THERMAL AND INDOOR AIR QUALITY EFFECTS ON PHYSIOLOGICAL RESPONSES, PERCEPTION AND PERFORMANCE OF TROPICALLY ACCLIMATIZED PEOPLE

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2006

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(B.Eng.(Arch.), M.Sc.(Bdg. Sc.))

A THESIS SUBMITTED

FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF BUILDING

NATIONAL UNIVERSITY OF SINGAPORE

2006

A JOINT DEGREE PROGRAMME BETWEEN

NATIONAL UNIVERSITY OF SINGAPORE

AND

TECHNICAL UNIVERSITY OF DENMARK

Acknowledgment

This thesis presents and synthesizes the outcomes of research conducted in the field laboratory of the Department of Building of National University of Singapore (NUS) as well as in three office buildings located in Singapore between August 2002 and October 2004. The research focuses on various occupants' responses to the indoor environment.

I am deeply grateful and indebted to many individuals for this research opportunity.

First, I would like to gratefully acknowledge the supports given by the Department of Building of NUS in conducting this research. I am also grateful for the research scholarship granted by the National University of Singapore.

I thankfully acknowledge the support and warm welcome from the International Center for Indoor Environment and Energy of the Technical University of Denmark during the period of study in Denmark under the joint PhD degree program of the National University of Singapore (NUS) and the Technical University of Denmark (DTU).

I express my highest gratitude to A/Prof Tham Kwok Wai for giving me the opportunity to be part of this research, for sharing his ideas and knowledge, and above all, for trusting and believing in me all the way with his unfailing supports and encouragements. It has been truly a great experience and a privilege to know, to interact and to learn so much from a person who has been a role model to me and many others.

I also thank A/Prof Pawel Wargocki for sharing his experiences in this area of research. Working with him has been an illumination to my understanding about various aspects within and without the human-environment interactions. It was also a great experience to be part of his research team in conducting field studies during my study in Denmark.

I am indebted to Prof David P. Wyon as one of my mentors in formulating the research design, for sharing his seemingly unlimited ideas, and for the review of and suggestions to the results obtained from the research.

I would like to thank Prof Bjarne W. Olesen as my academic supervisor during my study in the Technical University of Denmark. I shall gratefully acknowledge his comments and suggestions in the interpretation of the research results. I also thank him for supporting my application for an overseas conference grant.

I express my sincere gratitude to A/Prof S. Chandra Sekhar and A/Prof David Cheong, in particular, for the time and the numerous advices during the initial stage of the research work. I deeply appreciate their encouragements throughout my study in NUS.

I also express my fond admiration and appreciation to Prof P. Ole Fanger for the inspiring research work, ideas and visions on thermal comfort and indoor air quality research. I

thank him for sharing his knowledge through the lectures, giving advices, and showing the next important stage in the indoor environmental research.

Thanks are also due to A/Prof Geo Clausen for his time and effort in processing my enrolment as the PhD candidate of the Technical University of Denmark.

I warmly thank Prof David Koh, Ms Vivian Ng and Mr Andrew Wee from the School of Medicine of the National University of Singapore for their time and effort in the processing of the saliva samples and for sharing their knowledge about the applications of salivary biomarkers.

Special thanks are due to Ms Afizah, Mr Alvin Ang, Mr Asokan, Mr Foong, Ms Lily Koh, Ms Madeleine, and Mr Tham Khong Wing from the call center managements for their generous support, patience and kind cooperation during the preliminary stage and actual experimental period in the call centers.

I sincerely thank Prof Jan Sundell for sharing his knowledge in the interpretation of some results from the biomarkers data.

I warmly thank A/Prof Jørn Toftum for sharing his research work and giving useful suggestions for the post-analysis of the results and their interpretations.

I thank Prof Kirk Smith for sharing his passion in research for the betterment of air quality in the poor and developing countries. I truly enjoyed our discussions during his visit to the Technical University of Denmark.

The presented research results in this thesis testify to the contributions from many participants in the field investigations as well as the simulated office studies. I would like to extend many thanks and appreciations to all the participants for their commitments and patience.

I would like to thank all my friends, colleagues, laboratory officers, and the Departments' secretaries from the National University of Singapore and the Technical University of Denmark for their friendships, supports, and all the time and fun we shared throughout my study.

