Effects of Indoor Climate on Occupants’ Perception and Work Performance in Office Environment

Henna Maula
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A doctoral dissertation completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Engineering, at a public examination held at the lecture hall R1 of the school on 10 January 2018 at 12.

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This thesis examines the effects of indoor climate on occupants’ comfort, perception and work performance, and whether local cooling with cooling jet can improve the indoor environment in warm office conditions. The focus is on the effects of room air temperature, indoor air quality and airflow on occupants’ subjective reactions and performance. Four publications are included, in which one describes a series of laboratory experiments which study the room air flow pattern, and three are based on human subject experiments. The results show that the mean air speed seems to increase with cooling load and badly implemented layout in office can cause draught (Publication I). The flow pattern in the room is not stable and the position of draught risk areas can change in time and also due to changes in room heat sources (Publication I). On the other hand, insufficient air conditioning seems to have a negative effect especially on subjective measures (Publication II and III). Providing fresh air into workstation via cooling jet, seems to have a positive effect on subjective measures in slightly warm office environment (Publication IV). Inadequate air conditioning appears to affect thermal comfort (Publication II) and perceived indoor air quality (Publication III), which are both improved by the cooling jet (Publication IV). Results from objective measures show that cognitive performance may not be as sensitive to changes in temperature as suggested by Seppänen et al. (2006a) and that the effect of temperature on performance is task dependent (Publication II). Results also suggest that emissions from occupants, i.e. human bioeffluents do not have as strong effect as previously seen with emissions from external pollution source (Seppänen et al., 2006b; Publication III). However, according to subjective measures, the disturbance of heat on performance seems to be increased by slightly warm temperature (Publication II) and by low ventilation rate with elevated levels of human bioeffluents (Publication III). Slightly warm temperature also seems to increase the disturbance of stuffiness (Publication II). The cooling jet appears to decrease the disturbance of heat and the disturbance of stuffiness in slightly warm temperature (Publication IV). The energy consumption and risk of draught are among the main problems when air conditioning systems are used in offices with high thermal load, such as open-plan offices with high density of workstations. One solution may be to allow slightly elevated temperatures in the space and to provide local cooling using jet with fresh air into the workstation. This kind of solution together with personal control over the airflow allows occupants to adjust the individual thermal environment to gain better thermal comfort while energy consumption of air conditioning could be reduced. More research is needed to find the optimum indoor environment solution regarding energy savings and occupants’ comfort, in which room air temperature is slightly raised and individual control over the thermal environment at workstation is provided via cooling jet.

Keywords: airflow, thermal comfort, indoor air quality, cooling jet
My research work on ventilation and thermal comfort started at the Finnish Institute of Occupational Health (FIOH) in 2008. In addition of my full-time work at the FIOH, I started my doctoral studies in Aalto University as a part-time student in 2010. The research leading to this thesis was conducted in 2008-2017 at the Indoor Environment laboratory, which functioned in FIOH until the end of year 2015 and was moved to Turku University of Applied Sciences at the beginning of year 2016. During those years I had two maternity leaves from spring 2013 to spring 2014 and from summer 2015 to autumn 2016. All the projects were financially supported by Tekes (The Finnish Funding Agency for Technology and Innovation) and participating companies. Research work for all Publications (I-IV) was carried out in collaboration with my colleagues in Indoor Environment laboratory.

I first participated in the MAKSI project (Modelled and perceived indoor environment, 2005-2008), in which the aim was to improve the knowledge to create good thermal and acoustic environment in offices. The project included topics such as the effect of indoor environment on perception and work performance, modelling and design of indoor environment, and development and modelling of products used for controlling the indoor environment. The project was carried out in six sub-projects. Publication I of this dissertation presents the results of one sub-project regarding modelling of air flow patterns in rooms. The MAKSI project was the beginning of a nationally entirely new multidisciplinary research area which combines psychology, building physics and work environment research. After MAKSI project, the research in this area continued in the TOTI project (User-oriented Office Space, 2009-2012) and in the RYM Indoor Environment research program (2011-2015).

The aim of the TOTI project was to investigate the effects of a poorly planned indoor environment on open-plan office workers and how effective planning can help solve problems. Research methods included laboratory experiments, field surveys and longitudinal experiments. The project was carried out in four work packages. My main contribution was in the work package 1, where the effects of indoor environment factors, such as ventilation, temperature, noise, room acoustics and interior design on work performance and comfort was studied. Publications II and III presents results of two out of three laboratory experiments with human subjects in this dissertation. The work of the Publications II and III was carried out within the TOTI project and the RYM Indoor Environment research program.
The aim of the RYM Indoor Environment research program was to create solutions that promote productivity, comfort and health of space user in ecologically sustainable way. The research program was carried out in four work packages. My contribution was in work package called User-Centric Indoor Environment. Publication IV of this dissertation presents the results of one laboratory experiment with human subjects, which was done in that work package. The study is also part of IEA EBC Annex 62 Ventilative cooling.

It has been an honour to have Associate Professor Pawel Wargocki from Technical University of Denmark and Associate Professor Ilinca Năstase from Technical University of Civil Engineering of Bucharest, Romania, as the preliminary examiners of this thesis.

I want to express my sincere gratitude to my thesis advisor Adjutant Professor Valtteri Hongisto for the excellent scientific training and guidance, and invaluable advices.

I am grateful to Professor Arsen Krikor Melikov, my thesis second advisor, for all the valuable advices at the beginning of my studies, and for the possibility to visit Technical University of Denmark to gain practical lesson on performing human subject experiments.

I would like to thank my supervising professor Kai Sirén for letting me work very independently and for taking care that things went smoothly during my doctoral studies at Aalto University.

My special thanks go to my research colleagues Hannu Koskela, Annu Haapakangas and Johanna Varjo for their valuable feedback on my research work and useful advices. I’m grateful to David Oliva for programming and to Jarkko Hakala for the construction work in the laboratory and the help with the development of inlet device producing cooling jet (Publication IV). I would also like to thank Pekka Saarinen, Petri Kalliomäki, and the rest of the research group working in the Indoor Environment laboratory in Turku. I thank Esa Sandberg (Satakunta University of Applied Sciences) for his ideas for the ventilation design.

My sincere thanks go to all co-authors of the Publications (I-IV): Valtteri Hongisto, Hannu Koskela, Annu Haapakangas, Risto Kosonen, Mika Ruponen, Jukka Hyönpää, Lauri Östman and Viivi Naatula. I’m grateful for their contribution, and for all the suggestions on how to improve the papers.

The financial support of Tekes (The Finnish Funding Agency for Technology and Innovation), the Finnish Institute of Occupational Health, Turku University of Applied Sciences and several participating companies is gratefully acknowledged.

Finally, I would like to thank my husband Janne for his encouraging words and support during the whole thesis process, and my children Hanna and Akseli for bringing so much happiness and joy in my life.

Henna Maula
Turku, Finland, October 17, 2017
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List of Abbreviations and Symbols

$A_{oz}$  The floor area of the occupied zone (m$^2$)

$CO_2$  Carbon dioxide concentration level (ppm)

$DR$  Draught Rate (%)

$f_{cl}$  The clothing surface area factor

$h_c$  The convective heat transfer coefficient (W/(m$^2$·K))

$I_{cl}$  The clothing insulation (m$^2$·K/W)

$M$  The metabolic rate (W/m$^2$)

$p_a$  The water vapour partial pressure (Pa)

$PMV$  Predicted Mean Vote

$P_{oz}$  The number of people in occupied zone during typical usage (person)

$PPD$  Predicted Percentage Dissatisfied (%)

$Q$  Ventilation rate (L/s·person)

$RH$  Relative humidity (%)

$t_a$  The air temperature (°C)

$t_{a,t}$  The local air temperature (°C)

$t_{cl}$  The clothing surface temperature (°C)

$\bar{t}_r$  The mean radiant temperature (°C)

$Tu$  The local turbulence intensity (%)

$V_a$  The outdoor airflow rate required per unit area (L/s·m$^2$)

$\bar{v}_{a,t}$  The local mean air velocity (m/s)

$\nu_{ar}$  The relative air velocity (m/s)

$V_{oz}$  The outdoor airflow rate in occupied zone (L/s)

$V_p$  The outdoor airflow rate required per person (L/s·person)
$W$  The effective mechanical power (W/m²)
List of Publications

This doctoral dissertation consists of a summary and of the following publications which are referred to in the text by their numerals


III. Maula, Henna; Hongisto, Valtteri; Naatula, Viivi; Haapakangas, Annu; and Koskela, Hannu. The effect of low ventilation rate with elevated bioeffluent concentration on work performance, perceived indoor air quality and health symptoms. Indoor Air. 2017;00:1–13. DOI: 10.1111/ina.12387

Author’s Contribution

Publication 1: Air distribution in office environment with asymmetric workstation layout using chilled beams

The paper was planned, written and revised in collaboration with the other authors. The first author did the main writing of the article. The present author (Häggblom, current: Maula) did the set-up of the cases, measurements and the visualization of the flow pattern in the laboratory. Simulations were done by the first author.

Publication 2: The effect of slightly warm temperature on work performance and comfort in open-plan office

The paper was planned, written and revised in collaboration with second, fourth and fifth authors. The present author did the set-up of ventilation and the thermal environment, did the measurements regarding ventilation and thermal environment, analyzed the data collected from questionnaires and performance tasks, and did the main writing of the article. The experimental design was planned in collaboration with second, third, fourth and sixth authors, so that the third author did the main planning of the experimental design. The third author planned, organized and implemented the human subject experiments.

Publication 3: The effect of low ventilation rate with elevated bioeffluent concentration on work performance, perceived indoor air quality and health symptoms

The paper was planned, written and revised in collaboration with the second, fourth and fifth authors. The present author did the set-up of ventilation and the thermal environment, did the measurements regarding ventilation, thermal environment and indoor air quality, analysed the data collected from questionnaires and performance tasks, and did the main writing of the article. The second and third author planned the experimental design based on the experimental design in Publication II. The third author organized and implemented the human subject experiments.
Publication 4: The effect of cooling jet on work performance and comfort in warm office environment

The paper was planned, written and revised in collaboration with the other authors. The present author did the set-up of ventilation and the thermal environment, did the measurements of ventilation, thermal environment and indoor air quality, analyzed the data collected from questionnaires and performance tasks, and did the main writing of the article. The present author also did the main planning of the experimental design based on the experimental design in Publications II and III, organized and implemented the human subject experiments (recruited participants, planned the schedule of the whole experiment, made the procedure used during sessions, updated the previously used questionnaires to fit the current research question, and act as supervisor during sessions). The present author designed, with the help of third author, the device producing the cooling jet. Measurements regarding the airflow pattern of the jet were done by the present author. Simulations of the cooling jet were done by the third author.
Introduction
1. Introduction

Organizational changes in companies are often continuous and require flexible changes in workspaces. Efficiency demands have led to increased density of the workstations in offices. This development has increased internal heat loads in open-plan offices. On the other hand, compact construction in new office buildings prevents heat leakage through building structure leading to increased indoor temperature. Therefore, the need of cooling may occur in all seasons, even in winter season, in offices in Finland. Room air temperature can be controlled with an air conditioning system which typically provides consistent cooling not only to the occupied zone, but to the whole space. The costs and the energy consumption of air conditioning can be significant.

Thermal environment and indoor air quality are, after noise and lack of acoustic privacy, the most complained factors of the indoor environment in offices (Clements-Croome and Baizhan, 2000; Monn and Vanis, 2011; Pejtersen et al., 2006). Too high room temperature has been suggested to affect occupants’ comfort (Clausen et al., 1993; Clements-Croome, 2006), symptoms (Fang et al., 2004; Lan et al., 2011; Monn and Vanis, 2011) and work performance (Clements-Croome, 2006; Seppänen et al., 2003; Seppänen et al., 2006a). While the effect of temperature on comfort and symptoms is clearly observed in many studies, it seems that the effect of temperature on performance may be task dependent (Hancock et al., 2007; Häggblom et al., 2011; Tanabe and Nishihara, 2004). A deeper knowledge about task performance in cognitively complex tasks in thermally different office environments is needed.

