each task by each condition was calculated, as seen in Table 3.21 below.

Table 3.21 Mean performance for each task by condition in the upper part of the table. Below the percent-change from the reference condition is seen. Notice that the values are simple mean values by condition.

		Performance scores							
		Multiplication		Proof reading		Addition		Text typing	
		Speed	Error ratio	Speed	Error ratio[†]	Speed	Error ratio	Speed	Error ratio
		[problems/ min]	[errors/ problem]	[lines/ min]	[errors found/ line]	[problems/ min]	[errors/ problem]	[characters/ min]	[errors/ character]
Scores	23°C, no source	1.36 ± 0.4	0.186 ± 0.15	11.0 ± 3.5	0.154 ± 0.044	4.2 ± 1.2	0.050 ± 0.043	146.5 ± 34.2	0.0045 ± 0.0037
	18°C, no source	1.38 ± 0.4	0.198 ± 0.13	10.6 ± 3.7	0.149 ± 0.037	4.0 ± 1.1	0.047 ± 0.044	146.1 ± 33.7	0.0042 ± 0.0031
	18°, source	1.42 ± 0.4	0.199 ± 0.12	11.1 ± 3.8	0.149 ± 0.051	4.1 ± 1.3	0.068 ± 0.065	146.5 ± 34.8	0.0048 ± 0.0036
%-change from the reference condition	18°C, no source	1.6%	6.4%	-3.5%	-2.9%	-3.3%	-6.4%	-0.26%	-5.7%
	18°C, source	4.5%	6.5%	0.63%	-3.2%	-0.54%	34%	0.027%	7.8%

[†] Totals of the 4 types of proof reading errors. A higher score means that more errors were found. Therefore a high error ratio is better for the proof reading task, as opposed to the other tasks.

The results have been normalised for easier comparisons as seen on Figure 3.34 below.

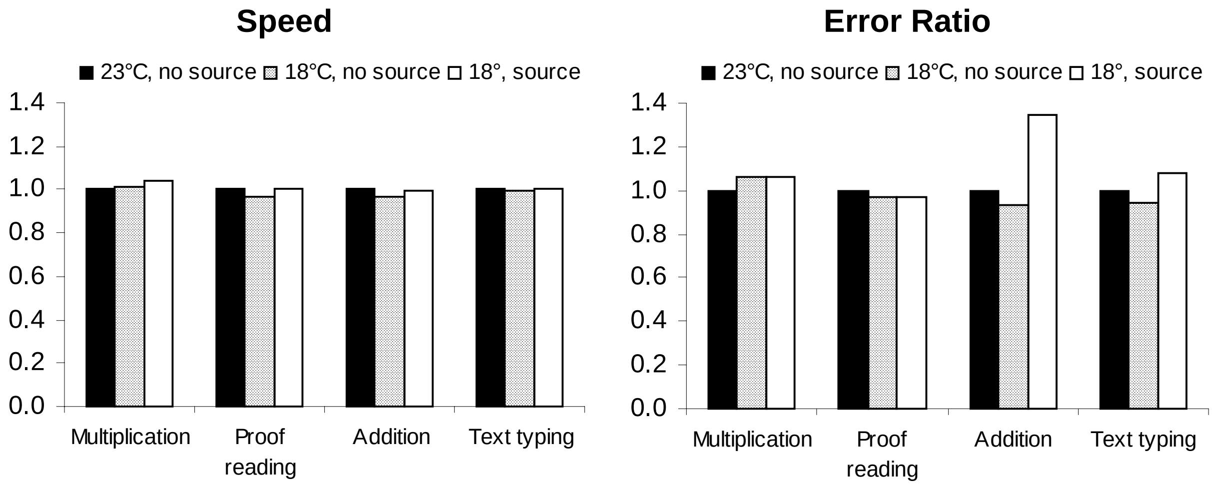


Figure 3.34 Normalised performance data; the 23°C condition is used as reference. A higher "speed" bar indicates higher performance. A higher "error ratio" indicates a higher error ratio, except for proof reading, where a higher bar indicated more errors correctly found, instead of errors made.

The differences in both speed and error ratios between conditions are small, with the exception of the addition error ratio.

The assumption checks and the results are seen in Table 3.22 below.

No significant effects of neither temperature nor the presence of a pollution source were found.

Table 3.22 Type of transformation used, assumption checks and p-values from the statistical analysis of the performance data. The general linear model was used when the requirements were met; otherwise an estimated t-test was used between reference and test conditions. Bartlett's test was used to test for homogenous variance and Shapiro Wilks' w-test was used to test for normal distribution. Insofar GLM-requirements were not met, an estimated t-test was used for the analysis.

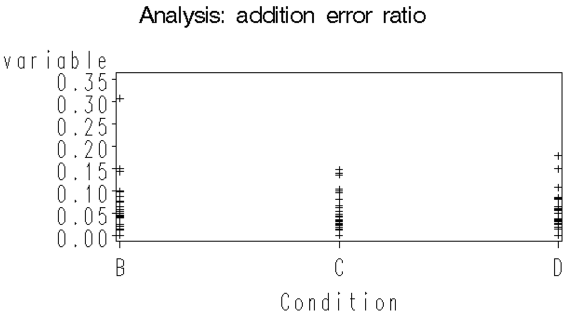
		Statistical analysis of performance data							
p-values [-]		Multiplication		Proof reading		Addition		Text typing	
		Speed	Error ratio	Speed	Error ratio	Speed	Error ratio	Speed	Error ratio
Transformation		-	Log	Log	-	Log	Arcsin	-	Arcsin
Assumption checks	Shapiro-Wilk's (p<0.1)	0.59	0.009	0.0001	0.032	0.037	0.0011	0.089	0.13
	Bartlett's (p<0.9)	0.30	0.39	0.194	0.73	0.32	0.94	0.013	0.35
Results: **Estimated t-tests**†	Temperature	0.61	-	-	-	-	0.57	1.00	0.87
	Pollution	0.68	-	-	-	-	0.37	0.73	0.28
Results: **GLM**	Temperature	-	0.64	0.54	0.46	0.49	-	-	-
	Pollution	-	0.42	0.88	0.75	0.066	-	-	-
	Appearance	-	-	0.0043	-	0.0004	-	-	-
	Group	-	0.079	<0.0001	<0.0001	<0.0001	-	-	-
	Sex	-	<0.0001	<0.0001	<0.0001	0.023	-	-	-
	Subject	-	0.0001	<0.0001	<0.0001	<0.0001	-	-	-

† Estimated t-test used between conditions: 18°C (no source) vs. 23°C (no source) for temperature; source present (18°C) vs. source absent (18°C) for pollution source.

Four sets of data applied for analysis with a general linear model. All of them were within the 10%-level of Shapiro-Wilk's *w*-test and within the 10%-level of Bartlett's test.

The general linear model was adjusted for each set of data being analysed, so that only significant effects were included (plus temperature and pollution).

Figure 3.34 indicated that a significant difference between conditions of the addition error ratio would be found. This was not the case. The reason being that one observation had an error ratio considerably higher than that of all other observations, thus increasing the mean value for that condition. Bartlett's test indicated that the variance was inhomogeneous between conditions, which was confirmed by a scatter plot of the addition error ratio, as found on Figure 3.35. Scatter plots of all performance data are found in appendix K.6 for comparison.



Conditions were coded as follows:

B: 18°C, source

C: 23°C, no source

D: 18°C, no source

Figure 3.35 Scatter plot of addition errors by condition. The plot shows the outlier at condition B (18°C, source).

As no reason for removing the outlying observation was found in the experimental protocol, it was included in the analysis. Outlying observations were present in most data sets, as seen in the appendix. They were not removed; removal of outliers requires strict objective criteria based on the information in the experimental protocol.

Day of week and workstation had significant impact on speed of multiplication and text typing, respectively. None of the two analyses fulfilled the requirements for the GLM; the results can therefore not be used for conclusions. No other GLM-analyses showed significant impacts on either day of week or workstation. No further investigations were done concerning these factors.

3.6.1 Proof Reading Error Types

Four types of errors were evenly scattered in the proof reading task. Analysis of variance was used to investigate whether any particular type of error was significantly influenced by one of the experimental conditions. The average number of errors found per line of text read is shown below at Figure 3.36.