I praise God for the opportunity to knowing you all.

Singapore, 18th March 2006

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Summary

The title of this thesis is "**Thermal and Indoor Air Quality Effects on Physiological Responses, Perception and Performance of Tropically Acclimatized People**".

Chapter 1 outlines the backgrounds of this research. Thermal environment and the indoor air quality effects on occupants' responses, in particular, their work performance are highlighted. A unified model is proposed to address the associations among the perceptual responses, physiological measures, and potential work performance outcomes as the results of changing air temperature or outdoor air supply rate. The potential economical gains of improved productivity with optimum indoor conditions are shown to exceed the costs and investments. The objectives of this research can be summarized as follows: to investigate the effects of air temperature and outdoor air supply rate on work performance, to study the mediating factors within these associations, such as perception, intensity of SBS symptoms, and physiological indicators, and finally, to develop a structural model representing the identified mechanisms for the tropically acclimatized office workers.

In **Chapter 2**, a detailed review of the literatures on various aspects related to thermal environment and the indoor air quality is provided. Thermal parameters affect occupants' skin/ cutaneous, behavioral and perceptual responses through the thermoregulatory mechanisms, while the indoor air quality defined by various determinants influences olfactory senses, irritations, and the intensity of SBS symptoms. The highlight of this chapter is the review on the application of salivary biomarkers as a new approach in characterizing the effects of indoor environmental parameters through the central nervous system controls and feedbacks. Other reviews on direct effects of either thermal or indoor air quality parameters have demonstrated the effects on work performance of workers acclimatized to the temperate climate. However, understanding of the contributions of various perceptual and physiological responses in the conceptual framework of the indoor environment - performance relationship is still limited. General factors affecting work performance including the speed and accuracy measures of performance are discussed towards the end of the chapter.

Chapter 3 is dedicated to the field studies conducted in three call centers. Six groups of call center operators or a total of 305 officers participated. Each call center was subjected to weekly blind interventions to either air temperature or outdoor air supply rate in balanced experimental design for a total of nine weeks. Alternating between 22.5 and 24.5°C affected workers' call handling performance by 3.0-5.7%, while doubling outdoor air supply rate improved performance by 5.1-8.2%. NPV cost-benefit analysis revealed that economical benefits arising from providing optimum air temperature and outdoor air supply rate for performance exceeded the costs by at least factors of 17 and 16, respectively. The effects on performance were associated with significant changes of subjective factors (principal components), revealing several plausible mechanisms.

Chapter 4 described the methods used in the field laboratory studies. In the simulated office, six groups of 16 subjects (a total of 96 subjects) performed various mental tasks and office component-skill measures. The experimental design was balanced for the order of presentation of the three settings in either air temperature or outdoor air supply experiment. Experimental protocols and schedules of various parametric measurements are discussed. Objective measurements of indoor air and thermal parameters, survey methods and questionnaire design, cutaneous measurement, saliva sampling protocols, and the performance measurements are described in detail together with their analysis methods.

Chapter 5 reports and discusses the results of field laboratory study of air temperature effects. The three air temperatures are 20.0, 23.0, and 26.0°C. Subjects perceived 23.0°C most comfortable throughout the 4-hour exposure. Continuous exposure to 20.0°C decreased thermal comfort, while exposure to 26.0°C improved thermal comfort with time. These effects were closely associated with subjects' thermal sensation. The latter was also linearly correlated with mean skin temperature (and likewise, between the local thermal sensations and the corresponding skin temperatures). Air temperature affected perceived air quality, following the effects on inhaled air thermal sensation. The local thermal sensation formed the most dominant subjective factor (principal components). Intensity of thermal-related symptoms and perceptual responses changed with air temperature in the expected direction, while neurobehavioral-related symptoms worsened with time and tended to be higher at 26.0°C. Tsai-partington test revealed that subjects experienced higher arousal at 20.0°C, a result strongly supported by the elevated α-Amylase level (higher activation level of the Sympathetic Nervous System (SNS)) with lower air temperature. Subjects' text-processing performance was also better at the lower air temperature. Text-typing performance was approximately 3.0% faster at 20.0°C. Subsequently, the structural model (MPIESM) was derived based on the postulated mechanisms. The model fit was accepted based on various criteria and confirmed several pathways within the indoor environment – performance relationship.