Improper ventilation has been found to affect symptoms, perceived indoor air quality and work performance (Bakó-Biró et al., 2004; Fanger, 2006; Seppänen et al., 1999; Seppänen et al., 2006b; Wargocki et al., 2000; Park and Yoon, 2011). Laboratory studies with external pollution source have observed significant effect of ventilation on perceived indoor air quality (Wyon, 2005). In modern clean offices, emissions from building materials are rather low due to indoor environment classifications, such as the M1 classification in LVI 05e10440 (2008) in Finland, leading to that the relative proportion of pollution load from occupants, that is, human bioeffluents, is rising and occupants themselves may often be the main pollution source. The effect of ventilation on symptoms, perceived indoor air quality and work performance may not be the same compared to above mentioned studies when only the level of bioeffluents is increased. There is a need for more studies to determine whether human bioeffluents have adverse effects on occupants in office environment.
Questionnaire surveys done in Finnish offices revealed that big part of thermal condition complaints are focused on draught (Hongisto et al., 2012). One factor causing draught problems is room airflow. It becomes a problem especially in offices with high thermal load when room airflow patterns are difficult to predict and control. Simulations can be used to predict thermal environment of a room. Measurements are needed to validate the models of simulations and to gain better understanding of the behavior of room airflow. Changes in thermal load and in layout can have a major impact on airflow patterns and occupants’ comfort. However, with a proper design of air condition, airflow can be used to improve thermal comfort, perceived indoor air quality and perceived performance.

ASHRAE 55 (2010), ISO 7730 (2005) and EN 15251 (2007) standards allow the use of elevated air speed to increase the maximum operative temperature for acceptability. The increased air movement with air terminal device installed into the desk has found to reduce the negative effect of increased air temperature on perceived air quality (Melikov and Kaczmarczyk, 2012). Using clean outdoor air in jet applications may be beneficial, since it seems to reduce the intensity of SBS symptoms while recirculated room air seems not (Melikov and Kaczmarczyk, 2012). However, installing an air terminal unit providing clean outdoor supply air into the desk might complicate the layout changes in offices. Integrating the cooling jet to the HVAC system and placing the air terminal unit into the ceiling, might be a solution which enables layout changes with less effort.

There is very little knowledge how cooling jet from the ceiling affects occupants’ perception, symptoms and working memory performance in warm office environment. The use of local cooling, e.g. cooling jet, may enable energy savings by allowing the room air temperature to rise without causing thermal discomfort. Therefore, it is important to study the effect of a cooling jet on occupant comfort, SBS symptoms and work performance.

1.1 Objectives

The main objective of this thesis was to examine the effect of room air temperature, indoor air quality and airflow on occupants’ perception, comfort and cognitive performance in a simulated office environment.

The specific objectives of this thesis are:

- to characterize the flow pattern and thermal conditions in a laboratory representing a flexible open-plan office with chilled beams.
- to examine the maximum air speed and draught risk in occupied zone in open-plan office laboratory with chilled beams.
- to determine the effect of slightly warm temperature of performance in tasks with different cognitive demand in open-plan office laboratory.
Introduction

- to assess the effect of temperature on perceived performance, thermal comfort, symptoms, perceived fatigue and subjective workload in open-plan office laboratory.
- to determine the effects of low ventilation rate with increased human bioeffluents on work performance in tasks with different cognitive demand in open-plan office laboratory.
- to assess the effect of low ventilation rate with increased human bioeffluents on perceived performance, perception of air quality, symptoms, subjective workload and perceived fatigue in open-plan office laboratory.
- to determine the effect of a cooling jet from the ceiling on cognitive performance, perceived performance, perceived indoor air quality, thermal comfort, symptoms, perceived fatigue and subjective workload in warm open-plan office laboratory.
- to study the perception of the jet in warm open-plan office laboratory.

1.2 Novelty aspects

The novelty aspect of the research included in this thesis is high. The main problems causing discomfort among occupants due to the incorrect use of air conditioning systems in offices with high thermal load are divided into sections. Each section is studied independently. Similar methods, measurement design, the same open-plan office laboratory with the same furniture and office equipment, and environment conditions, other than the studied independent variable, are used in all three human subject experiments.

The first novel feature of the work is that the effects of slightly warm room temperature and low ventilation rate with elevated levels of human bioeffluents on occupants’ subjective reactions and performance, are studied separately using the same methods, design and partially same questionnaires and performance tasks. Often, room temperature is raised while indoor air quality is reduced, making it difficult to draw conclusions only on temperature or indoor air quality. The literature is lacking this kind of parallel studies.

The second novelty is that the problems found in each section, such as increased local air speed (Publication I), raised temperature (Publication II) and perceived indoor air quality (Publication III), are taken into account and turned into a solution, i.e. the cooling jet, which could enable energy savings still maintaining occupants’ comfort. The effect of the cooling jet on occupants’ perception and performance is studied with same methods, design and part of objective and subjective measures as in studies regarding only room temperature or indoor air quality.

The third novel feature of the work is that wide variety of tasks measuring different cognitive processes are used in human subject experiments. Those tasks are well known in research field of psychology, but literature is still lacking the knowledge on how room air temperature and indoor air quality is affecting the performance in those tasks.
The fourth novelty is that performance results are compared to widely known models of the effect of temperature (Seppänen et al., 2006a) and the effect of ventilation rate (Seppänen et al., 2006b) on work performance. According to Seppänen et al. (2006a and 2006b), those models are applicable as a first approximation but they have high level of uncertainty. There is a need for studies in which comparisons of work performance measurement results and Seppänen’s models are done. So far, no such a comparison is done with tasks used in Publications II and III.

1.3 Limitations

Measurements in Publication I represent only the situation in that certain environment. Despite results are in agreement with previous findings, the specific flow patterns and air velocities cannot be generalized in to all office environments.

In Publications II-IV, subjects were given clothing instructions and reported values for clothing insulation was estimated according to the standard ISO 7730 (2005). The activity level was estimated according to the ISO 7730 standard using the main task (typing). The subjects’ clothing insulation and activity level were not measured and body composition was approximated to be equal for all subjects (as in ISO 7730), which may partly explain the large individual differences in thermal comfort (see deviations in thermal sensation votes in Figures 12 and 16).

Despite an extensive variety of different task types were used in Publications II and III, the tasks do not cover all kind of office work. Results cannot be directly applied for example to teamwork or communication tasks.

In Publication IV, the focus was on one type of jet with fixed room temperature, fixed jet temperature, air velocity, direction, distance between subject and the nozzles, relative humidity, and with subject’s fixed clothing insulation and activity level. There are limitations in generalizing the results in Publication IV, since there are numerous ways providing the cooling jet and other above-mentioned boundary parameters.

There are limitations to generalizing these results in practice. All of the subjects were healthy young adults. Different results might be possible with elderly subjects (Schellen et al., 2010). It should also be acknowledged that a shorter exposure time than a normal 8-h workday was used and the subjects knew how long the experiment would last. The effect of exertion cannot be ruled out.

1.4 Organization of the thesis

This thesis consists of introductory overview and four publications. In introductory overview the problems caused by improper ventilation are described first. Methods and experimental designs are explained second, and then the main results are represented separately for each publication. Publications I, II and III
are related to the problems caused by improper ventilation and Publication IV presents a solution which may enable energy savings by allowing the temperature to rise without causing thermal discomfort or weakened perceived indoor air quality in a modern clean office with low material and equipment emission load.

A series of laboratory experiments were done which studied the room air flow pattern (Publication I); the effect of warm office environment on thermal comfort, symptoms and cognitive performance (Publication II); the effect of low ventilation rate with increased human bioeffluents, on perceived indoor air quality, symptoms and cognitive performance (Publication III); and the effect of cooling jet on thermal comfort, indoor air quality, symptoms and cognitive performance in warm office environment (Publication IV).

Section 2 shortly describes the theoretical foundation of this thesis. First, airflow interactions, measurements and visualizations in office environment is described. Then target values regarding thermal comfort and indoor air quality are characterized. The effects of thermal comfort, indoor air quality and air movement providing local cooling on occupants’ comfort, symptoms and performance in office environment are described.

Section 3 presents the methods used in the measurements. First, laboratories and measurements of indoor environment and measurements of airflow patterns are described. Then summary of the methods used in human subject experiments is given. Performance measures, questionnaires and statistical analyses are described at the end of section 3.

Section 4 shows the main results of the publications. The results of each publication are presented separately.

Section 5 discusses the results and recommendations on future research. Conclusions are drawn in Section 6.
Introduction
2. Theoretical foundation

2.1 Airflow interactions in office environment

Forced flows generated by a ventilation system and convective flows generated by heat sources (occupants, computers, lights, warm or cold surfaces, such as windows) affects air distribution in an office. The interaction of cool downward flow from the ventilation and warm upward flow from the heat sources makes the room flow pattern complex and difficult to predict and control.

In cooling conditions, the room airflow pattern depends on the locations of air distribution units and the layout of the office. Asymmetry of the heat loads and the cooling device may cause strong circulation in the office shifting the downward supply air jet away from its original position (Figure 1).

Kosonen et al. (2007) studied the impact of heat load distribution and strength on the supply air flow pattern from chilled beams. They found that the maximum air speed in the occupied zone depends on location and thermal effect of the heat sources. The maximum velocity in the occupied zone has found to increase with the heat load (Müller et al., 2004). In ideal conditions, the positions of air distribution units and workstations would be symmetrical, which would make the control of conditions in workstations easier. However, the positions of the workstations are often varied according to the current use of the office and the layout of the chilled beams in relation to the workstations becomes asymmetric. Omission of adjusting the flow pattern may lead to reduced thermal comfort, such as draught problems, in workstations.

The airflow pattern can be determined by measurements and by visualization. Typically smoke is used in visualizations (Figure 1 b). Measurements can be done with different kind of anemometers, such as, thermal anemometers (hot-sphere anemometers and hot-wire anemometers), ultrasonic anemometers or laser Doppler anemometers. Despite different measurement techniques and physical properties of equipment, a good comparability between above-mentioned anemometers in a low turbulent velocity field has been observed (Kandzia et al., 2012). From the measurements and the visualization of the airflow pattern the disturbance of the airflow can be estimated and improvements can be done to increase occupants’ comfort.
Theoretical foundation

Figure 1. a) Example of an airflow pattern in an office room with chilled beam (marked with blue colour) and one occupant. Heat sources (lighting in the roof, heater beneath the windows and cylinder representing occupant) are coloured with yellow. Flow obstacles, such as office table and bookshelf are coloured with brown. b) Smoke visualizations of airflow pattern in the same office room. Three ultrasonic anemometer are installed in an automated traversing system. Upper pictures: Strong circulation, which is caused mainly by the heater beneath the windows, in longitudinal direction of the room shifting the supply air jet towards the right side of the office. Lower pictures: Transverse circulation at the middle of the room.

2.2 Thermal comfort in office environment

According to ASHRAE standard (2010), thermal comfort is defined as that condition of mind which expresses satisfaction with the thermal environment. The most important factors which influence thermal comfort are air temperature, mean radiant temperature, relative air velocity, water vapour pressure in ambient air, thermal resistance of clothing and activity level of the occupant. Best thermal environment for comfort is obtained when the occupant is in thermal neutrality. Fanger (1970) defined thermal neutrality for a person as the condition in which the occupant wouldn't prefer either warmer or cooler surroundings.

Due to individual differences, it is impossible to find one uniform thermal environment, where everybody would gain thermal neutrality. If individual control over the thermal environment is not provided, there will always be dissatisfied occupants. However, it is possible to specify thermal environment predicted to be acceptable by a certain percentage of occupants.