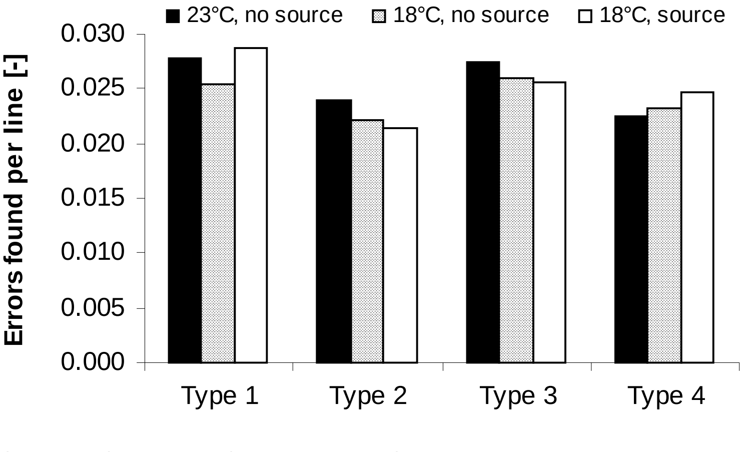


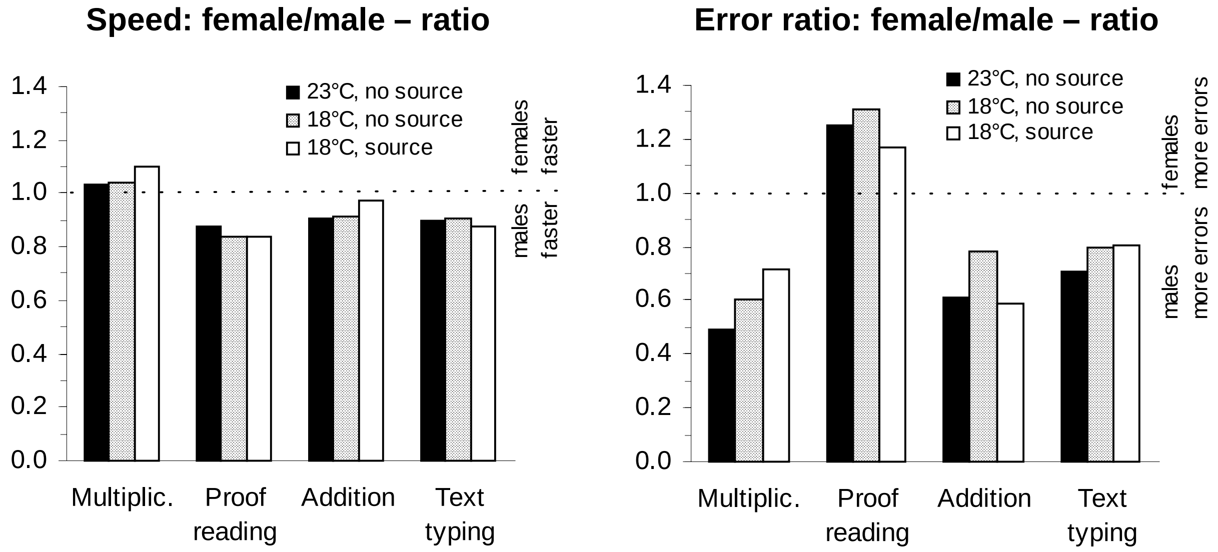
Figure 3.36 Number of errors of each type found at each of the three conditions.

The figure indicates that no individual type of error was more sensitive to the experimental conditions than others. This was supported by the analysis of variance, which showed no significant impact on any individual type of error.

The number of errors varied slightly between the sets of text, but as the variations were small and the sets mixed, this had no impact on the results.

3.6.2 Impact of Sex on Performance

A significant difference between the performances of the two sexes was found at the three tasks analysed with the general linear model. The ratio between the mean performance of females and that of males for each task is seen at Figure 3.37 below. The actual performance scores are found in appendix K.6.1.


Speed: female/male – ratio

Error ratio: female/male – ratio

Figure 3.37 Ratio between females and males of speed (left) and error ratio (right). A value above “1” on error ratio indicates that females made more errors; a value above “1” on speed indicates that females worked faster – with the exception of proof reading error ratio, for which a higher bar indicated more errors correctly found, instead of errors made.

It is dubious whether differences between the sexes reflected general tendencies, as each group was limited to 14 persons. It was therefore of greater interest whether there was a difference in the female/male ratio between conditions, indicating that the two sexes were influenced differently by the experimental conditions. This would be indicated by columns of different heights for a given task.

Slight differences between the sexes were seen on the impact of temperature and air quality on the speed of work. But the differences were small and did not show a systematic trend; reduced air quality, for example, caused females to work slower than males on the proof reading and text typing tasks, whereas females worked faster than males on the addition task when exposed to reduced air quality.

The differences between the sexes were greater on the error ratio, and in some cases statistically significant. A greater impact of the conditions was also seen on the error ratio. Females made more errors than males while exposed to cold air compared to the reference situation – this was the case for all tasks. The reduced air quality had a non-uniform impact on the female/male ratio; an increase was observed for text typing and multiplication, whereas a decrease was observed for proof reading and addition.

3.6.3 Impact of Learning on Performance

A significant impact of learning was found on the speed of text typing and proof reading, as seen from Table 3.22. Most subjects appeared 4 times, but 7 subjects appeared a fifth time also, as they participated in the additional exposures of Monday 29/2.

Mean values of speed and error ratios were estimated for each task and appearance. The estimates were based on the model estimates from the general linear model, which quantifies the absolute effect of each factor on the model. The requirements for using the GLM were only fulfilled in 4 of the 8 instances (Table 3.22), so the estimates were somewhat uncertain. They can, however, be used as indicators. Figure 3.38 below shows the time-course of the work speed and the error ratio. The values are found in appendix K.6.2.

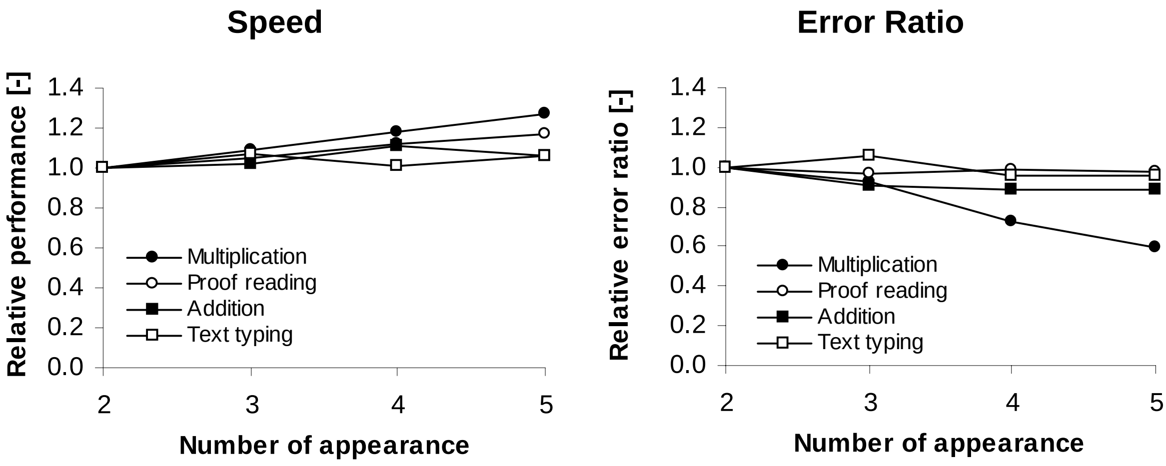


Figure 3.38 The time-course of work speed (left) and error ratio (right). Both speed and error ratios were normalised, using the score of the first appearance as the reference.

The first appearance was not included on the figures, as the data collected during the training session were not used for the analysis. Thus, the subjects were not unfamiliar with the tasks at appearance no. 2, which is used as reference on the figures.

A general trend towards higher speed and less errors was seen, as the subjects got more familiar with the tasks from one exposure to the next. The task that was influenced the most on both speed and error ratio was multiplication. Multiplication was used as the first task at each exposure, at a time when the metabolic rate of the subjects might not have stabilised. It was also the task to which the subjects were expected to be least familiar, wherefore a considerable improvement with appearance was expected.

The speed of the other three tasks, proof reading, addition and text typing was also increased from one appearance to the next. Proof reading speed was increased the most. Collectively for all the tasks an average increase in speed of about 3% per appearance was observed.