Chapter 6 reports and discusses the results of field laboratory study of the outdoor air supply rate effects. The range of outdoor air supply rate studied was between 4.5-18.0 L/s/p. Increasing outdoor air supply rates improved the sensory evaluation of indoor air quality by means of reducing perceivable odor, lowering perceived air stuffiness and air stillness, and improving acceptability (and thus lowering percentage dissatisfied) of the tropically acclimatized subjects. Introducing higher amount of outdoor air supply rates above 9.0 L/s/p with used ventilation filters seemingly increased the intensity of neurobehavioral-related symptoms and other breathing system-related symptoms, and tended to elevate irritation to the eyes. The neurobehavioral-related symptoms also formed the most dominant subjective factor. Higher salivary Cortisol and reduced salivary α-Amylase and sIgA levels were exclusively related to air quality at 18.0 L/s/p. Gradual improvements of creativity and numerical reasoning with increasing outdoor air supply rate were observed, while text-processing performance was reduced. The practical usefulness of the psycho-physiological biomarkers and the subjective evaluation of air quality and intensity of SBS symptoms in explaining some plausible mechanisms was demonstrated. These associations were evaluated simultaneously in the structural model (MPIESM) derived from the results of outdoor air supply rate experiment.

Chapter 7 is the concluding chapter of the thesis. It provides the overview of the overall results in the perspective of research objectives and hypotheses. The main conclusions derived from the results and discussions of the series of experiments were presented. Some recommendations for future research are characterization of the indoor air focusing on the episodes of indoor chemistry, conducting more studies in workplaces and other areas with the application of remote performance measurements, and exploring basic research of the identified mechanisms.

1

INTRODUCTION

This thesis presents concerted research efforts to address the occupants' responses associated with thermal environment in relation to air temperature and air quality as defined by the amount of outdoor air supply within the modern office environment. The effects of air temperature and outdoor air supply rate on work performance as the main outcomes of the present study are investigated independently. Results are derived from a series of intervention studies conducted in real offices, i.e. in three call centers, and subsequently, two main laboratory (simulated office) experiments to determine the effects of both parameters separately and to explore the mechanisms responsible for transducing the effects of the indoor environmental variables to changes in work performance. In the later approach, intervening variables that are crucial in depicting plausible mechanisms between indoor air parameters and occupants work output are included. These variables are some measurable and established physiological responses, which are associated with aspects of work performance and are potentially influenced by the thermal and air quality stressors.

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A substantial portion of the average life span of man is spent in his working environment. This has become more so in today's fast-paced modern office work, which often obliges people to work long hours, particularly within the Asia Pacific (including those in the tropics) and Latin American regions where work competition and pressure for family survival and coping with higher living standards are on the rise (Spector et al, 2004, Heymann et al, 2004). From another point of view, this often reflects dedication to economic goals, i.e. productivity. Although it may not be correct to associate high productivity with long working hours, inevitably, this is the most common norm adopted by many institutions and companies, particularly those that are profit-oriented. Interestingly, this association persists even in well-organized companies, indicating that it may not simply be a question of poor work management. This actually raises the question of whether it is possible to obtain a similar level of work output or perhaps better quality of work while working only the conventional or standard number of hours and if so, what are the factors that can cost-effectively be improved. More optimistically, priority should be given to promoting the well-being and health of workers to support their high workload and long working hours in the offices.

The rising expectations of healthier working environment and the role of health as an emerging competitive advantage are enforcing business leaders, building practitioners, and other occupational health professionals to reconsider the level of importance of indoor air quality (McCunney et al, 1997). Health organizations, engineer associations, research institutions, government bodies, and commercial sectors strive to define the unprecedented and multidisciplinary area of indoor air quality. From the perspective of public health, Bloom and Canning (2000) offered the following definition of productivity: "Healthier populations tend to have higher labor productivity because their workers are physically more energetic and mentally more robust." On this perspective, McCunney (2001) suggested that investing in workers' health could be the essential ingredient to the success of any organizations.