Thermal comfort can be estimated with PMV (Predicted Mean Vote) model (ISO 7730, 2005) and with PPD (Predicted Percentage Dissatisfied) index. The PMV model is based on the heat balance of the human body. Thermal sensation can be subjectively measured with seven point ASHRAE scale (-3 cold, -2 cool, -1 slightly cool, 0 neutral, +1 slightly warm, +2 warm, +3 hot). The PMV model
predicts the mean value of the thermal sensation votes of a large group of people exposed to the same thermal environment. It considers all six factors affecting thermal comfort which were mentioned above and gives the result in seven point ASHRAE scale. The model can be used to calculate the thermal sensation of the whole body, or to calculate in which conditions thermal neutrality is reached. The PMV is defined according to Equations (1) to (4).
Theoretical foundation

\[
PMV = \left[0,303 \cdot \exp(-0,036 \cdot M) + 0,028\right] \cdot \\
\left\{(M - W) - 3,05 \cdot 10^{-3} \cdot [5733 - 6,99 \cdot (M - W) - p_a] \\
-0,42 \cdot [(M - W) - 58,15] \\
-1,7 \cdot 10^{-5} \cdot M \cdot (5867 - p_a) - 0,0014 \cdot M \cdot (34 - t_a) \\
-3,96 \cdot 10^{-8} \cdot fcl \cdot [(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4] \\
-fcl \cdot h_c \cdot (t_{cl} - t_a)\right\}
\]

(1)

\[
t_{cl} = 35,7 - 0,028 \cdot (M - W) - I_{cl} \cdot \\
\{3,96 \cdot 10^{-8} \cdot fcl \cdot [(t_{cl} + 273)^4] + fcl \cdot h_c \cdot (t_{cl} - t_a)\}
\]

(2)

\[
h_{cl} = \left\{\begin{array}{ll}
2,38 \cdot |t_{cl} - t_a|^{0.25} & \text{for } 2,38 \cdot |t_{cl} - t_a|^{0.25} > 12,1 \cdot \sqrt{v_{ar}} \\
12,1 \cdot \sqrt{v_{ar}} & \text{for } 2,38 \cdot |t_{cl} - t_a|^{0.25} \leq 12,1 \cdot \sqrt{v_{ar}}
\end{array}\right\}
\]

(3)

\[
fcl = \left\{\begin{array}{ll}
1,00 + 1,290 \cdot I_{cl} & \text{for } I_{cl} \leq 0,078m^2 \cdot K/W \\
1,05 + 0,645 \cdot I_{cl} & \text{for } I_{cl} > 0,078m^2 \cdot K/W
\end{array}\right\}
\]

(4)

where,

- PMV is Predicted Mean Vote
- M is the metabolic rate (W/m²)
- W is the effective mechanical power (W/m²)
- I_{cl} is the clothing insulation (m²*K/W)
- f_{cl} is the clothing surface area factor
- t_a is the air temperature (°C)
- \bar{t}_r is the mean radiant temperature (°C)
- v_{ar} is the relative air velocity (m/s)
- p_a is the water vapour partial pressure (Pa)
- h_c is the convective heat transfer coefficient (W/(m²*K))
- t_{cl} is the clothing surface temperature (°C)

According to standard ISO 7730 (2005), the PMV index should be use only for values of predicted mean vote between -2 and +2, and when main parameters are within the following intervals:

- M 0.8 met to 4 met (46 W/m² to 232 W/m²)
Theoretical foundation

- \( l_{cl} \): 0 clo to 2 clo (0 \text{ m}^2\text{K/W} \text{ to } 0.310 \text{ m}^2\text{K/W})
- \( t_o \): 10 °C to 30 °C
- \( \bar{\ell}_r \): 10 °C to 40 °C
- \( v_{ar} \): 0 m/s to 1 m/s
- \( p_o \): 0 Pa to 2700 Pa

The PPD index provides a prediction of the percentage of thermally dissatisfied people. People are considered to be thermally unsatisfied when voting outside the range of -1 to +1 in ASHRAE scale, i.e. voting cold, cool, warm or hot (ASHRAE 55, 2010). According to the ASHRAE standard 55 (2010) acceptable thermal environment for general comfort is when PMV range is between -0.5 and +0.5. The PPD index can be calculated from the PMV value using Equation (5). Standard ISO 7730 (2005) gives categories for thermal environment using PMV and PPD (Table 1).

\[
PPD = 100 - 95 \cdot 10^{-0.03353 \cdot PMV + 0.2179 \cdot PMV^2} \quad (5)
\]

where,
- \( PPD \) is Predicted Percentage Dissatisfied
- \( PMV \) is Predicted Mean Vote

The PMV model and PPD index are not able to assess local thermal discomfort. Local thermal discomfort is caused by unwanted cooling or heating of one particular part of body due vertical temperature difference around the body, too high radiant temperature asymmetry or draught (ISO 7730, 2005). The most common cause of local discomfort is draught. The main focus of this thesis is on air velocity in warm environment. Therefore, the examination of percentage dissatisfied due vertical air temperature difference, warm or cool floor and radiant asymmetry is ruled out of this thesis.

During light, mainly sedentary, activity the increased air velocity can cause discomfort due sensation of draught. Draught rate (DR) is the percentage of people predicted to be dissatisfied due to draught. Draught rate is derived from three physical variables (ISO 7730, 2005):

\[
DR = (34 - t_{a,l})(\bar{v}_{a,l} - 0.05)^{0.62} (0.37 \cdot \bar{v}_{a,l} \cdot Tu + 3.14) \quad (6)
\]

where,
- \( t_{a,l} \) is the local air temperature in degrees Celsius, 20 °C to 26 °C;
- \( \bar{v}_{a,l} \) is the local mean air velocity in metres per second, < 0.5 m/s;
- \( Tu \) is the local turbulence intensity in percent, 10 % to 60 % (if unknown, 40 % may be used).
Though draught is a local discomfort, draught sensitivity is influenced by general thermal sensation (Toftum and Nielsen, 1996). Sedentary people typically have thermal sensation for the whole body closer to neutral, which makes them sensitive to local discomfort. With activity levels higher than sedentary, the DR model has found to underestimate the actual dissatisfaction from draught at low air velocities, and overestimate dissatisfaction at higher air velocities (Toftum, 1994). Categories for DR are shown in Table 1.

Table 1. Categories of thermal environment. All the criteria should be satisfied simultaneously for each category. The full categories including percentage dissatisfied due vertical air temperature difference, warm or cool floor and radiant asymmetry can be found from standard ISO 7730 (2005).

<table>
<thead>
<tr>
<th>Category</th>
<th>Thermal state of the body as a whole</th>
<th>Local discomfort</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PMV</td>
<td>PPD (%)</td>
</tr>
<tr>
<td>A</td>
<td>-0.2 &lt; PMV &lt; +0.2</td>
<td>&lt; 6</td>
</tr>
<tr>
<td>B</td>
<td>-0.5 &lt; PMV &lt; +0.5</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>C</td>
<td>-0.7 &lt; PMV &lt; +0.7</td>
<td>&lt; 15</td>
</tr>
</tbody>
</table>

Slightly warm room temperature, from 26 °C up to 30 °C, has been found to increase many Sick Building Syndrome (SBS) symptoms. The effect has been found in difficulties in thinking clearly and headache (Fang et al., 2004; Witterseh et al., 2004); intensity of fatigue (Fang et al., 2004; Lan et al., 2011); eye, nose and throat symptoms (Witterseh et al., 2004; Lan et al., 2011); and concentration (Witterseh et al., 2004).

Many studies have found an effect of slightly warm temperature on office work performance. Based on earlier studies, Seppänen et al. (2003) suggested that work performance is unaffected by temperature in the range from 21 °C to 25 °C, but decreases 2% per degree centigrade above 25 °C. Seppänen’s model is based on studies from call-centres, an apparel factory and climate chambers with performance measures such as customer service in call-centres, factory work, learning, addition, multiplication and memory tests. Seppänen’s model was updated using only studies with tasks related to office work such as addition, multiplication, text processing and customer service in call-centres (Seppänen et al., 2006a). Seppänen’s updated model can be described with an inverted U-shape curve (Figure 2). According to Seppänen et al. (2006a) the model is applicable to all types of office work as first approximation, but it includes a high level of uncertainty. There is a need for studies in which comparisons of work performance measurement results and Seppänen’s model are done.
2.3 Indoor air quality in office environment

Indoor air quality in healthy office buildings is affected mainly by emissions from building materials and equipment, such as paint and printers, and occupants (bioeffluents, CO₂ etc.). Poor indoor air quality seems to affect the perception of indoor air quality and environment, cause fatigue, impair work performance and, via various symptoms, decrease well-being. Good indoor air quality can be achieved and maintained with proper air conditioning system. The European standard EN 15251 (2007) and the ASHRAE standard 62.1 (2010) recommends minimum airflow rate for open-plan office where emissions from building materials are low (Table 2). The recommended ventilation rates are mainly based on the perception of air quality. EN 15251 is based on the visitor’s perception while entering a room. Instead, ASHRAE 62.1 is based on the perception of adapted occupants. The recommended minimum outdoor airflow rate in occupied zone can be calculated from equation 7. The European standard EN 15251 recommends the highest CO₂ concentration level in office not to exceed 800 ppm above outdoor concentration.
Table 2. Minimum airflow rates in offices where emissions from building materials are low.

<table>
<thead>
<tr>
<th></th>
<th>Human bioeffluents (L/s·person)</th>
<th>Building emissions (L/s·m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN 15251</td>
<td>4</td>
<td>0.2</td>
</tr>
<tr>
<td>ASHRAE 62.1</td>
<td>2.5</td>
<td>0.6</td>
</tr>
</tbody>
</table>

\[
V_{\text{oz}} = V_p \cdot P_{\text{oz}} + V_a \cdot A_{\text{oz}} \tag{7}
\]

where,
- \(V_{\text{oz}}\) is the recommended outdoor airflow rate in occupied zone (L/s)
- \(V_p\) is the outdoor airflow rate required per person (L/s·person)
- \(P_{\text{oz}}\) is the number of people in occupied zone during typical usage (person)
- \(V_a\) is the outdoor airflow rate required per unit area (L/s·m²)
- \(A_{\text{oz}}\) is the floor area of the occupied zone (m²).

Some studies in office environments have indicated that decreasing the ventilation rate decreases perceived indoor air quality and increases sick building syndrome symptoms (Bakó-Biró et al., 2004; Fanger, 2006; Seppänen et al., 1999; Wargocki et al., 2000; Wyon, 2005). Wyon’s (2005) description of series of laboratory experiments revealed that often symptoms, such as dryness of mouth and throat, irritation of eyes, headache, sleepiness, difficulties in concentration, and fatigue, are affected by indoor air quality. It seems that these symptoms are affected specially when there is a pollution source (e.g. old carpet or old PC’s) in the space.

Poor indoor air quality has been found to affect cognitive performance in task types that are related to office work (Bakó-Biró et al., 2004; Fanger, 2006; Seppänen et al., 2006b; Wargocki et al., 2000; Park and Yoon, 2011) and school work (Fanger, 2006; Shaughnessy et al., 2006; Haverinen-Shaughnessy et al., 2011; Wargocki and Wyon, 2007; Bakó-Biró et al., 2012; Twardella et al., 2012). Seppänen et al. (2006b) demonstrated a relationship between ventilation rate and performance in office work. They fitted the data from seven field studies and two laboratory studies by using 2-degree fractional polynomial regression models. All studies had used objective performance indicators relevant for office work, such as addition, multiplication, text processing, length of telephone customer service time, and total handling time per customer. The lowest average ventilation rate was 6.5 l/s per person, to which ventilation rate the results are valid according to Seppänen et al. (2006b). The model shows an improvement in performance with increasing ventilation rate up to 45 L/s·person. According to Seppänen et al. (2006b) the model has a high level of uncertainty. There is a need for studies in which comparisons of work performance measurement results and Seppänen’s model are done. In addition, temperature variations were present in field studies and an external pollution source were used in laboratory studies. In modern clean offices with low-polluting building materials (e.g. M1 classification in LVI 05e10440, 2008), the relative proportion of human bioeffluents is rising. The room air temperature can often be controlled with proper air conditioning systems independent from the fresh supply air flow rate.
Thus, the effects of ventilation rate should be studied independently of room air temperature.

2.4 Air movement providing local cooling in warm office environment

Air movement can be used to provide local cooling. It may enable energy savings by allowing the room air temperature to rise without causing thermal discomfort. ASHRAE 55 (2010), ISO 7730 (2005) and EN 15251 (2007) standards allow the use of increased air movement to increase the maximum operative temperature for acceptability. According to ASHRAE standard, if sedentary occupant in office does not have control over the local air speed, the upper limit to air speed should be 0.8 m/s for operative temperatures above 25.5 °C.

The airflow generated by table fans may be used as an effective method to maintain a comfortable environment at temperature range 28-32 °C (Huang et al., 2013). Zeng et al. (2002) and Melikov et al. (1994) reported large differences in the jet velocity preferred by the subjects. The preferred velocities were not the ones corresponding to thermal neutrality, but the ones that decreased the warmth sensation without causing too much discomfort due to draft.

Melikov and Kaczmarczyk (2012) studied the impact of air movement on perceived air quality and SBS symptoms by comparing the use of recirculated room air and clean outdoor air in a various combinations of relative humidity, temperature and pollution levels. An air terminal device that was installed on the desk produced the air movement. The increased air movement reduced the negative impact of increased air temperature, relative humidity and pollution level on perceived air quality. The recirculated room air did not reduce the intensity of SBS symptoms, but clean outdoor air did.

The effect of air movement on cognitive performance in slightly warm temperature has been seen as increment in speed of solving Sudoku task, when fresh supply air was provided in the jet above display (Melikov et al., 2013). No effect have been seen in other task types, such as memory task (table fan; Cui et al., 2013), addition (table fan; Cui et al., 2013), pattern matching (table fan; Cui et al., 2013) or multiplication task (jet with fresh air above the display; Melikov et al., 2013).