As expected, a smaller change in error ratio than speed with time was observed. The error ratio for the proof reading, addition and text typing tasks were reduced approximately 2% per appearance, with the addition error ratio being reduced the most.

3.6.4 Summary of Performance Results

- Neither air quality nor air temperature had a significant impact on the speed with which the subjects performed the four tasks that were used to measure their performance.
- Neither air quality nor air temperature had a significant impact on the error ratio with which the subjects performed the four tasks that were used to measure their performance.
- Females generally worked significantly slower than males, but also made significantly less errors than males. This difference in work and error rates was different for different tasks. But no difference caused by condition within a task was found.

- A significant impact of learning was found on the speed of work, but not on the ratio of errors made. It was found that the speed of work was increased by approximately 3% for every exposure.

3.7 Cross-Categorical Effects

This section investigates effects between the categories investigated: physical measurements, subjective measurements and performance.

3.7.1 Impact of Fingertip Temperature on Thermal Sensation and Acceptability

It was investigated whether the measured fingertip temperature had a significant impact on the thermal sensation or acceptability of the hands.

Three measurements of fingertip temperature were made at each exposure. The thermal sensation/acceptability votes associated with each measurement were the votes given just prior to measuring the fingertip temperature.

The thermal sensation and acceptability was depicted below, at Figure 3.39 and Figure 3.40, respectively.

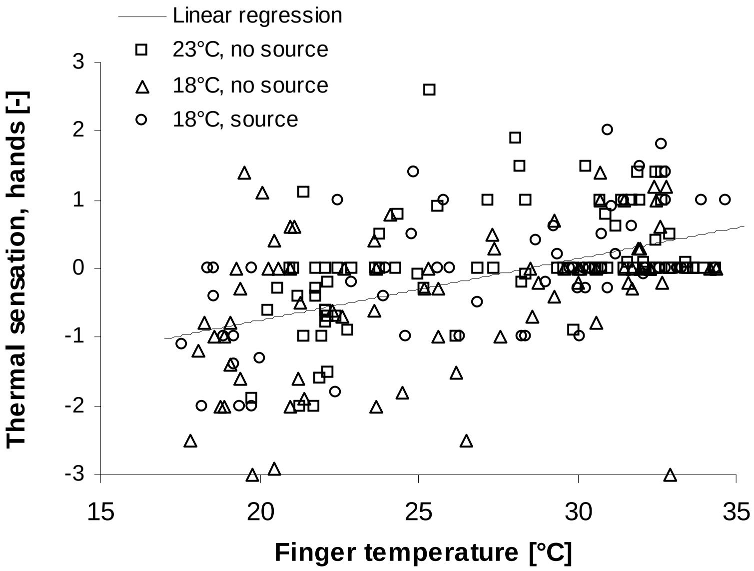


Figure 3.39 The thermal sensation of hands depicted as a function of the measured fingertip temperature. The thermal sensation was the one reported just prior to each measurement of fingertip temperature; three measurements were made at each exposure. The regression coefficient (R^2) was 0.2.

The thermal sensation showed a tendency to increase, as the fingertip temperature increased. The tendency was not strong; the linear regression yielded a correlation coefficient (R^2) of 0.2.

No noticeable difference between conditions was found, despite the considerable difference in air temperature.

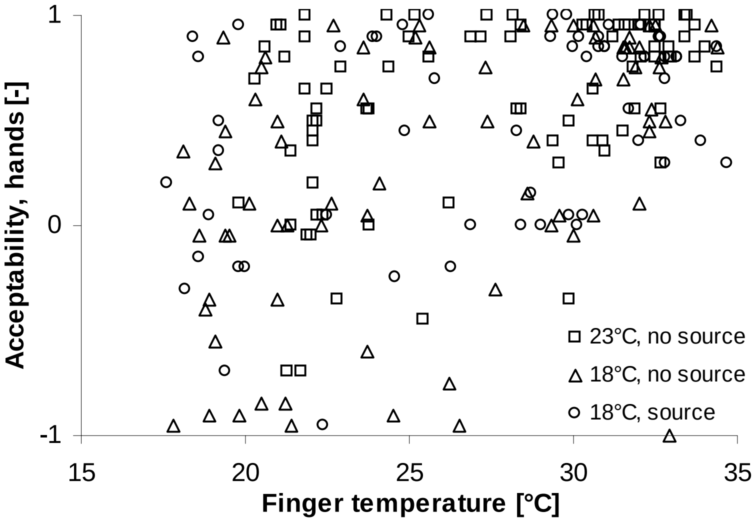


Figure 3.40 The thermal acceptability of hands depicted as a function of the measured fingertip temperature. The thermal acceptability was the one reported just prior to each measurement of fingertip temperature; three measurements were made at each exposure.

The thermal acceptability showed little correlation with the fingertip temperature, neither overall nor within conditions.

An increase in acceptability was seen with increasing fingertip temperature. No peak acceptability was found.

3.7.2 Impact of Fingertip Temperature on Text Typing Performance

An analysis was made, to investigate whether the measured fingertip temperatures had an impact on the speed of text typing or the text typing error ratio. This was done, because text typing was the task expected to be most sensitive to fingertip temperature, and subsequently the fingertip dexterity. At Figure 3.41, the speed and error ratio of text typing is depicted as a function of the fingertip temperature.

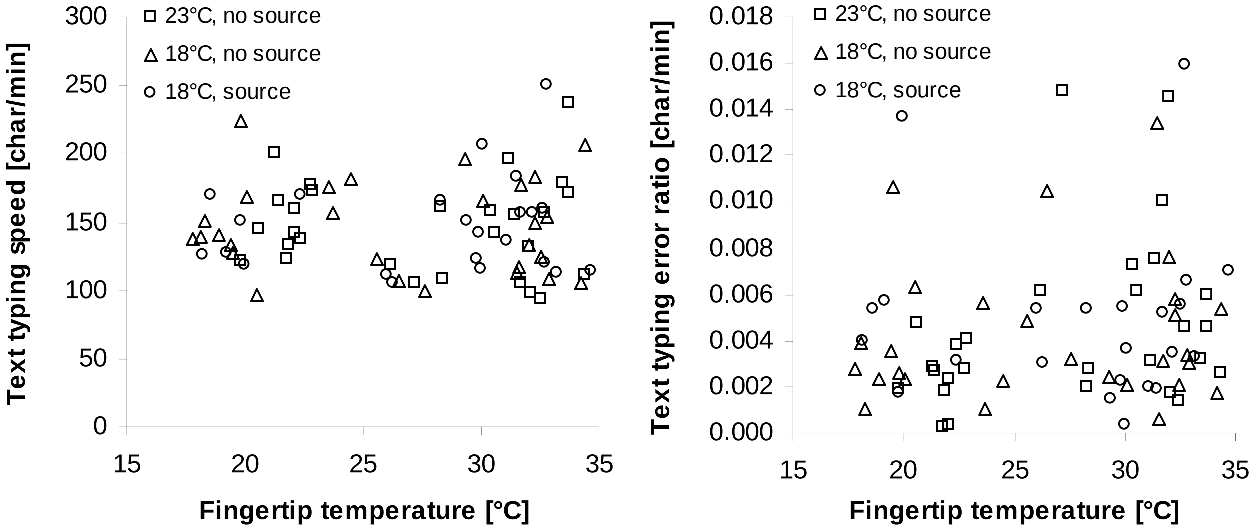


Figure 3.41 Speed and error ratio of text typing as a function of the fingertip temperature measured in the break of the text typing task. The results from all conditions are depicted on the same graph, because they showed the same tendency.

No correlation between fingertip temperature and neither speed nor error ratio was found for any of the conditions. For the error ratio, a weak trend towards rising error ratio with rising temperature was found.

The fingertip temperature measured in the break of the text typing task was used as a covariate in the statistical analysis. The general linear model that was used previously was modified to include the fingertip temperature as a covariate.

The results from the "speed" analysis are presented in Table 3.23. The error ratio analysis showed a similar result.

Table 3.23 Covariate analysis of the impact of fingertip temperature on text typing speed. Non-principal, non-significant factors (time of day and weekday) were excluded from the model. The analysis used a general linear model, for which the requirements were fulfilled.