The importance of indoor environmental quality has often been overlooked in the effort to achieve greater productivity. Consequently, building practices and standards that specify the minimum requirements for many indoor environment parameters are usually adopted literally as the sole benchmark to achieve a comfortable, healthy, and productive working environment. It is pertinent to note that many of the standards were developed to protect people from suffering actual physiological damage. Now, however, efficient and error-free performance should be the principal criterion for contemporary working environments, as continuing exposure after work performance efficiency begins to fail, but before physical damage occurs, is inappropriate for both health and performance. Moreover, most recommendations for current practices are based on studies that were performed in temperate climate regions and insofar as building practices in the tropical regions are concerned, understanding how the indoor environment should be designed and operated to provide the most conducive working environment constitutes a knowledge gap that urgently needs to be addressed. The complex nature of the interfaces between building occupants and their environment, not only in terms of perceptual response but also in terms of physiological mechanisms, may differ greatly between people in the temperate region and those living in the tropics.

1.1. Thermal environment and indoor air quality parameters

Both ISO 7730 (1994) and ASHRAE 55 (2004) specify the range of room air temperature for thermal comfort based on combined air properties that will elicit desired level of physiological comfort. The recommended range of operative temperature, of which more than 80% of occupants will find the thermal condition acceptable, is 20.0-24.0°C in the winter and 23.0-26.0°C in the summer for sedentary activities. These standard ranges were derived based upon the thermal comfort indices i.e. the predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD) as conceptualized by Fanger (1970). However, since the PMV-PPD derivations were developed from subjective thermal responses of people acclimatized to the temperate climate, its direct application to the tropical context has been met with challenges related to physiological and behavioral adaptations (Machle, 1947, Prosser, 1958, Wyndham, 1968, Humphreys, 1976, Sharma and Ali, 1986, Busch, 1992). In the hot and humid climate, the influence of thermal adaptation causes greater deviation between the predicted and observed occupants' thermal response as temperature increases (de Dear and Brager, 1998). This could be accounted for by introducing an expectation index (Fanger and Toftum, 2002). Despite general acceptance that PMV model approximates the observed thermal response quite accurately in the air-conditioned environment (Olesen and Parsons, 2002), Humphreys and Nicol (2002) argued that deviations between predicted and observed thermal sensations caused by climatic differences could still occur within the relatively small range of air temperature variations, which indicates that PMV model may overestimate the thermal response of tropically acclimatized people with increasing room air temperature. In other words, people in the tropics may be more tolerant towards higher room air temperature and feel less comfortable at the lower temperature. The perceptual, behavioral, and physiological differences suggest that various aspects of work performance of people in the temperate climate and those in the tropics could also be affected to different extents by their thermal environment.

Clearly, thermal environment that causes thermal stress would affect work performance. Room air temperature could affect office work performance by lowering arousal, elevating the Sick Building Syndrome (SBS) symptoms and reducing manual dexterity (Wyon and Wargocki, 2005). Moderate thermal stress in the warm could negatively affect performance through arousal mechanisms. On the other hand, tasks requiring manual dexterity could be impaired during moderate cold exposure. This depends largely on the optimization of various factors within a person in dealing with a specific task. Within the moderate thermal stress, thermal environment could play the role of either a distracter or facilitator in achieving the optimum performance. Little information is available concerning the effects of air temperature on the work performance of tropically acclimatized occupants in the modern office settings. In a study conducted in Singapore, Tham and Willem (2004) reported the positive association between room air temperature and the work performance as indicated by the call duration spent on the phone between the customer service officers and their clients. The study showed that decreasing air temperature from 24.5 to 22.5°C, which corresponded to a marginal shift of occupants' thermal sensation from slightly warm to slightly cool, potentially improved call handling performance between 5.0-13.0% and that this improvement was accompanied by lower intensity of neurobehavioral-related symptoms such as difficulty to think, dizziness, fatigue, and headache, to name a few. In a review and meta-analysis based on 26 studies, which reported the effects of room air temperature on work performance, Seppänen and Fisk (2005) derived a temperature-dependent function of change-in-performance within air temperature of 15.0-35.0°C. This model suggested that raising air temperature up to a range between 20.0-23.0°C would improve performance while increasing air temperature beyond and above 23.0-24.0°C would lead to performance decrease and that maximum performance occurred at an air temperature of 21.6°C. The acceptable air temperature range for performance is therefore between 20.0-24.0°C with an optimum level on the cooler side of the range, which is consistent with the finding of study conducted in the tropics (Tham and Willem, 2004). In view of the plausible mechanisms related to thermo-sensory and SBS symptoms responses, these observations require more investigations involving various physiological indicators that could further elucidate the effects of air temperature on work performance, particularly in the tropical context.