Providing local cooling with elevated air speed seem to have many benefits for occupants and it allows energy savings via reduced need of cooling. However, there are numerous ways of providing elevated air speed and more research is needed to gain information of the effect of air speed from different types of air terminal units and cooling jet parameter solutions on occupants’ perception and comfort.
3. Methods

This thesis comprises four publications which were published in international reviewed journals. All publications deal with measurements in open-plan office laboratories. Publications I, II and III concerns possible problems from disfunctioning HVAC system causing discomfort among occupants in office. Publication IV gives a solution proposal covering some of the problems from each Publication I-III. Measurements of airflow patterns are done in two Publications (I, IV) and three Publications concerns human subject experiments (II, III, IV).

3.1 Measurements of indoor environment and airflow patterns in office laboratories

The experiments in Publication I were done in office laboratory (33.6 m²) at The Finnish Institute of Occupational Health in Turku, Finland. The office laboratory represents a typical building module of a modern flexible office building (Figure 3). One wall of the test room had six windows of size 1.22 m x 1.47 m. Their surface temperature was controlled by blowing air into the chamber behind them. Convective heaters were placed under the windows and were only used in the winter test case. Cooling in the office laboratory was realized with active chilled beams installed 0.15m distance from the ceiling.

The persons were simulated with cylinders (height 1.1 m, diameter 0.3 m) containing 2 light bulbs of total 80W of heat power. Each workstation had a PC under the table with power consumption adjusted to 90W. Three lamps with power consumption of 120W each were installed between the chilled beams at height of 2.3 m.

![Figure 3. Dimensions and the layout of office laboratory used in Publication I.](image)
The measurements of air velocity were carried out by using ultrasonic anemometers (Kaijo Denki WA-390, accuracy ±0.02 m/s), moved by an automated traversing system. The averaging time in each measurement point was 60 seconds. The measurement grid density was 0.1 m x 0.1 m. Additional measurements were done using Dantec 54N10 flow analyzer with hot sphere sensors. The locations of the measurement planes were selected to cover four workstations in the central part of the room. The measurement heights were 0.1 m and 1.2 m. Measurement height 1.2 m was used with the automated traversing system instead of the standard height 1.1 m because of obstacles. The flow pattern was visualized using smoke and video recorder.

Three test cases were measured: summer case (100 W/m² cooling load, warm windows and direct solar heat load), spring/autumn case (45 W/m² cooling load, cool windows) and winter case (45 W/m² cooling load, cold windows and heaters under them).

Another office laboratory (82 m²) at Finnish Institute of Occupational Health in Turku, Finland was used in Publications II, III and IV (Figure 4). Fresh air to the whole laboratory was supplied with inlet units in the suspended ceiling (height 2.55 m, Publications II, III and IV) and with the studied jet nozzles (Publication IV). Table 3 shows the mean values of all independent variables and relative humidity in Publications II-IV. In Publication III independent variables represents the whole condition including changes in ventilation rate, human bioeffluent concentration and other emissions from occupants, materials and equipment. More detailed descriptions of conditions in Publication III are shown in Table 7.

Figure 4. Dimensions and the layout of office laboratory used in Publications II, III and IV.
Table 3. The means of main indoor environment conditions in Publications II-IV. Other conditions, such as, room acoustics, and lighting conditions met the current recommendations in Finland (LVI 05e10440, 2008). Independent variable of each publication is marked as grey background colour of the cell.

<table>
<thead>
<tr>
<th>Independent variable</th>
<th>Publication II</th>
<th>Publication III</th>
<th>Publication IV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Neutral tem.</td>
<td>Warm tem.</td>
<td>Condition A</td>
</tr>
<tr>
<td>Air temperature (°C)</td>
<td>23.5</td>
<td>29.5</td>
<td>23.6</td>
</tr>
<tr>
<td>Fresh air flow rate (L/s·person)</td>
<td>17</td>
<td>17</td>
<td>28.2</td>
</tr>
<tr>
<td>Carbon dioxide content (ppm)</td>
<td>704</td>
<td>687</td>
<td>540</td>
</tr>
<tr>
<td>Air velocity at the occupied zone (m/s)</td>
<td>0.08</td>
<td>0.06</td>
<td>&lt;0.20</td>
</tr>
<tr>
<td>Relative humidity (%)</td>
<td>34</td>
<td>21</td>
<td>32</td>
</tr>
</tbody>
</table>

*Target velocity in the facial region

To maintain the control of the room temperature (nominal value 23.5 °C) in Publication III, air flow rate through inlets was not changed between experimental conditions. Therefore, in the low ventilation rate setup, a loop was constructed with a fan from the exhaust duct to the inlet duct and exhaust air was used as main part of the supply air. The supply air flow rate was 28.2 l/s-person, of which 2.3 l/s-person was fresh outdoor air and the rest (25.9 l/s-person) was circulated room air. In the high ventilation rate setup, only fresh outdoor air was supplied. To achieve the human bioeffluent level corresponding to the CO2 level of 2260 ppm, eight researchers worked in the laboratory for 4.5 hours before the subjects entered the room (Figure 5).

![Figure 5](image)

**Figure 5.** The development of CO2 concentration level on a function of time in one session of low ventilation rate (upper curve) and in one session of high ventilation rate (lower curve) in Publication III.

In Publication IV, air velocity distribution at the workstations 1 and 2 (Figure 6) was measured with Dantec Flow Analyzer 54N10 and Dantec 9054R0102 low velocity transducers while dummy subjects (heat load 90 W/ dummy) were present. The velocity measurement accuracy with the system was 5% of reading ±0.01 m/s. Air velocity was sampled in each measurement point for 60 s (240 samples). Mean velocity, standard deviation and turbulence intensity (standard
deviation divided by the mean) were calculated from the samples by the analyzer.

The cooling jet in Publication IV was introduced from seven adjustable nozzles installed symmetrically into the end of one of the inlet ducts in the suspended ceiling (Figure 6). The jet was provided in an angle of $\alpha = 45^\circ$ from vertical axes. The temperature difference between fresh air in the jet and room air was $\Delta T = -3.5^\circ C$.

![Figure 6. Left: Open-plan office laboratory and the workstations used in Publication IV (A = acclimatization, 1 = Without the jet, and 2 = With the jet). Middle: The position for the jet. Right: Seven adjustable nozzles installed symmetrically into the end of one of the inlet ducts to produce the jet.](image)

### 3.2 Psychological experiments

The repeated measures design was used in experiments (Publications II, III and IV). It means that each subject was exposed to both conditions and served as their own control, minimizing the effect of participants' individual differences on results. The order of the conditions was counterbalanced between subjects to control possible order effects, such as learning and habituation effects. Table 4 shows the basic information regarding the subjects and procedure used in each publication. Undergraduate university students were volunteered in all three publications. The main activity of the subjects during the session in each publication was typing. The estimated activity level was 1.1 met (ISO 7730, 2005).

The independent variables in Publications II-IV are presented in Table 3. The dependent variables were the performance measures and the subjective ratings regarding several factors relating to the environment and well-being. Some dependent variables were presented more than once to gain information about interaction between independent variable and exposure time.
### Table 4. The number of subjects, gender distribution, median age, clothing value and exposure time used in each Publication II-IV. Acclimatization (in brackets) is included to the given exposure time.

<table>
<thead>
<tr>
<th></th>
<th>The number of subjects</th>
<th>female</th>
<th>male</th>
<th>median age</th>
<th>clothing value (clo)</th>
<th>participation to the conditions</th>
<th>exposure time (min/condition)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pub. II</td>
<td>33</td>
<td>16</td>
<td>17</td>
<td>23</td>
<td>0.83*</td>
<td>subsequent weeks</td>
<td>210 (65)</td>
</tr>
<tr>
<td>Pub. III</td>
<td>36</td>
<td>21</td>
<td>15</td>
<td>25</td>
<td>0.83*</td>
<td>subsequent weeks</td>
<td>235 (75)</td>
</tr>
<tr>
<td>Pub. IV</td>
<td>29</td>
<td>16</td>
<td>13</td>
<td>24</td>
<td>0.71**</td>
<td>straight after each other</td>
<td>40***</td>
</tr>
</tbody>
</table>

* Trousers, long-sleeve t-shirt, t-shirt, socks and ankle-length shoes (office chair included, ISO 7730, 2005).
** Trousers, t-shirt, socks and ankle-length shoes (office chair included, ISO 7730, 2005).
*** Acclimatization is excluded from the value since the whole experimental session (110 min) included first 30 min acclimatization, then first sub-session (40 min) with one thermal condition, and straight after the second sub-session (40 min) with other thermal condition.

#### 3.2.1 Measures of cognitive performance

Several tasks which measure different processes of cognitive performance were used in Publications II-IV (Table 5). Whenever several versions of the task were used in one publication, the order of the versions was counterbalanced between conditions (independent variable) and exposure time. Short description of the tasks is presented below. See Publications for more detailed information.

### Table 5. Tasks used in performance measurements in Publications II-IV.

<table>
<thead>
<tr>
<th>Task</th>
<th>Cognitive process</th>
<th>Measure</th>
<th>Publication II</th>
<th>Publication III</th>
<th>Publication IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typing</td>
<td>Psychomotor performance</td>
<td>Speed</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Accuracy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Star counting</td>
<td>Attention</td>
<td>Speed</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Accuracy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vigilance</td>
<td>Attention</td>
<td>Speed</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Accuracy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operation Span</td>
<td>Working memory</td>
<td>Accuracy</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>N-back</td>
<td>Working memory</td>
<td>Speed</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Accuracy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long-term memory</td>
<td>Long-term memory</td>
<td>Accuracy</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Information retrieval</td>
<td>Working memory</td>
<td>Speed</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Accuracy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Creative thinking</td>
<td>Creativity</td>
<td>Ideational fluency</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ideational originality</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Serial recall</td>
<td>Short-term memory</td>
<td>Accuracy</td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

Typing task involves a complex interaction of perceptual, cognitive and motor processes (Salthouse, 1968). The task was to copy a given text precisely to computer as fast as possible and to correct any typing errors if detected.

Star counting task requires attention (de Jong and Das-Smaal, 1990). The task consisted of a starting number in the top left corner of the computer display,
followed by three rows of x-letters with plus and minus signs in between. The
task was to count x-letters row-wise from left to right starting from given num-
ber. The signs denoted the direction in which subsequent x-letters had to be
counted. The number of the last x-letter was typed as an answer.

The vigilance task requires regulation and maintenance of attention (Warm et
al., 2008). The task was to monitor the letters appearing on the display and to
react to every ‘x’-letter by pressing a key as quickly as possible and to ignore any
other letter.

Operation span task is a classic working memory test (Unsworth et. al, 2005).
The task consisted of pairs of mathematical equations and words, for example,
2x3+6=13 and ‘CASTLE’. First, an equation appeared on the computer display.
Subject had 10 seconds to decide whether the presented equation was true or
false by clicking the appropriate option on the computer display. After each
equation, a word appeared on the display and subjects had two seconds to mem-
orize the word. After a predetermined number of equation-word pairs were pre-
sented, subject typed in all the words they remembered. The purpose of the
arithmetic task was to interfere with the primary task of memorizing the words.
To ensure that subjects focused on both, equations and words, subjects were
instructed to aim to at least 85 % accuracy on the equations. Subjects received
feedback on the percentage on the display after typing the words before the start
of the next equation-word pair.

The N-back task requires on-line monitoring, updating and manipulation of
information in working memory (Owen et. al, 2005). In this task, sequences of
letters were presented on the display one letter at a time for 500 ms with a 2500
ms inter-stimulus-interval. Four difficulty levels were used (0-back, 1-back, 2-
back and 3-back). In 0-back, the task was to press ‘YES’ every time the letter ‘X’
appeared on the display and press ‘NO’ for all other letters. This was the baseline
level with no demands on working memory. In 1-back, subjects were required
to respond whether the presented letter was identical to the one immediately
preceding it. Upper and lower case letters were varied to prevent subjects from
relying on visual recognition only. In 2-back, subjects were required to respond
whether the presented letter was identical to the one presented two trials back.
In 3-back, subjects were required to respond whether the presented letter was
identical to the one presented three trials back. Subjects were instructed to re-
spond quickly, but accurately by pressing a key on the keyboard labelled YES
(left arrow) of NO (downward arrow).