Factor	Degrees of freedom	Sum of squares	F	p
Fingertip temperature	1	13.0	0.27	0.60
Air temperature	1	35.8	0.75	0.39
Pollution	1	0.85	0.018	0.89
Appearance	3	766	5.4	0.0031
Group	6	6985	25	<0.0001
Sex	1	5552	117	<0.0001
Workstation	3	926	6.5	0.0010
Subject	20	70838	75	<0.0001
Error	42	1990		

The analysis showed no significant impact of fingertip temperature on the speed of text typing. The effect of fingertip temperature ($p<0.60$) was less than that of air temperature ($p<0.39$), and too insignificant to be considered a trend.

3.7.3 Impact of Thermal Sensation on Text Typing Speed

The impact of the thermal sensation of the hands on productivity was investigated. As text typing was expected to be most sensitive to temperature, the speed of text typing was investigated. The thermal sensation votes for hands given in the break of the text typing tasks were used as the factor of which the impact on speed was investigated. Figure 3.42 below shows the speed of text typing as a function of thermal sensation.

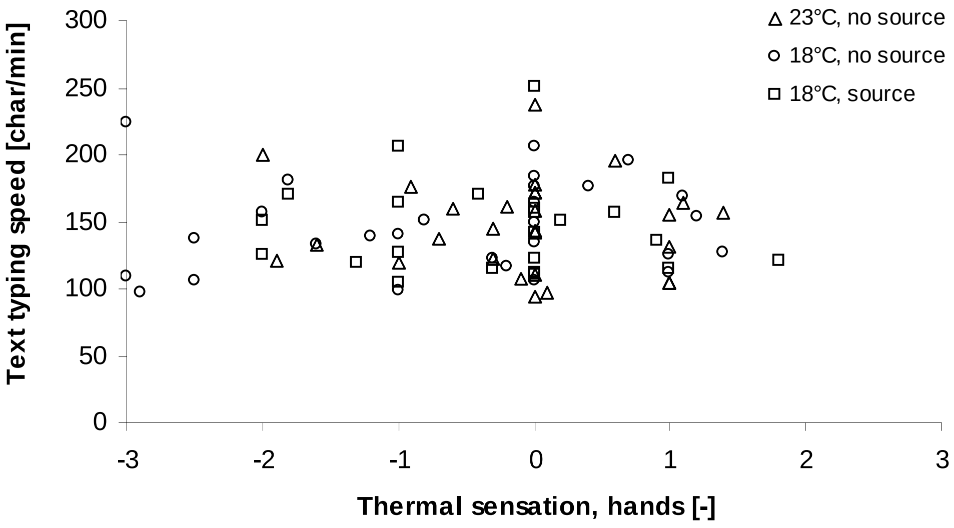


Figure 3.42 Speed of text typing depicted as a function of the thermal sensation of hands. The thermal sensation vote used, was the one given in the break of the text typing task.

A weak correlation between speed and thermal sensation was found. A trend towards the speed peaking at a zero thermal sensation vote was seen.

Similar investigations were made of the correlation between 1) the thermal acceptability of hands and the speed of text typing and 2) the thermal sensation of the entire body and the speed of text typing. No strong correlations were found in either case.

A statistical analysis of the speed of text typing was made, that used the thermal sensation of the hands as a covariate. The analysis used a general linear model, but the impact of thermal sensation on speed of text typing was not significant ($p<0.7$).

3.7.4 Impact of Self-Evaluated Performance on Measured Performance

It was hinted by several subjects, that their self-evaluation of performance that was part of the Exit questionnaire was an expression of their well being that particular day. It was investigated whether the self-evaluated performance had on impact on the measured performance.

This was done statistically, by using the self-evaluated performance as a covariate in the analysis of performance. A general linear model was used to investigate the impact on the speed of text typing.

No impact on the speed of text typing was found of self-evaluated performance ($p<0.7$).

3.7.5 Summary of Cross-Categorical Effects Results

- The measured fingertip temperature was correlated with the subjective thermal sensation of the hands. A tendency towards increasing thermal sensation was seen with increasing fingertip temperature.
- The impact of fingertip temperature on speed of text typing was investigated. No significant impact was found.
- The impact of self-evaluated performance on speed of text typing was investigated. No significant impact was found.

4 Discussion

The discussion is divided into a main section, followed by smaller subsections that discuss specific issues from the study.

The main hypothesis of the present study was that a reduction of the air temperature from 23°C to 18°C would improve the perceived air quality, reduce the prevalence of symptoms and increase the performance of human subjects that remain thermally neutral.

In the experiments, the reference condition was within the comfort limits of ISO 7730 with regards to air temperature and draught. The ventilation rate was 45 l/s/person, which was much higher than recommended by for example CR 1752 or ASHRAE 62. Thus, the main hypothesis was investigated by improving an already acceptable indoor environment. Several aspects of the main hypothesis were confirmed.

A significant improvement of the perceived air quality from 20% dissatisfied to 6% dissatisfied ($p<0.03$) was found when the air temperature was reduced from 23°C to 18°C. The perceived freshness of the air was also significantly increased ($p<0.001$). This follows the studies of Fang (1997) and Toftum et al. (1998), who found an increase in the acceptability of air when the air temperature was decreased.

Decreasing the air temperature from 23°C to 18°C tended to cause a reduction in the prevalence of symptoms, namely increased ease of concentration, awakeness and self-evaluated work ability while the prevalence of headaches and dizziness was reduced. The temperature reduction also made the subjects more tired, which indicates that they exerted a greater effort in solving the tasks while exposed to the air at 18°C. These tendencies were consistent but not statistically significant. No difference in performance was found between the two air temperatures. This follows a similar study by Wyon et al. (1975), who found no impact of air temperature on the prevalence of symptoms.

These findings indicate that reducing the air temperature per se increases the perceived air quality. The findings indicate that reducing the air temperature might also reduce the prevalence of symptoms.

While thermal neutrality of the body was obtained at both temperatures, the thermal acceptability of the body's thermal state was different. This could most likely be attributed to local thermal discomfort, which arose from a combination of cooler air and higher air velocities at the 18°C conditions than at the 23°C condition. The average number of subjects feeling unacceptable air movement was 22% at the 18°C conditions, whereas the corresponding number was 4% for the 23°C condition. The higher air velocity at the 18°C conditions was a consequence of the more convective environment, i.e. higher temperature gradients between surfaces and air, as the ventilation rate and adjustment of fans were identical at each of the two temperature conditions. The higher local thermal discomfort could also be attributed to a higher level of clothing insulation asymmetry at the 18°C conditions (Olesen et al., 1988). The radiant panels only partially eliminated the difference in clothing asymmetries at the two temperature conditions, as additional clothing had to be used when going for the 23°C condition to the 18°C conditions in order to keep the subjects thermally neutral. Collectively, the higher air velocity and higher clothing insulation level at the 18°C led to higher local thermal discomfort, which may have had an inhibitive effect on the findings, as the thermal acceptability was not identical at the 23°C and 18°C conditions.

A relation between the improved perceived air quality and the decreased thermal acceptability at 18°C could be found in the assessment of the general indoor environment. The general indoor environment was assessed as being practically equally acceptable at 18°C and at 23°C, though a slightly higher acceptability was found at 18°C.

The assessment of the general indoor environment was used by Witterseh (2001) as an overall indicator for the impact of combined effects; an impact on the acceptability was found of air temperature and noise. Witterseh suggested that the observed decrease in acceptability when increasing the air temperature was due to the worsened perceived air quality at higher air temperatures. If the same mechanism had persisted in the present study, the improved perceived air quality at 18°C would have caused a significant increase in the acceptability of the general indoor environment. It is suggested that the local thermal discomfort inhibited a significant increase in the acceptability of the general indoor environment. In short, the improved perceived air quality could have been counteracted by the decreased thermal acceptability in the assessment of the overall indoor environment.

The secondary hypothesis was that the presence of an old carpet from a building with a history of SBS symptoms would increase the dissatisfaction with the air quality of air at 18°C. And that the combined change in satisfaction due to the pollution source and the reduced air temperature would cause no change in the satisfaction with the indoor environment in general.

While 6% were dissatisfied with the unpolluted air at 18°C, 14% were dissatisfied when a pollution source was added to the air at 18°C. This finding follows the studies of Wargocki (1998) and Lagercrantz (2000) who also found a negative impact of an added pollution source on the acceptability of indoor air.

When exposed to the polluted air at 18°C the subjects reported the most symptoms of all conditions. They were sleepier, more tired, and dizzier. They found it harder to concentrate and reported stronger headaches. Though non-significant, these tendencies support the findings by Wargocki (1998), who reported a higher prevalence of symptoms when exposing subjects to air with an added pollution source and Pejtersen (2000) who found a higher prevalence of symptoms in buildings with a higher sensory pollution load.