Another determinant of the indoor environment associated with the building-related illnesses or the SBS symptoms (Mendell, 1993, Sundell et al, 1994, Menzies and Borbeau, 1997) and office productivity in terms of sickness absenteeism (Milton et al, 2000), the component-skill performance (Wargocki et al 2000, Lagercrantz et al, 2000, Bako-Biro et al, 2004) and the actual office performance (Wargocki et al, 2004, Tham and Willem, 2005) is the indoor air quality as characterized by the air contaminants, their inter-reactions and the varying concentrations in the air. These strongly persuasive evidences support the notion of providing good air quality to the occupants through the introduction of clean air to the breathing zone. Among the most recommended approaches to improve air quality are pollution source control and increasing ventilation as the means to reduce emissions of contaminants and to provide higher dilution factor, respectively.

Comparing results from objective measures of air constituents and the occupants' feedback related to the indoor air quality and the prevalence or intensity of SBS symptoms often leads to differing conclusions. This is in part due to the lack of measurements capability to characterize the presence and concentrations of and the reactions among the various air contaminants, while on the other hand, the self-reported perceptual responses could be influenced by occupants' personal- and work-related factors. In response to the former drawback, indoor air scientists have turned their attention to human's olfactory senses in perceiving and judging the air quality (Yaglou et al, 1936, Berg-Munch et al, 1986, Iwashita et al, 1990). Fanger (1988a) introduced the predictive model for perceived air quality that accounts for the total mixture of air contaminants in the air using human olfactory senses as the evaluation tool with the reference unit based on perceived pollution generated by one standard person. The model also estimates the percentage dissatisfied (PD) with air quality. ASHRAE 62-1 (2004) recommended that indoor air quality can be classified as "free of annoying contaminants" if at least 80.0% of either occupants or panel of visitors deem the air not to be objectionable or percentage dissatisfied (PD) of 20.0% or less. The standard specifies the minimum ventilation rates in breathing zone based on the required dilutions according to number of occupants (2.5 L/s/p) and areas to be ventilated (0.3 L/s/m^2). Taking an example from an office in the present study, the recommended minimum outdoor air supply rates (Class 1 category) for 28 people in the office with an area of about 275m^2 at the breathing zone is calculated at approximately 151.2 L/s or 5.4 L/s/p. In the light of previous positive associations between outdoor air supply rates and work performance, attributable to better perceptions of air quality and reduced intensity of SBS symptoms, introducing outdoor air supply at the minimum may not be sufficient to achieve greater productivity. Seppänen et al (2006) demonstrated the positive correlation between the percentage change in the work performance and the outdoor air supply rate. The derived relationship based on meta-analysis implied the continuous increase in work performance per unit increase of outdoor air supply rate up to 15.0 L/s/p, beyond which the work performance improvements due to increasing ventilation would diminish. Demonstrating the effects of improved air quality, i.e. by increasing outdoor air supply rate, on work performance in the tropical context would have enormous practical implication and economical significance. Current building practices still favor lower outdoor air intake due to energy usage concerns. Evidence of increased productivity as the consequence of providing higher fresh air provision would therefore change the paradigm of air conditioning strategies. This is not to mention that other benefits of reduced sickness absenteeism and lower risk of infectious disease would eventually contribute to overall productivity gain.

1.2. A unified model of mechanisms

The study of interactions between occupants as the subject, indoor environment as the interface and work output as the goal involves a multidimensional approach. Many previous studies have only partially observed the postulated interrelationships that govern occupants – indoor environment interactions and although to some extent it is possible to compile these findings and postulate the overall mechanisms involved, the inconsistencies and even contradictory findings have made it difficult to obtain a reliable and complete model of the whole spectrum. Some inconsistencies emerge due to the lack of coherent approach among the many studies spanning decades of research. Additionally, changing expectations and technological advances as well as higher living standards all play a major role in the changing acceptance and tolerance levels. Thus, in exploring mechanisms that could facilitate an understanding of the effects of indoor environmental factors on work performance particularly among tropically acclimatized office workers, a carefully considered study that maps the plausible linkages, as a unified model, is needed.