Long-term memory task requires reading comprehension, learning and long-
term memory. The task was to memorize facts about a specific new theme, for
example, to learn about one rare illness in a three-page text covering four dif-
ferent rare illnesses (Kaakinen, Hyönä and Keenan, 2003). After reading the
text, the subjects performed other tasks which created a delay between reading
and recall. This was done to prevent active maintenance of the text in short-term
memory between reading and recall. In recall, subjects had four minutes to write
as much as they could remember about the target disease.

Information retrieval task requires working memory, attention and strategic
executive functions (Jahncke and Halin, 2012). The task was to search for the
Methods

object that met the presented criterion from table of 20 rows and seven columns with both categorical and numerical values (e.g., a table of 20 countries included information about population, multilinguality, area, highest point in meters, major religion, polity and gross national income). Subjects had to inspect three columns e.g. “Which multilingual country with area over 100 000 km² has the highest gross national income?”

Creative thinking task was formulated from Guilford’s Alternative Uses Task (Wyon, 1996). The task was to write down on a paper as many alternative uses for an ordinary object as possible in three minutes. The objects were a brick, a car tire, a barrel, a shoe, a pen and a hanger.

The serial recall task is a classical short-term memory task where subjects have to recall randomly presented digits from 1 to 9 in the correct order. Numbers were presented on the display one by one at the rate of 1 per second with an inter-digit interval of 1.5 s. During recall, the numbers from 1 to 9 appeared in a 3 x 3 array on the display and subjects recalled the numbers by clicking with the mouse.

3.2.2 Questionnaires

Questionnaires included questions about thermal comfort, perceived indoor air quality, symptoms, perceived fatigue, subjective workload, disturbance of different environment factors and statements about work environment. For the comparison of Publications II-IV, Table 6 shows dependent variables that were used in more than one publication, their questions, response scales and in which Publication (II-IV) the dependent variable was used. Questionnaires were developed for each publication separately. Some items or response scales may differ between publications. These dependent variables are marked in Table 6. In addition, questions about background information, such as age, gender, smoking, asthma, sleep quality during the preceding night and presence of possible factor reducing the ability to function (e.g. pain, flu, headache and hangover), were presented at the beginning of session. Dependent variables, that were used only in one publication (for example odour intensity in Publication III or questions related to the cooling jet in Publication IV), are excluded from Table 6. More information regarding those dependent variables can be found in Publications. Questionnaires were presented in Finnish.

In Publications II and IV, questions related to thermal comfort were presented using paper, other questions were presented using computer. In Publication III, all questions were presented using computer. Thermal sensation was measured with a continuous scale in Publications II and IV, and with a seven point discontinuous scale in Publication III. Thermal satisfaction was measured with a continuous scale, in which subjects were forced to decide whether they are satisfied with the thermal environment or not. Perceived fatigue was measured with a modified version of the Swedish Occupational Fatigue Inventory, SOFI, including three factors: tiredness, lack of energy and lack of motivation (Åhsberg, 1998). Each factor included three items (tiredness: sleepy, yawning, drowsy; lack of energy: worn out, exhausted, drained; lack of motivation: uninterested,
indifferent, passive). Subjective workload was measured with selected items modified from NASA Task Load Index (Hart & Staveland, 1988). Different items were selected to each Publication (II-IV).
Table 6. The dependent variable, questions, response scales and in which Publications they were used. Dependent variables that have some variations between Publications are marked with asterisks.

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Question</th>
<th>Response scale</th>
<th>Publication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole body thermal sensation* **</td>
<td>Mark your current thermal sensation into the scale</td>
<td>-3 Cold, -2 Cool, -1 Slightly cool, 0 Neutral, +1 Slightly warm, +2 Warm, +3 Hot</td>
<td>II, III, IV</td>
</tr>
<tr>
<td>Whole body thermal satisfaction* **</td>
<td>How satisfactory do you find the thermal environment?</td>
<td>-1 Completely unsatisfactory, -0.1 Just unsatisfactory, +0.1 Just satisfactory, +1 Completely satisfactory</td>
<td>II, IV</td>
</tr>
<tr>
<td>Local thermal sensation* **</td>
<td>Mark your current thermal sensation in to the scale (11 body parts, see Table 8)</td>
<td>-3 Cold, -2 Cool, -1 Slightly cool, 0 Neutral, +1 Slightly warm, +2 Warm, +3 Hot</td>
<td>II, IV</td>
</tr>
<tr>
<td>Local thermal satisfaction* **</td>
<td>How satisfactory you think the thermal environment is? (11 body parts, see Table 8)</td>
<td>-1 Completely unsatisfactory, -0.1 Just unsatisfactory, +0.1 Just satisfactory, +1 Completely satisfactory</td>
<td>II, IV</td>
</tr>
<tr>
<td>Draughtiness</td>
<td>The workstation is draughty.</td>
<td>1 Completely agree, 2 Slightly agree, 3 Slightly disagree, 4 Completely disagree</td>
<td>II, IV</td>
</tr>
<tr>
<td>Perceived air quality* **</td>
<td>Estimate the air quality</td>
<td>1 Stuffy – 7 Fresh</td>
<td>III, IV</td>
</tr>
<tr>
<td>Perceived fatigue</td>
<td>Tiredness</td>
<td>Sleepy, Yawning, Drowsy</td>
<td>II, III, IV</td>
</tr>
<tr>
<td></td>
<td>Lack of energy</td>
<td>Worn out, Exhausted, Drained</td>
<td>II, IV</td>
</tr>
<tr>
<td></td>
<td>Lack of motivation</td>
<td>Uninterested, Indifferent, Passive</td>
<td>III, IV</td>
</tr>
<tr>
<td>Symptoms</td>
<td>Headache</td>
<td>Do you have at the moment…</td>
<td>II, III, IV</td>
</tr>
<tr>
<td></td>
<td>Nasal symptoms</td>
<td>1 Not at all, 2 Slightly, 3 To some extent, 4 Quite a lot, 5 Very much</td>
<td>II, III, IV</td>
</tr>
<tr>
<td></td>
<td>Throat symptoms</td>
<td>1 Not at all, 2 Slightly, 3 To some extent, 4 Quite a lot, 5 Very much</td>
<td>II, III, IV</td>
</tr>
<tr>
<td></td>
<td>Dryness and irritation of eyes</td>
<td>1 Not at all, 2 Slightly, 3 To some extent, 4 Quite a lot, 5 Very much</td>
<td>II, III, IV</td>
</tr>
<tr>
<td></td>
<td>Difficulties in concentration</td>
<td>1 Not at all, 2 Slightly, 3 To some extent, 4 Quite a lot, 5 Very much</td>
<td>II, III, IV</td>
</tr>
<tr>
<td></td>
<td>Feeling of being unwell</td>
<td>1 Not at all, 2 Slightly, 3 To some extent, 4 Quite a lot, 5 Very much</td>
<td>II, III, IV</td>
</tr>
<tr>
<td></td>
<td>Sweating</td>
<td>1 Not at all, 2 Slightly, 3 To some extent, 4 Quite a lot, 5 Very much</td>
<td>II, III, IV</td>
</tr>
<tr>
<td>Subjective workload* **</td>
<td>Workload</td>
<td>1 Not at all, 2 Slightly, 3 To some extent, 4 Quite a lot, 5 Very much</td>
<td>III, IV</td>
</tr>
<tr>
<td></td>
<td>Frustration</td>
<td>1 Not at all, 2 Slightly, 3 To some extent, 4 Quite a lot, 5 Very much</td>
<td>III, IV</td>
</tr>
<tr>
<td></td>
<td>Exertion</td>
<td>Did you exert to be able to get the tasks well done?</td>
<td>III, IV</td>
</tr>
<tr>
<td></td>
<td>Performance</td>
<td>How well did you perform the tasks?</td>
<td>II, III, IV</td>
</tr>
<tr>
<td></td>
<td>Mental demand</td>
<td>How mentally demanding it was to perform the tasks?</td>
<td>II, IV</td>
</tr>
<tr>
<td></td>
<td>Physical demand</td>
<td>How physically demanding it was to perform the tasks?</td>
<td>II, IV</td>
</tr>
</tbody>
</table>

*The question varied between Publications

**The response scale varied between Publications
Table 6 (continued).

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Question</th>
<th>Response scale</th>
<th>Publication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disturbance of different environment factors</td>
<td>Odours: How much did the following environmental factors disturb your performance?</td>
<td>1 Not at all, 2 Slightly, 3 To some extent, 4 Quite a lot, 5 Very much</td>
<td>II, III, IV</td>
</tr>
<tr>
<td></td>
<td>Heat: The work environment is pleasant.</td>
<td>1 Not at all, 2 Slightly, 3 To some extent, 4 Quite a lot, 5 Very much</td>
<td>II, III, IV</td>
</tr>
<tr>
<td></td>
<td>Coldness: The temperature of the work environment is suitable for working.</td>
<td></td>
<td>II, III</td>
</tr>
<tr>
<td></td>
<td>Air stuffiness: I could work in this kind of circumstances effectively for a long period of time.</td>
<td></td>
<td>II</td>
</tr>
<tr>
<td></td>
<td>Air dryness: The working environment as a whole was good for working.</td>
<td>1 Not at all, 2 Slightly, 3 To some extent, 4 Quite a lot, 5 Very much</td>
<td>II, III, IV</td>
</tr>
<tr>
<td>Work environment statements (How well does the following statements describe your experience during the last working period?)</td>
<td>Pleasantness of the environment: The work environment is pleasant.</td>
<td>1 Not at all, 2 Slightly, 3 To some extent, 4 Quite a lot, 5 Very much</td>
<td>II, III, IV</td>
</tr>
<tr>
<td></td>
<td>Thermal suitability: The temperature of the work environment is suitable for working.</td>
<td></td>
<td>II, III</td>
</tr>
<tr>
<td></td>
<td>The possibility to work effectively: I could work in this kind of circumstances effectively for a long period of time.</td>
<td></td>
<td>II</td>
</tr>
<tr>
<td>Overall experience of the environment: The working environment as a whole was good for working.</td>
<td>1 Not at all, 2 Slightly, 3 To some extent, 4 Quite a lot, 5 Very much</td>
<td>II, III, IV</td>
<td></td>
</tr>
</tbody>
</table>

*The question varied between Publications

**The response scale varied between Publications

3.2.3 Statistical analyses

Statistical analyses were conducted with SPSS (IBM SPSS Statistics for Windows, Version 20.0, Armonk, NY: IBM Corp.). The normality of the data was tested with the Shapiro-Wilk test. When data was normally distributed or when distributions were similarly skewed, a repeated measures ANOVA or paired samples t-test (two-tailed) was used. The N-back task was analysed with a 2 (independent variable) x 2 (exposure time) x 4 (difficulty level) repeated measures ANOVA. Perceived fatigue was analysed using a 2 (independent variable) x 2 (exposure time) repeated measures ANOVA. Homogeneity of variance was estimated with Mauchly’s test of sphericity. The Greenhouse-Geisser correction was applied when Mauchly’s test indicated a violation of sphericity, and the corresponding p-values are reported. The analyses regarding thermal comfort varied between publications due changes in response scale; parametric methods were used whenever continuous response scale was used in questionnaires (and when data was normally distributed or distributions were similarly skewed), and non-parametric methods were used for the rest. Questionnaires, other than perceived fatigue and above-mentioned thermal comfort, was analysed using non-parametric methods. Paired comparison was done using Wilcoxon’s signed rank test. Friedman test was used to analyse changes due exposure time within one condition. Whenever significant differences were found, paired comparison was done using Wilcoxon’s signed rank test and the Benjamini-Hochberg procedure was used for alpha-error adjustment.
Whenever statistically significant differences in performance measures were found, effect sizes were estimated. Cohen’s $d$ (Equation 7) was used for parametric statistical tests and $r$ (Equation 8) for nonparametric tests (Cohen 1988). General guidelines for interpreting the $d$ values are that large effect is 0.8, medium effect is 0.5 and small effect is 0.2, and for interpreting the $r$ values are that large effect is 0.5, medium effect is 0.3 and small effect is 0.1.

$$d = \frac{x_1 - x_2}{s}$$  \hspace{1cm} (7)

where,
$x_1$ is the mean value of the dependent variable in condition 1
$x_2$ is the mean value of the dependent variable in condition 2
$s$ is the pooled standard deviation

$$r = \frac{z}{\sqrt{N}}$$  \hspace{1cm} (8)

where,
$z$ is the $z$-score of the nonparametric test
$N$ is the sample size

Few exceptions from above mentioned methods in the analysis were done. In Publication III, the information retrieval task was analyzed using between-groups design due to a systematic error which disturbed the data saving in first days of the experiment. Therefore, part of the information retrieval task data from the first session was missing and analyses were done with nonparametric Mann-Whitney U test using only data from the second session. In Publication III there was a failure of complete counterbalance on the texts in long-term memory task, which disturbed the performance results in paired samples t-test. The task was analyzed using between-groups design with independent samples t-test. Two texts (rare illnesses and small countries) were analysed separately. Analyses were done only to those 22 subjects who had rare illnesses text in the first session (14 in Condition A and 8 in Condition B) and small countries text in the second session (8 in Condition A and 14 in Condition B).