The subjects were least tired when exposed to the air at 23°C, and most tired when exposed to the polluted air at 18°C. It seems that the subjects exerted a greater effort when exposed to the polluted air at 18°C in order to perform the same at all conditions; self-evaluated work ability and overall performance was practically identical at all conditions.

It was suggested above that the improved perceived air quality at 18°C was counteracted by the decreased thermal acceptability in the assessment of the general indoor environment. When exposed to the polluted air at 18°C, the subjects assessed the general indoor environment as being significantly less acceptable than at the other two conditions.

It is suggested that three factors had a dominant impact on the assessment of the general indoor environment in the present study, namely the air temperature, the presence of a pollution source and the thermal acceptability.

Wargocki (1998) and Lagercrantz et al. (2000) found that exposing subjects to air with an added pollution source had a significant negative impact on the performance. Though a difference in the perceived air quality at the two temperatures was found in the present study, no impact on performance was found. As the impact of air temperature on performance was studied previously without finding a relationship, it is not known whether a relationship does exist. The present study does not suggest that an impact of reduced air temperature on performance can be expected.

4.1 Perceived Air Quality

Two of the eight air quality assessments were done with the subjects functioning as visitors, in that they refreshed their senses on the corridor outside the field lab prior to entering the room. The first visitor-assessment was made prior to the exposure (denoted entry), and the last visitor-assessment was made immediately after the exposure (denoted re-entry), when the air was polluted with bioeffluents. No significant difference was seen between the two assessments. This is in contrast to the study by Wargocki (1998), in which a significant impact of bioeffluents was found on the acceptability reported by subjects exposed in the same office at a ventilation rate of 10 l/s/person.

The high ventilation rate in the present study (6 h^{-1}, corresponding to 45 l/s/person) meant that a small impact on air quality acceptability of bioeffluents was expected. This was indicated by the low indoor CO_2 concentration, which was approximately 100 ppm above the outdoor level.

The meeting room might have caused a reduction in the acceptability at the entry-assessment. The air temperature was high (approximately 25°C) and no possibility of decreasing it existed. The subjects spent 5-10 minutes in the meeting room, whereupon they spent 1 minute on the corridor and subsequently assessed the air quality in the field lab. Though instructed not to let the air temperature have an influence on their assessments, this might have been the case for several assessments. Partly basing the air quality assessments on the air temperature and thermal sensation of the body offers an additional explanation of why the acceptability at the entry-assessment was as low as at the re-entry assessment.

The ventilation rate was high in the present study, and the range of percentages of dissatisfied with the air quality low (4% to 20%). In a study of the impact of different ventilation rates, Wargocki (2000) used the same field laboratory as in the present study. Wargocki found that increasing the ventilation rate reduced the percentage dissatisfied, and specifically, that 14% of the subjects were dissatisfied when exposed to unpolluted air at 22°C and a ventilation rate of 30 l/s/person.

A lower percentage dissatisfied with the air quality than 14% at 23°C was therefore expected for the present study. The meeting room, as suggested above, could explain that 20% were dissatisfied.

During occupation of the field lab, the subjects assessed the air quality six times as occupants. An immediate rise in the acceptability was seen between the entry-assessment and the first assessment as occupants. This was most likely caused by adaptation. Wargocki (1998) and Fang (1997) found a similar adaptation to take place. During occupation, the acceptability of the air remained stabile. The acceptability of the polluted air at 18°C was decreased after the first two assessments, but remained stabile for the rest of the exposures.

The re-entry-assessment of the polluted air differed from the other two conditions, as the acceptability of the air at re-entry dropped less markedly. A possible explanation to this observation is that the subjects might have adapted themselves to the pollution source.

A difference between the assessments of males and females was found, as males assessed the air as being more acceptable. The difference was not significant for the unpolluted air at 18°C or 23°C. For the polluted air at 18°C a significant difference between the sexes was found for one assessment ($p<0.03$) and the remaining assessments followed this trend, despite the small groups (14 males and 14 females). This follows Hedge et al. (1996) who, in a study of 4479 workers, found that women were more sensitive to indoor air quality than men.

The absolute levels of percentages dissatisfied with the air quality were predicted in the Experimental Method chapter, based on the sensory pollution load of the field lab determined by Wargocki (1998). The predicted percentages of dissatisfied with the air quality were 8% for the unpolluted air and 14% for the air polluted by the carpet. The predictions corresponded well with the findings for the air at 18°C, as 6% were dissatisfied with the unpolluted air (18°C) and 14% were dissatisfied with the polluted air (18°C). The prediction did not consider the effect of air temperature, which has a strong impact on the perceived air quality (Fang, 1997; Toftum et al., 1998). Based on the findings of Fang and Toftum et al., a higher acceptability at 18°C than the one predicted based on the sensory pollution load could have been expected due to the reduced air temperature. The absence of this finding was attributed the meeting room.

The studies by Fang et al. (1996) and Toftum et al. (1998) showed a linear correlation between the enthalpy and acceptability of air. For the present study, the enthalpy content of the air was varied from 36 kJ/kg (23°C/30%) to 29 kJ/kg (18°C/34%), which caused a significant increase in the acceptability of air from 0.21 to 0.47. The data are plotted in Figure 4.1 together with the linear correlations found by Fang et al. (1996) and Toftum et al. (1998).

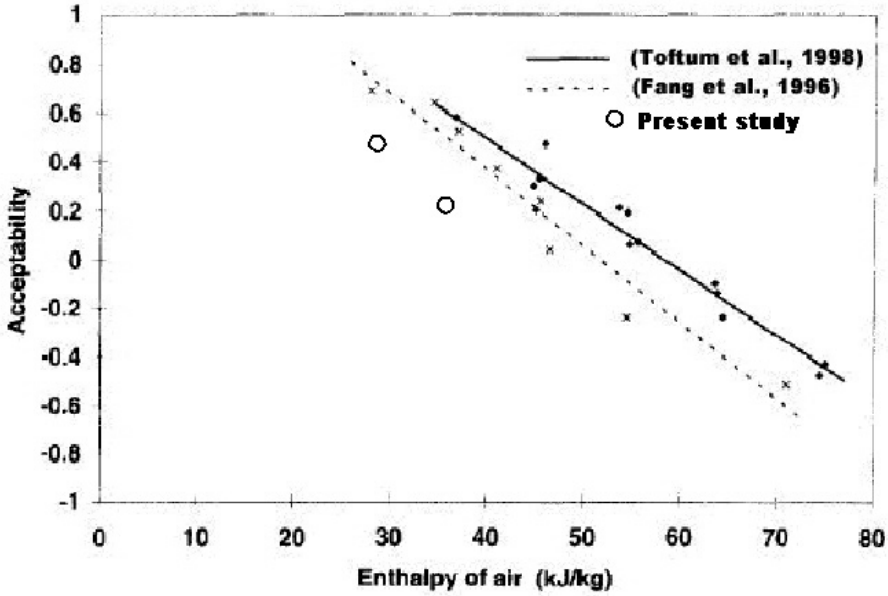


Figure 4.1 Data of the present study plotted with data showing linear correlation between air acceptability and enthalpy (Fang et al., 1996; Toftum et al., 1998). Data are collected differently but show the same tendencies; Fang et al. (1996) used a facial exposure to clean air, Toftum et al. (1998) exposed the entire head to clean air, whereas the present study exposed the entire body to clean air.

Figure 4.1 shows that the two data points of the present study yield smaller values for air acceptability than predicted by the linear correlations by Fang et al. (1996) and Toftum et al. (1998). The deviation is a natural consequence of the fact that full body exposures of air were used for this present study, whereas facial and head exposures were used for the other two studies. Changes in environment are felt more strongly for full body exposures (Fang, 1996), thus values of air acceptability of this present study were expected to give lower values as observed in Figure 4.1.

The study by Wyon et al. (1975) exposed subjects to two conditions of different air enthalpies, namely 46 kJ/kg (23.2°C/50%) and 36 kJ/kg (18.7°C/50%). The subjects were thermally neutral at each condition and wore 0.6 and 1.15 clo, respectively. Each experiment lasted for 2.5 hours and no significant influence of enthalpy on performance was detected (Wyon et al., 1975). The findings were similar to an unpublished study by Fang (1998), who did not observe any significant improvement in performance when exposing thermally neutral subjects to air enthalpies of 35 kJ/kg (20°C/40%), 45 kJ/kg (23ºC/50%) and 58 kJ/kg (26ºC/60%). The results of the two studies are summarised in Figure 4.2 below together with the findings of this present study.