One element in the complex occupant – indoor environment interactions that has long been of major research interest is the observation of how people perceive or subjectively evaluate their working environment, because this is assumed to affect their work performance and thus, overall productivity. The paths by which indoor environmental conditions can affect a person's perception have not been fully explored for workers of the tropics. In the past, multipurpose research with varying approaches provide a poor basis for deriving the right improvement strategies. The same drawback applies to the relationships reported from past research about the influence of different types of indoor contaminants, level of contamination and ventilation design and operation that lead to negative health effects and the phenomena of SBS symptoms. However, most of the studies express a general agreement that since these symptoms are commonly reported during working hours, it is most relevant to relate them to the environment to which workers are exposed continuously, i.e. as the product of multiple indoor environment determinants. Numerous studies have shown that exposure to poor indoor air quality is probably the main culprit for the increase in the prevalence and/or intensity of SBS symptoms, and could even be associated with or preceded by measurable physiological responses.

The explorations of physiological responses have focused on the human biomarkers directly associated with the indoor environmental variables. As the response measures of the thermal environment, variations of skin temperature, internal body temperature, heart rate, and sweat rate/ loss as the apparent consequences of thermal conditions are the most common measures. In contrast to the established measures to thermal effects, physiological indicator of the indoor air quality as defined by the air constituents is still lacking partly because of its relatively undefined and sparse associations with any specific physiological traits. Recently, Tanabe and Nishihara (2004) suggested that cerebral blood flow is positively associated with the subjective measure of mental fatigue. However, in a subsequent study, Nishihara et al (2005) did not obtain the associative evidence between the changes in cerebral blood flow and work performance as well as reported intensity of SBS symptoms. Bakó-Biró et al (2005) hypothesized and demonstrated that polluted air causes the unconscious shallow breathing mechanisms, indicated by the lower CO_2 generation rate. They further argued that this would increase CO_2 level in the blood and, thus, could induce or elevate various SBS symptoms. The eye blink-rate and eye tear-film stability were also employed in assessing the irritation and dryness effects to the eyes. The method, however, has only been applied in conjunction with the evaluation on work performance in a series of study associated with low relative humidity (Wyon et al, 2003), while others have used this method to evaluate eyes sensitivity to various irritants such as high CO_2 level (Kjærgaard et al, 2004), office dust (Molhave et al, 2002), and combined limonene oxidation products and nitrate radicals (Kleno and Wolkoff, 2004). Wyon et al (2003) reported a significantly higher eye blink-rate under exposure to 5.0%Rh and reduced eye tear-film quality starting from 25.0%Rh as air humidity was lowered, which were accompanied by lower rate of simulated office tasks performance, i.e. text-typing, proofreading, and the 2-digit number serial addition.

Application of the above biomarkers would provide objective evidence of thermal and air quality effects on occupants' physiology. In turn, these associations could indicate the progressive effects on the workers' performance. Nevertheless, as jobs demographics evolves from the industry and agriculture to the more sedentary office professions over the last 50 years or so, the application of some of the direct indicators that reflects the manual dexterity has become less relevant. Nowadays, office activities emphasize the mental processing and acquired skills such as, but not limited to, creative thinking, problem solving, arithmetic and language-processing performance, and communication skills. Physiological measures of the central nervous system activities that bridge the knowledge gaps in the understanding of how indoor environmental stressors could physiologically affect occupants and how these effects are further transduced into changes in work performance is essentially required. The identification of these biomarkers would enable the detection of any early biological effects that could deteriorate workers' performance and thus allowing for a more effective exposure control.

A unified model as shown in Figure 1.1 represents the mechanisms explored in the present study. The hypothesized model is derived based on constructive relationships observed in the literature and the plausible mechanisms discussed above. The figure depicts direct effects of the environmental stressors on work performance, which are plausibly mediated by two main factors, i.e. the perceptual and physiological responses. Subjective or perceptual responses include thermal and indoor air quality perceptions as well as the SBS symptoms. Cutaneous indicators as the measure of thermoregulatory response and the neural and immune system indicators as the measure of the brain activation and health status are among the range of investigated physiological traits.