In both Publications II and III in the operation span task, multivariate outliers were checked using Mahalanobis distance for identifying possible changes in performance strategy. This was done, instead of excluding subjects who failed to achieve 85% level on equation accuracy, because the independent variable could also have affected subjects’ performance strategy. As a result, one subject was excluded in the analysis of the task in Publication II and four in Publication III.
Methods
4. Results

4.1 Air distribution in office environment with cooling conditions

Publication I deals with air flow patterns and mean air speeds measured under laboratory conditions representing a full scale open-plan office. The results of a Publication I showed that the heat sources seemed to have a notable influence on the flow pattern and badly implemented layout can cause local draught risk, especially if the workstation is located in the downfall area of the inlet jet.

The main flow patterns detected from smoke visualizations are shown in Figure 7. Figure 8 shows the distribution of air speed at two horizontal planes at 0.1 m and 1.1 m heights in all three cases. In summer case, the inlet jets from the chilled beam first attached to the ceiling and then collided with the jet from the neighboring beam or with a wall turning downwards to the occupied zone. A large circulation was formed in the room in the longitudinal direction. This was caused by the asymmetric layout of the chilled beams in relation to the workstations. The warm windows created upward thermal plumes that continued along the ceiling colliding with the inlet jets from the chilled beams. The inlet jets were turned towards the corridor wall and a second circulation perpendicular to the main circulation was developed. In spring/autumn case, the longitudinal circulation was weaker compared to the summer case. Also the downward plumes from the cool window were weak and no transverse circulation was developed. In winter case, the longitudinal circulation was weaker compared to the summer case. The heaters under the windows created upward plumes as in the summer case. These plumes turned the inlet jets somewhat towards the corridor wall in the experiments creating a transverse circulation weaker than in the summer case. The maximum air speed was highest in summer case and lowest in winter case.
Results

Figure 7. Flow pattern in the open-plan office laboratory. Up: Summer case, middle: spring/autumn case and down: winter case.

Figure 8. The distribution of the mean air speed at 0.1m (left) and at 1.2m (right). Up: Summer case, middle: spring/autumn case and down: winter case.
Figure 9 shows the measured mean and maximum draught rates in the test cases calculated from Equation (6). As seen from Table 1, the mean draught rates at 0.1 m level fall into ISO 7730 category B (< 20%, spring/autumn case and winter case) or C (< 30%, summer case), and at 1.2 m level into category A (< 10%, summer and spring/autumn case) or B (winter case). The maximum draught rates fall into category C, except in the summer case at the 0.1 m level, where it is outside category C.

![Figure 9. The mean and maximum draught rates at the heights of a) 0.1 m and b) 1.2 m.](image)

The heat sources had a notable influence on the flow pattern in the room affecting the direction of inlet jets and causing large scale circulation. The mean air speed was locally rather high at the floor level but low at the head level. The air speed was highest in the summer case with high cooling load.

Two main causes of draught risk were found: a) downfall of colliding inlet jets causing local maxima of air speed and b) large scale circulation caused by asymmetric room layout of chilled beams and heat sources. The first phenomenon (a) can cause local draught risk if the workstation is located in the downfall area. The flow pattern in the room is not stable and the position of draught risk areas can change in time and also due to changes in room heat sources. The second phenomenon (b) can cause more constant high air speeds on at the floor level.

4.2 The effect of slightly warm temperature on perception and work performance

Publication II concerned the effect of slightly warm temperature (29 °C) on occupants’ perception, comfort and work performance. The results showed that the effect of temperature on performance seems to be task dependent and performance may not be as sensitive to temperature changes as suggested in Seppänen’s model (Seppänen et al., 2006a). According to the subjective measures, it is obvious that 29 °C is not an optimal temperature for office work and the use of mental resources was needed to compensate for the adverse effects of the slightly warm temperature.
Results

Temperature had an effect on performance only in the N-back working memory task. Temperature had no effect on psychomotor performance, attention, long-term memory or perceived performance (all $p$’s > 0.05). In the N-back task, performance decreased significantly in slightly warm temperature in terms of both reaction time ($Z = -5.01, p < 0.001$) and accuracy ($Z = -4.98, p < 0.001$) when the overall performance combining all N-back levels was analyzed (Figure 10). Further analysis showed that reaction times were significantly longer at all N-back levels at a slightly warm temperature, which indicates increased cognitive load (Figure 11). Accuracy was reduced significantly at the most demanding difficulty level, that is, 3-back, at 29 °C (Figure 11). There was no effect of temperature on accuracy in 1-back ($p > 0.05$) or 2-back ($p > 0.05$). Unexpectedly, there was an improvement of accuracy in 0-back at a slightly warm temperature. The improved accuracy, combined with longer reaction times, can be interpreted as a sign of a speed–accuracy trade-off, not improved performance, at slightly warm temperature. In other words, when cognitive demand was the lowest (0-back), subjects were able to compensate for the effect of slightly warm temperature by focusing on accuracy at the cost of speed. It seems that the deteriorating effect of slightly warm temperature increased with increasing cognitive demand (1-back, 2-back, and 3-back): firstly in the form of longer reaction times indicative of increased cognitive load and then finally as a drop in accuracy when the most demanding memory load was reached.

Figure 10. Mean performance in the N-back working memory task.
The intensity of all symptoms was low under both thermal conditions. Subjects reported significantly more difficulties in concentration at 29 °C at the end of the session ($p < 0.05$). Difficulties in concentration increased over time at 29 °C ($p < 0.01$) but not at 23 °C ($p > 0.05$). Throat symptoms were found to increase over time at 29 °C ($p < 0.05$), but no change was seen at 23 °C ($p > 0.05$). No effect of temperature on other symptoms was found (all $p$’s $> 0.05$).

No main effect of temperature or interaction effect between temperature and exposure time on perceived fatigue was found in any of the three factors (tiredness, lack of energy, and lack of motivation; all $p$’s $> 0.05$).

Temperature had an effect on subjective workload in one factor. Performing tasks at the slightly warm temperature was perceived as physically more demanding ($p < 0.05$). No effect was found on mental demand ($p > 0.05$).

Heat ($p < 0.001$), stuffiness of the air ($p < 0.001$), and dryness of the air ($p < 0.05$) were rated to impair performance more at 29 °C. Subjects rated the working environment as significantly better at 23 °C ($p < 0.001$). Subjects also rated the working conditions at 23 °C to be better for working efficiently for a long period of time ($p < 0.001$).

The differences in thermal sensation ($p < 0.001$) and in thermal satisfaction ($p < 0.001$) were significant. The temperature of 23 °C was perceived as neutral (median) and 29 °C as warm (median; Figure 12). The percentage of subjects dissatisfied with the thermal environment at the end of the session was 30% at 23 °C and 91% at 29 °C. Gender had no main effect on the mean thermal sensation ($p > 0.05$) or thermal satisfaction ($p > 0.05$) when both temperatures were considered. However, an interaction between temperature and gender was found in the mean thermal sensation ($p < 0.01$). There were no gender differences in the perception of a temperature of 29 °C ($p > 0.05$), but women found the temperature of 23 °C cooler than men ($p < 0.01$; Figure 12).
4.3 The effect of low ventilation rate with increased bioeffluents concentration on perceived indoor air quality, symptoms and work performance

Publication III concerns the effects of ventilation rate and air quality on occupants’ perception, comfort and work performance in a laboratory representing modern open-plan office with rather low material and equipment emissions. The results suggest that the human bioeffluents do not have as strong effect on work performance and perception as seen in literature in studies with external pollution sources. However, according to the results ventilation rate 2.3 l/s per person seems not to be enough for office work even when emissions from building materials are low.

Independent variables, i.e. Conditions A and B, are presented in Table 7. Condition B had a weak negative effect on performance only in informational retrieval task ($U=77, p<0.01$). Nearly significant negative effect of Condition B was seen in the operation span task ($t(31)=2.0, p=0.051$). The amount of correct responses in information retrieval task did not vary between the two ventilation rates, but subjects performed the task slower and ran out of time more often in low ventilation rate. The weak effect in operation span task was seen in accuracy. Ventilation rate had no effect on the performance in N-back, attention, creative thinking, psychomotor or long-term memory tasks.

Condition B increased slightly perceived fatigue. The increment was seen in in two out of three items. Lack of energy ($p<0.05$) and lack of motivation ($p<0.01$) were slightly higher in Condition B. No effect was found on tiredness ($p>0.05$). The overall level of perceived fatigue in all items was low with both experimental conditions.
Table 7. Factors affecting the indoor air quality differences between Condition A and Condition B.

<table>
<thead>
<tr>
<th></th>
<th>Condition A</th>
<th>Condition B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outdoor air flow rate [l/s per person]</td>
<td>28.2</td>
<td>2.3</td>
</tr>
<tr>
<td>Carbon dioxide content [ppm]</td>
<td>540</td>
<td>2260</td>
</tr>
<tr>
<td>TVOC [µg/m³]</td>
<td>70</td>
<td>320</td>
</tr>
<tr>
<td>Particle concentration ≥ 0.5 µm [particles/l]</td>
<td>620</td>
<td>1240</td>
</tr>
<tr>
<td>Particle concentration ≥ 5 µm [particles/l]</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

Workload increased with exposure time in both experimental conditions, but it was slightly higher at the end of session in Condition B ($p<0.05$). Experimental condition had no effect on other items of subjective workload (perceived frustration, exertion, and performance; $p>0.05$).

No effects on symptoms were found (all $p's>0.05$). The intensity of all symptoms was low with both experimental conditions.

Experimental condition had an effect on perceived air quality ($p<0.05$) and observed odour intensity ($p<0.05$) only in the beginning of the session (Figure 13). The observed odour intensity was significantly higher at the beginning of session in Condition B compared to all other exposure times (all $p's<0.05$), but did not change in Condition A ($p>.05$). The mean values of observed odour intensity were very low.

![Figure 13](image_url)

Figure 13. The mean values of perceived air quality (left, 1=stuffy, 7=fresh) and observed odour intensity (right, 1=no odour, 6=unbearable strong odour).

Although the room temperature was controlled in both experimental conditions, the heat was perceived to impair the performance more in Condition B ($p<.01$). Room temperature was perceived as neutral in both ventilation rates and mean thermal sensation vote did not vary between ventilation rates ($p>.05$). No differences were found in the other parameters of disturbance ($p>.05$). Overall, the disturbance levels were very low.
4.4 The effect of cooling jet on perception and work performance

Publication IV deals with the use of cooling jet in warm offices. The effect of cooling jet on cognitive performance, subjective workload, perceived fatigue, thermal comfort, symptoms and perceived working conditions was measured. The results support the use of cooling jet in offices with high thermal loads where individual control over the air temperature is not possible via air conditioning. It seems, however, that there is a need for individual control over the jet already when the target velocity is set to the upper limit according to ASHRAE standard 55 (2010).

Figure 14 shows the velocity distribution of the jet in a vertical plane in front of the dummy subject. The target velocity in the facial region was \( v = 0.8 \) m/s. The jet temperature in subject’s facial region was 1 °C cooler than the room air temperature.

![Figure 14. The velocity distribution (m/s) of the jet in a vertical plane in front of the person.](image)

The jet improved the speed of response in a working memory task with increasing exposure time (\( t(27)=2.61, p < 0.05 \); Figure 15) but did not affect other performance measures. Pairwise comparison revealed an almost significant difference between thermal conditions in speed in N-back task after 30 min exposure (\( t(27)=2.67, p=0.051 \)).