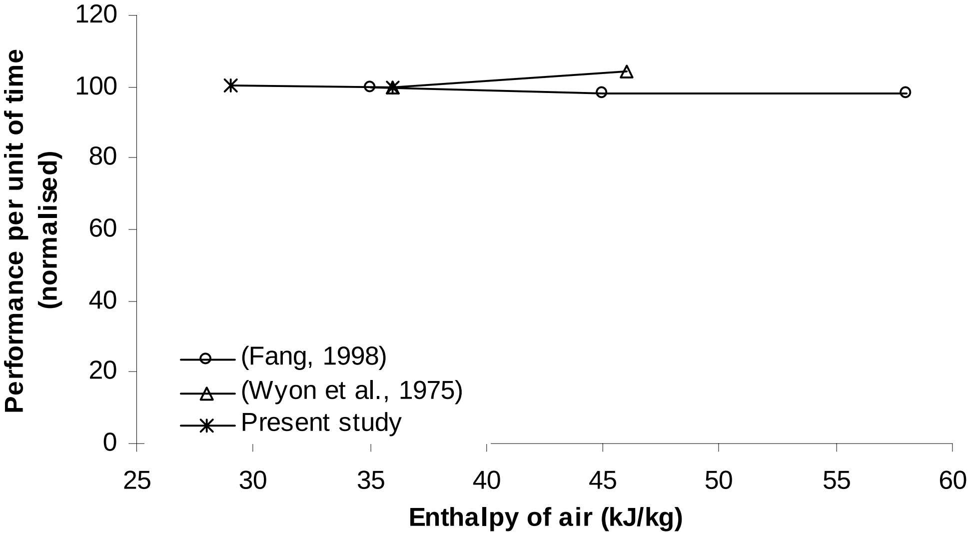


Figure 4.2: Performance as a function of enthalpy in studies by Fang (1998), Wyon et al. (1975) and the present study. No significant impact of enthalpy on performance was found for any of the three studies. The performance data of the studies are text typing (Fang, 1998), addition (Wyon et al., 1975) and text typing (present study).

Figure 4.2 shows that none of the three studies support the hypothesis of the present study of increased performance for decreased enthalpy. The present study distinguished itself from the studies by Wyon et al. (1975) and Fang (1998) by using radiant heating and by exposing subjects to the lowest enthalpies. Neither appeared to have a noticeable effect on productivity, however, occurrence of local thermal discomfort at the 18°C condition (29 kJ/kg) might have inhibited effects on productivity to develop (Figure 4.2).

4.2 Compensation with Clothing and Radiant Heating

Two previous studies investigated the impact of reduced air temperature on performance but found no significant impact (Wyon et al., 1975; Fang, 1998). In both studies the subjects had remained thermally neutral exclusively by modifying their clothing and to an extent the air temperature.

In the present study, the subjects maintained thermal neutrality when exposed to both the air at 23°C and to the air at 18°C. While exposed to the air at 18°C, they compensated evenly with additional clothing and with radiant heating.

Radiant heating was used to reduce the local thermal discomfort of particularly the hands. When a high clothing insulation level is required to maintain thermal neutrality, the hands are likely to become cold, as they are uncovered by clothing. The subjects' assessment of the thermal acceptability of the hands indicated that a higher radiant temperature might have been required, if local thermal discomfort should have been avoided. A study of clothing insulation asymmetry by Olesen et al. (1988) found that increasing the clothing insulation asymmetry raised the preferred thermal sensation of the subjects, due to local thermal discomfort.

The difference in clothing insulation between the two temperature conditions was 0.33 clo, which corresponded to a difference in operative temperature of 2.0°C. Adding this difference of 2.0 °C to the measured operative temperature at the 18°C conditions (20.8°C) returned an equivalent operative temperature of 22.8°C. This is practically the same as the measured operative temperature at the 23°C condition, as this was 22.5°C. Thus the two temperature conditions were comparable in temperature, which follows the finding that the subjects were thermally neutral at both conditions.

The fact that the higher air velocities at 18°C caused draught, added to the local thermal discomfort. But the preferred operative temperature remained the same, as was found by Olesen et al. (1988).

The psychological mechanisms of indoor environment studies were not investigated in the present study. It was decided not to give the subjects individual control of the radiant heating panels, as this would have confounded the benefit of individual control with the reduced air temperature conditions. Wyon (1996) found that individual control of the microclimate alone caused an increase in performance of 5%. Rohles (1986) found that psychological effects had a significant impact on the satisfaction with the indoor environment.

With the additional clothing (leg warmers and fleece jacket) that was provided to the subjects, they wore more clothes than what is typically worn indoors. This could also have reduced the satisfaction with the indoor environment.

One other psychological effect might have occurred. The subjects were exposed to two different air temperatures, which they obviously were aware of. They were asked to wear more clothes at the 18°C conditions. And though they considered themselves thermally neutral, the unusual sensation of being kept warm in an office with radiant heating might have led them to think that the scope of the experiment was to investigate the negative impact of being too cold. If this was the case, they would have considered the reference condition as the "good" condition, and the 18°C conditions as the "bad" ones. Such a distinction could have had an influence on the subjects' assessments. This rather speculative point has not been confirmed from any of the assessments.

4.3 Local Thermal Discomfort

It was found that thermal acceptability peaked at TS = 0.4 when exposed to the air at 23°C, and that the acceptability peaked at TS = 0.5 when exposed to the air at 18°C. Little weight should be put on the absolute values of these findings, but they indicate that the subjects preferred a positive thermal sensation. This follows the finding by Berglund and Fobelets (1987), who found an optimal thermal sensation of 0.2 for a wide variety of moderate indoor environments.

In the present study, the tendency towards a preferred positive thermal sensation is attributed local thermal discomfort. As an indicator of the magnitude of local thermal discomfort, the standard deviation of the thermal sensation votes for individual body parts were used, as suggested by Olesen (1985). It was found, that the standard deviation of the body parts susceptible to local thermal discomfort (hands, feet, neck and face) was higher when exposed to air at 18°C than when exposed to air at 23°C.

A correlation was expected between the temperature of the subjects' hands and their thermal sensation, but also between the fingertip temperature and the speed or error ratio with which the subjects performed the text typing task, and possibly other tasks as well.

A significant difference was found between the fingertip temperatures of subjects exposed to air at 23°C and of subjects exposed to unpolluted air at 18°C, whereas no difference was found between the subjects exposed to air at 23°C and the subjects exposed to the polluted air at 18°C. This unexpected impact of the pollution source on fingertip temperature remains unexplained.

In a study by Witterseh (2001), the fingertip temperature of subjects exposed to three different operative temperatures (22.5°C, 26.0°C and 29.7°C, respectively) increased significantly with the operative temperature. In the present study, the differences in operative temperature between conditions were smaller, which could explain why no significant difference between conditions was found.

A correlation between the thermal sensation votes for the hands and fingertip temperature was found, indicating that fingertip temperature measured with thermistors was a reasonable objective expression of the thermal state of the subjects' hands. A thermographic camera was also used to measure the temperature of the hands, and the photos were used to validate the measurements made with thermistors. A generally good correspondence was found between the two measurements. But some thermistor measurements were substantially (approximately 5°C) lower than the corresponding thermographic measurements. This is taken as an indication of bad thermal contact between hands and thermistors; some subjects might not have held the thermistor correctly between thumb and index finger. Inaccurate thermistor measurements could explain why no systematic increase in fingertip temperature was seen with increasing operative temperature.

The results from the post experimental questionnaire also indicate that local thermal discomfort had been prevalent. The subjects reported that they were more comfortable at 23°C, but more productive at 18°C. They also found that low finger temperature had reduced their performance in the tasks, in particular the text typing task.

This was not supported by the measurements, as no correlation was found between neither the speed nor error ratio of the text typing task. An unexpected trend towards a higher error ratio at higher fingertip temperatures was found. This could be explained by inaccurate fingertip temperature measurements.

Another finding from the post experimental questionnaire was that 12% of the subjects believed that the temperature of the radiant heating panels was adjusted according to their votes on the thermal comfort questionnaire. This is in good accordance with the intention of not confounding the benefits of individual control with any single condition.

The post experimental questionnaire itself is somewhat dubious, as not all subjects returned it, and as the answers could be influenced by the type of questions asked. Brauer et al. (2000) report that the prevalence of symptoms rise, when the questions are suggestive of a problem.

4.4 Limitations of the Methodology and Physical Conditions

The choice of experimental conditions were limited by the available facilities. The cooling capacity of the field laboratory limited the amount of radiant heating that could be supplied. It might have been advantageous to have the subjects wear the same clothes at all conditions, and compensate entirely with radiant heating instead. This would have reduced the discomfort due to clothing insulation level asymmetry. But as the draught appears to have been associated with the reduced air temperature conditions, increased draught is expected, if further cooling of the air should be performed. Vertical air temperature differences might also cause discomfort, which was not the case in the present study.

The even compensation of the reduced air temperature by clothing and radiant heating therefore seems a reasonable choice, for studies performed in the field laboratory. Better results are expected from climate chamber studies, as high airflow rates can be maintained without causing substantial dissatisfaction. The new climate chambers at the International Centre for Indoor Environment and Energy are well suited, as they resemble typical offices in appearance.

The air temperatures used for the experiments (18°C and 23°C) were chosen, as they were considered the lower and upper limits of what subjects clad for winter could be exposed to. Reducing the air temperature below 18°C was not considered, as it would have required further cooling and might have caused substantial discomfort. It was considered to have the subjects wear the same clothes in terms of clothing insulation level at all conditions. This required the warm condition air temperature to be 20.5°C instead of 23°C. Such a difference was insufficient to show an impact of the reduced air temperature, and the idea of using air at 20.5°C was given up.

A higher air temperature than 23°C could have been used. This would have made it more difficult to change conditions (on most days, only 1 hour separated two different conditions). More importantly, it was desired that the condition with high temperature should be a reference situation, which resembled the typical office environment. For this purpose, 23°C was a reasonable choice.

The calculation of the operative temperature required knowledge of the shape factor between a seated body and the radiant heating panels. A reasonable estimate was made, but a thermal manikin was required for a more accurate determination. As the thermal manikin was unavailable before the conduction of the experiments, the shape factor was not determined until after the experiments. The shape factor determined with the thermal manikin was 0.18, and the estimated shape factor was 0.20. As the surface and air temperatures used to calculate the operative temperature were recorded, it would have been possible to recalculate the operative temperature based on the correct shape factor. This was not done, as the inaccuracy in the calculation of the operative temperature was small.

The mean air temperature of the workstations matched the target for all sessions. But systematic differences between the workstations were observed. The air in workstations 1 and 2 was lower than the air temperature in workstations 3 and 4. The difference is explained by the flows of cold air from the technical zone to the occupied zone, which bypassed workstations 3 and 4, thus cooling workstations 1 and 2 more. This could have had an impact on the results. The impact of differences between the workstations was investigated by including the workstation numbers as factors in the analyses of variance. Generally no impact of workstation number was seen on the results, which indicates that the differences were insignificant.

Time of day and weekday were also considered to be factors that could have had an impact on the results. These factors were also used as factors in the analyses of variance. No impact of neither time of day nor weekday was seen in general. This was also the case for such perceptions as “tiredness” and “sleepiness”. Thus, conducting experiments in the evenings between 19:00 and 22:00, and in the weekends between 10:00 and 13:00 should not be avoided from fear of confounding factors of interest with time of day or weekday.

The sets of tasks used for the proof reading and text typing tasks could have been different in difficulty or how interesting the subjects considered them. This could have had an impact on the results, but generally no significant difference between the sets of tasks were found.

4.5 Practical Applications

The combination of reduced air temperature and radiant heating is expected to be beneficial to the human perception of the indoor environment, if the local thermal discomfort issues can be properly addressed.

In the present study, the air temperature was kept low while radiant heating was supplied. The radiant heating panels used a substantial amount of energy, which was removed from the room by air conditioning, and by maintaining a high ventilation rate. The set-up, as it was used for the present study, is therefore not suited for practical use; the electricity consumption is unacceptably high compared to the benefits from an increased air quality. It was not the purpose of the present study to develop a complete system. For commercial applications, simultaneous heating and cooling is unethical and altogether unacceptable.

Applications are therefore limited to situations with substantial heating requirements. These could include office environments in cold climates, where radiant heating could be used in the workplaces to locally increase the operative temperature while the air temperature remains considerably lower. For example, workstations at assembly lines in big factory halls requiring high ventilation rates could make use of radiant heating for establishment of local comfortable microclimates. This could yield substantial energy savings.

Other applications could be found, where local differences in temperature or clothing insulation level must be upheld. One example is a supermarket in winter, where the customers will expect a thermal environment suitable for their overcoats, while the employees might wear less clothes and have a lower metabolism, and thus prefer a higher temperature. Increasing the operative temperature in the employees’ workplaces with radiant heating could be a solution.

As reducing the air temperature improved the perceived air quality, reduced air temperature could be used instead of increasing the ventilation rate, insofar no health risks are created.

But the practical problems of locating radiant heating panels close to the workplace of occupants pose a barrier, as does (at least in Denmark) the use of electricity for comfort heating.

4.6 Further Research

Further research of the impact of reduced air temperature on the prevalence symptoms and performance is needed. The present study confirmed the impact of reduced air temperature on perceived air quality that was found in the studies by Fang (1997) and Toftum et al. (1998). The indication of a reduced prevalence of symptoms at reduced air temperatures should be investigated further.

Local thermal discomfort should be addressed, so that it is not confounded with any single condition. This could be done by conducting the experiments in a climate chamber, where a high ventilation rate can be maintained without causing discomfort from draught.

Discomfort due to clothing insulation asymmetry should also be addressed. Ideally, the difference in clothing insulation level should be sufficiently small not to cause any dissatisfaction. This could be done by using radiant heating to a larger extent.

5 Conclusions

- Reducing the air temperature from 23°C to 18°C significantly decreased the number of dissatisfied with the air quality from 20% dissatisfied to 6% dissatisfied. The air at 18°C was also perceived as being fresher than the air at 23°C.
- A tendency towards a lower prevalence of symptoms among subjects exposed to air at 18°C was found. No impact on performance of neither air temperature nor pollution source was found. The pollution source used was 80m² of old carpet.
- Though thermally neutral under all conditions, the thermal acceptability of the body was lower at 18°C (13% dissatisfied) than at 23°C (5% dissatisfied), due to higher local thermal discomfort. This was caused by increased draught and clothing asymmetry at the 18°C condition. A tendency towards preferring a thermal sensation of the body higher than zero was observed at both temperature levels.
- Reducing the air temperature and adding a pollution source decreased the percentage dissatisfied with the air quality from 20% to 14%. The polluted air at 18°C was more satisfactory than the unpolluted air at 23°C, but less satisfactory than the unpolluted air at 18°C.
- Females were more dissatisfied with the polluted air than males.
- Reducing the air temperature thus increased the acceptability of the air quality, while decreasing the thermal acceptability. This could have had an impact on the small difference in symptom prevalence. As a result, no significant change was found in the subjects' assessments of the general indoor environment between the two air temperatures.
- Reducing the air temperature and introducing a pollution source significantly increased the percentage dissatisfied with the general indoor environment. A tendency towards the prevalence of symptoms being highest when exposed to the polluted air was found.

References

ASHRAE Standard 62 (1989) “Ventilation for Acceptable Indoor Air Quality.”

ASHRAE Thermal Comfort Tool, version 1.00. Software for PMV calculations.

Awbi, H.B. (1991) “Ventilation of Buildings”, E & FN Spon. ISBN 0-419-21080-9.

Bachmann, M.O. and Myers, J.E. (1995). “Influences on Sick Building Syndrome Symptoms in three Buildings”. Soc. Sci. Med., Vol. 40, no. 2, pp. 245-251.

Berglund, L.G. and Fobelets, A.P.R. (1987) “Subjective Human Response to Low-level Air Currents and Asymmetric Radiation.” ASHRAE Transactions, Vol. 93, pp. 497-523.

Bholah, R.; Fagoonee, I.; Subratty, A.H. (2000). “Sick Building Syndrome in Mauritius: Are Symptoms Associated with Office Environment”. Indoor Built Environment, 2000, 9:44-51.

Bland, M. (1999) “An Introduction to Medical Statistics”, Oxford Medical Publications. ISBN 0-19-262428-8.