The effect of cooling jet was seen in two dimensions of subjective workload. Perceived performance was higher with the jet (\( p < 0.01 \)) and frustration was lower with the jet (\( p < 0.05 \)). No effect was found on the other four dimensions of subjective workload (mental demand, physical demand, exertion and workload; all \( p's > 0.05 \)).
The cooling jet improved whole body thermal sensation ($p < 0.001$; Figure 16) and whole body thermal satisfaction ($p < 0.001$). No gender differences were found. The percentage of dissatisfied with thermal environment at the end of the sub-session was 72% without the jet, and 38% with the jet. Local thermal sensation (all $p$'s $< 0.05$) and local thermal satisfaction (all $p$’s $< 0.05$, except feet with a similar non-significant trend) were significantly better with the jet (Table 8). Draughtiness was perceived higher with the jet both in the beginning ($p < 0.001$) and at the end of the sub-session ($p < 0.001$). However, the draughtiness with the jet was low throughout the sub-session. Suitability of thermal environment was better with the jet both in the beginning ($p < 0.001$) and at the end of the sub-session ($p < 0.01$).
Table 8. The mean values of local thermal sensation and local thermal satisfaction. Standard deviations are presented in brackets. Response scales are clarified in Table 6.

<table>
<thead>
<tr>
<th></th>
<th>Local thermal sensation</th>
<th>Local thermal satisfaction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without the jet</td>
<td>With the jet</td>
</tr>
<tr>
<td>Top of head</td>
<td>1.4 (0.8)</td>
<td>0.7 (0.9)</td>
</tr>
<tr>
<td>Face</td>
<td>1.6 (0.8)</td>
<td>0.9 (1.0)</td>
</tr>
<tr>
<td>Back neck</td>
<td>1.4 (0.8)</td>
<td>1.0 (0.8)</td>
</tr>
<tr>
<td>Front neck</td>
<td>1.3 (0.8)</td>
<td>0.8 (0.7)</td>
</tr>
<tr>
<td>Torso</td>
<td>1.7 (0.9)</td>
<td>1.2 (0.9)</td>
</tr>
<tr>
<td>Back</td>
<td>1.7 (1.0)</td>
<td>1.3 (0.8)</td>
</tr>
<tr>
<td>Arms</td>
<td>1.4 (1.0)</td>
<td>0.7 (1.1)</td>
</tr>
<tr>
<td>Hands</td>
<td>1.8 (0.9)</td>
<td>1.2 (0.9)</td>
</tr>
<tr>
<td>Thighs</td>
<td>1.7 (1.0)</td>
<td>1.3 (0.8)</td>
</tr>
<tr>
<td>Legs</td>
<td>1.6 (0.9)</td>
<td>1.2 (0.9)</td>
</tr>
<tr>
<td>Feet</td>
<td>2.0 (0.9)</td>
<td>1.8 (0.7)</td>
</tr>
</tbody>
</table>

The perceived air quality was fresher with the jet \((p < 0.001)\). The adequacy of environment was better with the jet \((p < 0.05)\). Pleasantness of environment was higher with the jet both in the beginning \((p < 0.05)\) and at the end of the sub-session \((p < 0.05)\).

An effect of the jet was observed in many dimensions of disturbance of performance. Heat \((p < 0.05)\) and stuffiness \((p < 0.01)\) were perceived to disturb performance more without the jet. Draught was perceived to disturb performance more with the jet \((p < 0.01)\). However, with the jet, heat \((p < 0.01)\) and stuffiness \((p < 0.05)\) were rated to disturb performance more than draught.

The thermal condition had no main effect on perceived fatigue. However, an interaction between thermal condition and exposure time was found on one factor of perceived fatigue, tiredness \((p < 0.05)\). Tiredness did not change with exposure time with the jet \((p > 0.05)\), but increased with exposure time without the jet \((p < 0.01)\). Thermal condition had no effect on other dimensions of perceived fatigue, namely lack of energy and lack of motivation \((p > 0.05)\).

The intensity of eye symptoms was low at the end of both thermal conditions, but the difference was significant between thermal conditions \((p < 0.05)\). Eye symptoms increased over time with the jet \((p < 0.001)\) but did not change with exposure time without the jet \((p > 0.05)\). Sweating was significantly higher at the end of the sub-session without the jet \((p < 0.05)\). Paired comparison showed no effect of thermal condition on throat symptoms, difficulties in concentration, headache, nasal symptoms or feeling of being unwell \((all \ p's > 0.05)\).

Comments regarding the jet revealed that the target velocity and the orientation of the jet divided opinions. Also local pleasantness of jet and local unpleasantness of jet had large variations (Table 9).
Table 9. The percentage of subjects (100% equals 29 subjects) reporting the jet to be pleasant or unpleasant in certain body parts. No votes were given to back, thighs, legs or feet.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Top of head</th>
<th>Face</th>
<th>Back neck</th>
<th>Front neck</th>
<th>Torso</th>
<th>Arms</th>
<th>Hands</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pleasant</td>
<td>52</td>
<td>66</td>
<td>7</td>
<td>38</td>
<td>45</td>
<td>72</td>
<td>31</td>
</tr>
<tr>
<td>Unpleasant</td>
<td>21</td>
<td>41</td>
<td>10</td>
<td>10</td>
<td>0</td>
<td>10</td>
<td>0</td>
</tr>
</tbody>
</table>

4.5 Summary of results

In Publication I, heat sources seemed to have a notable influence on the flow pattern and badly implemented layout can cause draught risk due local air movement, especially if the workstation is located in the downfall area of the inlet jet. The mean air speed seems to increase with cooling load. The flow pattern in the room is not stable and the position of draught risk areas can change in time and also due to changes in room heat sources. This makes it difficult to achieve thermally comfortable environment at each workstation in open-plan office.

The dependent variables from Publications II-IV which are affected by the independent variable are collected in Table 10. Table 11 shows the absolute values of effect sizes, i.e. Cohen’s $d$ values for parametric tests and effect size estimate for Mann-Whitney nonparametric test. Effect sizes are calculated only for the performance measures which are significantly affected by the independent variable.

The slightly warm temperature (Publication II) and Condition B (low ventilation rate with increased human bioeffluents, Publication III) seems to have only a weak negative effect on cognitive performance, while the use of cooling jet in a slightly warm office (Publication IV) seems to improve the speed of response in a working memory task. Perceived performance was improved with the cooling jet (Publication IV). No effect of warm temperature or low ventilation rate with increased human bioeffluents on perceived performance was observed (Publications II and III).

The intensity of symptoms and perceived fatigue was low in all three Publications (II, III and IV). Some effects of independent variable were seen on subjective workload in all three Publications. Independent variable affected thermal comfort (Publication II) and perceived indoor air quality (Publication III), which both were improved by the cooling jet (Publication IV).

The disturbance of heat on performance was increased by slightly warm temperature (Publication II) and by low ventilation rate with increased human bioeffluents (Publication III). Slightly warm temperature also increased the disturbance of stuffiness (Publication II). The cooling jet decreased the disturbance of heat and the disturbance of stuffiness (Publication IV).
Table 10. The dependent variables which are significantly affected by the independent variable at least in one Publication (II-IV). Dependent variables affected by independent variable are marked with letter "X" in the independent variable column. Dependent variables are not comparable between Publications due to difference in questions or response scales (see Table 6).

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Used in Publication</th>
<th>Independent variable</th>
<th>Temperature (Publication II)</th>
<th>Ventilation rate (Publication III)</th>
<th>Cooling jet (Publication IV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance</td>
<td>N-back (working memory)</td>
<td>II, III, IV</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Information retrieval (working memory)</td>
<td>III</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Whole body thermal sensation*</td>
<td>II, III, IV</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Whole body thermal satisfaction*</td>
<td>II, IV</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Local thermal sensation*</td>
<td>II, IV</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Local thermal satisfaction*</td>
<td>II, IV</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Draughtiness</td>
<td>II, IV</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Perceived air quality*</td>
<td>III, IV</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Perceived odour intensity</td>
<td>III</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Perceived fatigue</td>
<td>Tiredness</td>
<td>II, III, IV</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lack of energy</td>
<td>II, III, IV</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lack of motivation</td>
<td>II, III, IV</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Symptoms</td>
<td>Throat symptoms</td>
<td>II, III, IV</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dryness and irritation of eyes</td>
<td>II, III, IV</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Difficulties in concentration</td>
<td>II, III, IV</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Sweating</td>
<td>II, IV</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Subjective workload*</td>
<td>Workload</td>
<td>III, IV</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Frustration</td>
<td>III, IV</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Performance</td>
<td>III, IV</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Physical demand</td>
<td>II, IV</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Disturbance of different environment factors</td>
<td>Heat</td>
<td>II, III, IV</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Coldness</td>
<td>II, III, IV</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Air stuffiness</td>
<td>II, III, IV</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Air dryness</td>
<td>II, III</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Draught</td>
<td>II, IV</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Work environment statements*</td>
<td>Pleasants of the environment</td>
<td>II, III, IV</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>The possibility to work effectively</td>
<td>II, III</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Overall experience of the environment</td>
<td>II, III, IV</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

*Differences in questions or response scales.

Table 11. The absolute values of effect sizes of performance measures, which are significantly affected by the independent variable. Size ranges are described in paragraph 3.2.3.

<table>
<thead>
<tr>
<th>Independent variable</th>
<th>Performance measure</th>
<th>Difficulty level</th>
<th>Cohen's d</th>
<th>r</th>
<th>Size range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (Publication II)</td>
<td>N-back</td>
<td>Accuracy (correct responses, %)</td>
<td>All combined</td>
<td>2.90*</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>0-back</td>
<td>2.70*</td>
<td>-</td>
<td>Large</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2-back</td>
<td>2.06*</td>
<td>-</td>
<td>Large</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Speed (reaction time, ms)</td>
<td>All combined</td>
<td>1.77*</td>
<td>-</td>
<td>Large</td>
</tr>
<tr>
<td></td>
<td>0-back</td>
<td>0.89*</td>
<td>-</td>
<td>Large</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1-back</td>
<td>0.76*</td>
<td>-</td>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2-back</td>
<td>1.53*</td>
<td>-</td>
<td>Large</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3-back</td>
<td>0.75*</td>
<td>-</td>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td>Ventilation rate (Publication III)</td>
<td>Information retrieval</td>
<td>Speed (number of unanswered questions)</td>
<td>-</td>
<td>-</td>
<td>0.44*</td>
</tr>
<tr>
<td>Cooling jet (Publication IV)</td>
<td>N-back</td>
<td>Speed (reaction time, ms)</td>
<td>All combined</td>
<td>0.15*</td>
<td>-</td>
</tr>
</tbody>
</table>

*Interaction between independent variable and exposure time. Effect size calculated within independent variable, i.e. speed at the beginning of sub-session vs. speed at the end of sub-session.
5. Discussion

5.1 Theoretical implications

The results of Publication I are in agreement with previous findings regarding airflow pattern and the maximum air speed (Kosonen et al., 2007; Müller et al., 2004). The heat sources seemed to have a notable influence on the flow pattern and the maximum air speed was highest in summer case, which had the highest cooling load.

In Publication II the performance findings are in partial contradiction with some well-known models (Clements-Croome, 2006; Seppänen et al., 2006a). It seems that within this temperature range, performance in cognitively demanding tasks is not as sensitive to temperature changes as the model of Seppänen et al. (2006a) suggests. Figure 17 shows the comparison between Seppänen’s model and performance results in Publication II. However, temperature had a significant effect on subjective performance measures and comfort, which may indirectly influence actual performance in all task types over time, as the maximal adaptability model by Hancock and Vasmatzidis (1998) suggests (Figure 18). This model suggests an extended U-shape curve, showing that mental resources are used to compensate for the adverse effects of temperature outside the range of optimal temperature, which allow optimal performance to be maintained to some extent. The adaptation is possible up to a certain point, which may depend on the temperature and also on the exposure time. The higher the temperature, the shorter the time for which one may be able to make increased efforts. It seems that 3.5 h of exposure time at 29 °C is not a sufficiently strong thermal exposure to produce a significant performance decrement when the activity levels are low, as they usually are at office work. According to the subjective measures, it is obvious that 29 °C is not an optimal temperature for office work and the use of mental resources was needed to compensate for the negative effects of the slightly warm temperature.

The PMV model was able to predict well the mean vote of subjects’ thermal sensation at 23.5 °C, which was ‘neutral’ (Publication II). However, it underestimated the mean vote to be ‘slightly warm’ at 29.5 °C while the mean vote of subjects’ thermal sensation was ‘warm’ in both Publications II and IV. The predictions of the PPD model underestimated the percentage of subjects dissatisfied with thermal environment in both Publications II and IV (Table 12).
Figure 17. The comparison between Seppänen’s model (Seppänen et al., 2006a) and performance results in Publication II. Graph includes tasks where performance accuracy (%) is measured. Data from Publication II is fitted into the model so that the measured performance in 23.5 °C equals the value gain from the model at 23.5 °C and measured performance difference between 23.5 °C and 29.5 °C still remains.