Bluyssen, P.M. and Fanger, P.O. (1991) “Addition of Olfs from Different Pollution Sources, determined by a Trained Panel.” Indoor Air, 4, pp 414 – 421.

Brauer, C.; Mikkelsen, S.; Skov, P. (2000). ”Reliabiliteten og validiteten af et nyt spørgeskema til undersøgelse af indeklimasymptomer og oplevelse af indeklimaet”. Arbejdsmedicinsk klinik, Amtssygehuset i Glostrup.

CEN Report CR 1752 (1998) “Ventilation for buildings – Design criteria for the indoor environment.”

Clausen, G., Carrick; L., Fanger, P.O.; Kim, S.W.; Poulsen, T. and Rindel, J.H. (1993) “A Comparative Study of Discomfort caused by Indoor Air Pollution, Thermal Load and Noise.” Indoor Air, Vol. 3, pp. 255-262.

Conradsen, K. (1995) “En introduktion til statistik”, 6. udgave. Institut for Matematisk Modelering. Danmarks Tekniske Universitet.

Fang, L. (1998) Unpublished study of human performance at different enthalpies of air . International Centre for Indoor Environment and Energy.

Fang, L. (1997) “Impact of Temperature and Humidity on Perceived Indoor Air Quality.” Department of Energy Engineering, Technical University of Denmark.

Fanger, P.O. (1970) ”Thermal Comfort.” Danish Technical Press.

Fanger, P.O.; Ipsen, B.M.; Langkilde, G.; Olesen, B.W.; Christensen, N.K. and Tanabe, S. (1985) “Comfort limits for Asymmetric Thermal Radiation”. Energy and Buildings, 8, pp. 225-236.

Gunnarsen, L. and Fanger, P. O. (1989) “The Influence of Adaptation on Acceptability of Indoor Air Pollution”. Proceedings of Clima 2000, Sarajevo, Yugoslavia, Vol. 3, 49-54.

Gunnarsen, L. and Fanger, P. O. (1992) ”Adaptation to Indoor Air Pollution”. Energy and Buildings, 18, 43-54.

Hansen, H.E. et al. (1992) ”Indeklima. Varme- og klimateknik: Danvak grundbog.” Danvak Aps. Teknisk Forlag, Denmark.

Hedge, A.; Erickson, W.A. and Rubin, G. (1996). “Predicting Sick Building Syndrome at the Individual and Aggregate Level”. Environment International, Vol. 22, No. 1, pp 3-19.

Heinemeier, K.E.; Schiller, G.E. and Beneton, C.C. (1990) “Task Conditioning for the Workplace: Issues and Challenges.” ASHRAE Transactions 1990, part 2, pp. 678-689.

Imamura, R. et al (1998) ”Manual performance in cold conditions while wearing NBC clothing”. Ergonomics 41/10, pp. 1421 – 1431.

ISO 7730 (1994) “Moderate thermal environments – Determination of the PMV and PPD indices and specification of the conditions for thermal comfort.”

ISO 9920 (1995) “Ergonomics of the thermal environment – Estimation of the thermal insulation and evaporative resistance of a clothing ensemble”. First edition.

Jaakkola, J.J.K; Heinonen, O.P; Seppanen, O. (1989) “Sick building syndrome sensation of dryness and thermal comfort in relation to room temperature in an office building. Need for individual control of temperature”. Environment International, Vol.15, pp. 163-168.

Lagercrantz, L. et al. (2000) ”Negative Impact of Air Pollution on Productivity: Previous Danish Findings reapeated in new Swedish Test Room”. Proceedings of Healthy Buildings 2000.

Langkilde, G.; Alexandersen, K.; Wyon, D.P. (1973) “Mental Performance During Slight Cool or Warm Discomfort”. Arch. Sci. Physiol., Vol. 27, A, pp. 511-518.

Melikov, A. (1999) “Assesment of Air Distribution Performance for a Thermal Microclimate”. Task description for course 77384: Indoor Climate. International Centre for Indoor Environment and Energy. Technical University of Denmark.

Mendell, M. J.; Fisk, W.J. et al. (1996). ”Elevated Symptom Prevalence Associated with Ventilation Type in Office Buildings”. Epdemiology 1996, 7/6, pp. 583-589.

Menzies, D; Tamblyn, R.M. et al. (1996) “Exposure to Varying Levels of Contaminants and Symptoms among Workers in two Office Buildings”. American Journal of Public Health, 1996 86/11, pp. 1629-1633.

McIntyre, D.A.; Griffiths, I.D. (1972) “Subjective Response to Radiant and Convective Environments.” Environmental Research 5, pp. 471-482.

McNall, P.E. Jr. and Biddison, R.E. (1970) “Thermal and Comfort Sensations of Sedentary Persons Exposed to Asymmetric Radiant Fields.” ASHRAE Transactions, Vol. 76, Part 1, pp. 123-136.

Mills, A. F. (1992) “Heat Transfer.” Richard D. Irwin.

Montgomery, D.C. (1997) “Design and Analysis of Experiments.” Fifth edition, John Wiley and Sons, New York.

Olesen, B.W.; Hasebe, Y. and Dear, R.J. de (1988) “Clothing Insulation Asymmetry and Thermal Comfort”. ASHRAE Transactions 1988 Vol. 94, part 1, pp. 32-51.

Olesen, B.W. (1985) “Local Thermal Discomfort”. Technical Review, no. 1. Brüel & Kjær. Denmark.

Rasmussen, L.W. (1997) ”Individuel regulering af det termiske indeklima”. Institut for Energiteknik. Laboratoriet for Indeklima og Energi. Danmarks Tekniske Universitet.

Rode, C. (1998) ”Fugttransport. Opstilling af regneark til beregning af fugtdiffusion after Glasers metode”. Undervisningsnotat U-022. Department of Buildings and Energy, Technical University of Denmark.

Rohles, F.H. Jr. (1986) “Temperature or Temperament: A Psychologist looks at Thermal Comfort.” ASHRAE Transactions 1986, part 1, pp. 541-551.

Spliid, H. (2001) DTU-course: Design and Analysis of Experiments. Department of Mathematical Modelling. Technical University of Denmark.

Tanabe, S., Zhang, H.; Arens, E.A., Madsen, T.L. and Bauman, F.S. (1994) ”Evaluating Thermal Environments by using a Thermal Manikin with Controlled Skin Surface Temperature” ASHRAE Transactions 1994, Vol. 100, issue 1, pp. 39-48.

Toftum, J.; Jørgensen, A.S. and Fanger, P.O. (1998) “Upper limits of Air Humidity for Preventing Warm Respiratory Discomfort”. Energy and Buildings, Vol. 28, (1), pp. 15-23.

Wargocki, P. (1998) “Human Perception, Productivity and Symptoms Related to Indoor Air Quality.” Centre for Indoor Environment and Energy, Technical University of Denmark. ISBN: 87-7475-201-4.

Wargocki, P. (1999) “Perceived Air Quality, Sick Building Syndrome (SBS) Symptoms and Productivity in an Office with Two Different Pollution Loads.” Indoor Air 9, pp 165 -179.

Wargocki, P. (2000) “The Effects of Outdoor Air Supply Rate in an Office on Perceived Air Quality, Sick Building Syndrome Symptoms (SBS) Symptoms and Performance”. Indoor Air 10, pp. 222-236.

Witterseh, T. (2001) “Environmental Perception, SBS symptoms and the Performance of Office Work under Combined Exposures to Temperature, Noise and Air Pollution” Ph.D. Thesis, MEK-I-Ph.D. 01-01. International Centre for Indoor Environment and Energy. Department of Mechanical Engineering. Technical University of Denmark.

Wyon, D.P. (1996) “Individual Microclimate Control: Required Range, Probable Benefits and Current Feasibility.” Indoor Air ’96, Vol. 1, pp. 1067-1072.

Wyon, D.P.; Fanger, P.O.; Olesen, B.W. and Pedersen, C.J.K. (1975) “The Mental Performance of Subjects Clothed for Comfort at Two Different Air Temperatures.” Ergonomics 18. pp. 359-374.

Wyon, D.P. (2001) “Methodology for Indoor Environmental Research”. International Centre for Indoor Environment and Energy. Contribution to the ICIE Symposium held 20 March 2001 to mark the official opening of the 6-climate-chamber experimental suite.

Zar, J.H. (1999) “Biostatistical Analysis” 4th edition, Prentice.