Figure 18. The extended U-shape curve describing the maximal adaptability model by Hancock and Vasmatzidis (1998). The grey area indicates optimal temperature.

Table 12. Percentage dissatisfied to thermal environment (PD, gain from questionnaires in Publications II and IV), and the predicted percentage dissatisfied (the PPD model, Equation 5), respectively.

<table>
<thead>
<tr>
<th>Temperature [°C]</th>
<th>Publication II*</th>
<th>Publication IV**</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PD [%]</td>
<td>PPD [%]</td>
</tr>
<tr>
<td>23.5</td>
<td>30</td>
<td>6</td>
</tr>
<tr>
<td>29.5</td>
<td>91</td>
<td>46</td>
</tr>
</tbody>
</table>

*With estimated clothing value of 0.83 clo.

**With estimated clothing value of 0.71 clo, and without the jet.
The performance results in Publication III could not confirm Seppänen’s model regarding the relationship of ventilation rate and performance (Seppänen et al., 2006b). However, selected studies with external pollution source were included in the model and temperature variations were present in the studies in which the model is based on. Therefore, differences in exposure prevent direct comparison between Publication III and Seppänen’s model. In addition, according to Seppänen et al., (2006b), the model is not valid for ventilation rates lower 6.5 L/s per person, yet, it is likely that the adverse effects of low ventilation rates below 6.5 L/s per person become stronger than with higher ventilation rates. The performance results in Publication III and Seppänen’s model are collected into same figure to see if they had a similar trend (Figure 19). The model was drawn to the lowest ventilation rate, 6.5 L/s per person, where the model should be valid, and performance results in Publication III was drawn using the same logic as in model (performance is 100% in lower ventilation rate and the relative performance was calculated for higher ventilation rate from the measurement results). Performance increment with increased ventilation rate in Operation span task had a similar trend as in Seppänen’s model. Other tasks could not confirm Seppänen’s model. On the other hand, the performance results of Publication III are in partial agreement with study by Zhang et al. (2016). They measured cognitive performance of 25 subjects in a stainless-steel climate chamber with human produced CO₂ with bioeffluents. They compared exposure conditions of human bioeffluents CO₂ levels (1000 ppm and 3000 ppm) to reference condition 500 ppm CO₂. Among many tasks examining the impact of exposure conditions on performance of tasks which measures basic cognitive functions, there were only 3 (addition, redirection and Tsai-Partington tests) in which conditions had a significant effect on performance. No effect was found on typing, as in Publication III.

An effect of ventilation rate on perceived air quality and on odour intensity was found in Publication III in the beginning of the session, but no effect was found at other exposure times. This supports the findings of Zhang et al. (2016), that elevated levels of bioeffluents seems to affect negatively on acceptability of air quality, odour intensity and air freshness upon entering the room. The result is consistent also with ASHRAE standard 62.1 which considers adapted occupants.
Figure 19. The performance results in Publication III and Seppänen’s model (Seppänen et al., 2006b). The model was drawn to the lowest ventilation rate, 6.5 L/s per person, where the model should be valid, and performance results in Publication III was drawn using the same logic as in model (performance is 100% in lower ventilation rate and the relative performance was calculated for higher ventilation rate from the measurement results). The effect of increased ventilation rate with reduced human bioeffluents on performance in Operation span task was nearly significant ($p=0.051$). The effect on performance in other tasks was insignificant.

The intensity of all symptoms in Publication III was low with both conditions and no effects of ventilation rate on symptoms were found. This result in Publication III agrees with results of Zhang et al. (2016), in which subjects were exposed to bioeffluents with CO$_2$ levels of 1000 ppm and 3000 ppm and no statistically significant differences were observed, other than on headache. They found a trend that poor indoor air quality increased the intensity of fatigue, sleepiness and difficulties in thinking clearly, but the difference was insignificant. They also compared conditions where pure CO$_2$ was added (1000 ppm and 3000 ppm), and found no effect of indoor air quality on symptoms.

In Publication IV, the jet improved speed in N-back task with increasing exposure time. Reaction times are generally interpreted to reflect underlying mental processing and, thus, improved speed is an indication of enhanced information processing. The result is unexpected, since we expected to find differences only in subjective measures, based on findings from previous studies (Cui et al., 2013; Melikov et al., 2013). However, this improvement in performance was very small (Table 11), and it did not manifest in the accuracy in N-back task. Likewise, accuracy in serial recall task was not affected by the jet. The N-back working memory task has been sensitive to temperature differences (Häggblom et al., 2011; Publication II). The result found in performance in N-back task (Publication IV) agrees with findings of Schiavon et al. (2016) that increasing the temperature to 29 °C reduced the speed of performance and having a fan only partially compensated, i.e. the effect size with the fan was smaller than the performance decrease at 29 °C compared to 26 °C. They used working memory task such as 2-back in Publications II-IV, but instead of analysing the N-back task alone, they compounded the results of different tasks before analyses,
which makes direct comparison between Publication IV and their results difficult. In Publication IV no effect of cooling jet was seen on performance in short-term memory task. This result is in agreement with Cui et al. (2013) where no effect of air movement on memory performance in very similar task, as the short-term memory task in Publication IV, was seen when table fans were used in warm climate chamber.

In Publication IV the jet improved local thermal comfort in all body parts. Local thermal comfort was improved even in the body parts which were out of the direct reach of the airflow (back, thighs, legs and feet). This is in agreement with earlier findings by Yang (2009). Subjective measures consistently indicate an improvement of working conditions with the jet. However, eye symptoms increased with time when the jet was provided. Lipczynska et al. (2014) suggested that the use of individual control over supplied airflow’s direction and velocity of the jet might be one of the main solutions to avoid eye irritation caused by elevated air movement. The results on subjective workload and perceived fatigue suggest possible indirect effect of the jet on overall performance. In the thermal condition without the jet, subjects may have increased their effort to compensate for an anticipated negative effect of thermal condition on performance (Hancock and Vastmatzidis, 1998). Increased effort could decrease differences in performance but emphasize the differences in subjective measures. The large variation in the perception of the jet shows a need for individual control over the jet already when the target velocity is set to the upper limit according to ASHRAE standard 55 (2010).

5.2 Practical implications

The room air flow pattern in cooling conditions depends on the relative locations of air distribution units and heat sources. In ideal conditions, the air distribution units and workstations would be placed symmetrically, which would make it easier to control the conditions in workstations. In practice, the workstation layout is not necessarily symmetric compared to the air distribution. When the office layout is changed, the ventilation flow pattern should also be adjusted to avoid draught problems in workstations. However, the adjustments are not always conducted and the thermal environment in individual workstations can differ notably.

The effects of temperature and ventilation rate (i.e. human bioeffluents) on occupant were studied separately. It seems that cognitive performance is not as sensitive to changes in temperature as suggested by Seppänen et al. (2006a) and that the effect of temperature on performance is task dependent. Results also suggest that emissions from occupants, i.e. human bioeffluents do not have as strong effect as previously seen with emissions from external pollution source (Seppänen et al., 2006b). Both higher temperature and lower ventilation rate
with increased human bioeffluents had a significant effect on subjective measures.

A cooling jet from the ceiling improved the occupants’ perception of the environment and comfort in warm office environment. It seems that a cooling jet from the ceiling can be used to provide beneficial local cooling even with constant airflow. In addition, the use of airflow to provide local cooling enables the individual control over the thermal environment. Individual control is desirable since there is some evidence that improving the adjustability of various factors of the physical environment in a workplace could improve occupants’ perception (O’Neill and Miller, 1992; Hongisto et al., 2016).

The practical importance of findings related to work performance in Publications II-IV can be estimated with calculated effect sizes (Table 11). Although, effect sizes cannot be directly compared between Publications, cautious approximations can be made based on the verbal size range. The deteriorating effect of high temperature (Publication II) and low ventilation rate (Publication III) on performance appeared to be much greater than the improving effect of cooling jet (Publication IV). Ventilation rate seemed to have medium effect on performance in information retrieval task, while temperature seemed to have large effect on the accuracy of N-back task and large or medium effect on speed (reaction time). However, the unit of reaction time was ms, which is very small and the unit size is not taken into account in Cohen’s $d$. Therefore, large effect size in speed in N-back task may still have minor practical importance. Thus, the practical meaning of the very small effect size in performance measures in Publication IV, is negligible.

The energy consumption and risk of draught are among the main problems when air conditioning systems are used in offices with high thermal load. One solution may be to allow slightly elevated temperatures in the space and to provide local cooling using jet with individual control into the workstation. This kind of solution allows occupants to adjust the individual thermal environment to gain better thermal comfort while energy consumption of air conditioning could be reduced.

5.3 Recommendations for future research

There is a need to improve the predictions of the airflow pattern in office with variety of boundary conditions and the predictions of thermal comfort in asymmetric office layouts with HVAC system. The effect of airflow pattern in office on thermal comfort could be studied by using physical measurements of room airflow pattern together with human subject experiments. What are the different boundary condition combinations, when air movement starts to be perceived as unpleasant? Thereafter, how the seasonal and layout changes of heat sources effects on thermal comfort?

The effect of warm office temperature on performance according to the maximal adaptability model by Hancock and Vasmazidis (1998, Figure 18) needs be
studied more with different tasks measuring different cognitive processes and different kind of office work, for example, teamwork and communication tasks.

There is a need for further studies to determine the threshold level of CO₂ concentration at which bioeffluents have adverse effects on occupants. Could the maximal adaptability model by Hancock and Vasmatzidis (1998) be also applicable to predict the effect of ventilation rate on performance in low polluting offices where pollution load is mainly from occupants, i.e. bioeffluents?

It might be valuable to investigate the effect of other individual factors, such as age, health, body-mass-index BMI (Tuomaala et al., 2013), activity level etc., and not just ventilation rate or level of bioeffluents.

Modifying different parameters of a cooling jet may have significant effect on the subjects’ perception of the jet, and the effect is not always easy to predict. Therefore, there is a need for more research of the effect of a cooling jet on occupant comfort and SBS symptoms with different types of air terminal units and cooling jet parameter solutions.

It seems that individual control over the cooling jet should be provided. It is important to investigate an individually controlled jet solution which could also be implemented in a real product and integrated to the air conditioning system. Therefore, more studies of the effect of room airflow pattern on the cooling jets’ flow pattern in different office layouts and mean air speeds of supply air are needed.

The use of cooling jet may enable energy savings by allowing the room air temperature to rise without causing thermal discomfort. More research is needed to find the optimum indoor environment solution regarding energy savings and occupants’ comfort, in which room air temperature is slightly raised and individual control over the thermal environment at workstation is provided via cooling jet. How the cooling jet is perceived when thermal sensation vote without the jet is slightly warm? What is then the effect of individually controlled cooling jet on thermal comfort, SBS symptoms, perception and work performance?
6. Conclusions

This thesis describes, in Publications I-III, problems caused by improper air conditioning, and then introduces a cooling jet from the ceiling as a solution which may enable energy savings by allowing the temperature to rise without causing thermal discomfort or weakening perceived indoor air quality in a modern clean office with a low emission load (Publication IV). Laboratory experiments were done in all Publications. The main conclusions of the present thesis are summarized in the following:

- Heat sources may have a notable influence on the flow pattern in office and badly implemented layout can cause draught risk due local air movement, especially if the workstation is located in the downfall area of the inlet jet.

- The mean air speed in office seems to increase with cooling load, which may lead to increased risk of draught.

- The flow pattern in the room is not stable and the position of draught risk areas can change in time and also due to changes in room heat sources making it difficult to achieve thermally comfortable environment at each workstation in open-plan office.

- The slightly warm temperature may affect thermal comfort negatively and increased level of human bioeffluents may affect perceived indoor air quality negatively, which both seemed to be improved by the cooling jet.

- The disturbance of heat on performance seemed to be increased by slightly warm temperature (29.5 °C) and by high concentration of human bioeffluents (CO₂ 2260 ppm) compared to neutral condition (approximately 23.5 °C, CO₂ 600 ppm). Slightly warm temperature also seemed to increase the disturbance of stuffiness. The cooling jet may decrease the disturbance of heat and the disturbance of stuffiness in slightly warm temperature.
References


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This thesis examines the effects of thermal conditions and ventilation rate on occupants’ comfort, perception and work performance in office environment. The focus is on the effects of room air temperature, indoor air quality and airflow on occupants’ subjective reactions and performance. First, the problems caused by improper ventilation is described. Then a cooling jet from the ceiling is introduced as a solution which could enable energy savings by allowing the temperature to rise without causing thermal discomfort or weakening perceived indoor air quality in a modern clean office with a low emission load.