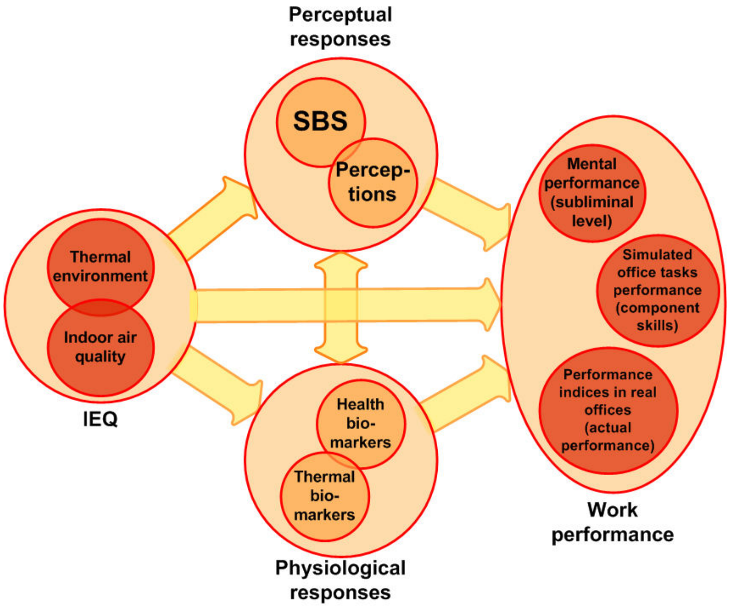

Figure 1.1 Postulated mechanisms explored in the present study.

The model also highlights the various stages and definitions of office work performance reported in this thesis. The mental and simulated office tasks are explored in the laboratory experiments while the actual office performance is measured in several real offices. The reliability and applicability of laboratory experiments results in real working environment are often questioned despite the major advantages of having better or even full control of all relevant environmental variables. On the other hand, studies conducted in a real office environment are clearly the most realistic but they are often characterized by poor control and difficulty in achieving certain required conditions, especially when using the intervention approach. Both approaches, however, compliment each other and when combined they eradicate the disadvantages. The findings in the laboratory experiment are validated in a field study while the variability observed in field studies may be explained through mechanisms tested using the better-controlled and less confounded laboratory experiments.

1.3. Productivity gain

Occupant – indoor environment interactions that affect productivity have strong economical implications. Unfortunately, the influence of the indoor environment on office productivity within the tropical population has never been reported before although studies in temperate climate regions have shown that considerable returns are achievable by optimizing the levels of several different indoor environmental parameters. Fisk and Rosenfeld (1997) had reported that enormous economic losses are suffered every year due to productivity decrements caused by inadequate indoor environmental conditions. Using very conservative assumptions, they also estimated that the US suffers a total loss of US30 billion to 150 billion dollars annually and that the benefit-to-cost ratios for improving indoor environmental quality are very high, approximately 50 to 1 for increased ventilation, and 20 to 1 for improved filtration. Milton et al (2000) conducted a large-scale field survey on work absenteeism as a function of outdoor air supply rate. The study, which involves 3720 employees in 40 buildings, shows that a 35.0% risk of short-term sick leave among the office workers is attributable to the exposure to lower outdoor air supply rate and that this could result in an estimated productivity loss of US22.8 billion dollars per annum in the US alone. Wargocki and Djukanovic (2003) calculated the economic benefit of improving indoor air quality by altering the outdoor air supply rate or the pollution load to attain different levels of percentage dissatisfied with air quality. The estimation was made considering the office work performance improvements (Wargocki et al, 2000a) and adjusted for the life-cycle costs in upgrading, operating and maintaining the HVAC system. Their results suggested that net productivity gain could exceed the investment costs by a factor of 60 with a turnover period of no more than 2.1 years, which was equivalent to extra revenue of approximately US2.5 million dollars over a period of 25 years in a small-scale office with 100 workers. In Singapore, Chew et al (1999) estimated that the health costs due to asthma are US33.9 million dollars per annum, of which US12.7 million dollars was attributed to loss in productivity, and since asthma was associated with several types of indoor air pollutants, particularly microbial, they called for improvements in indoor air quality to reduce the incidence level. For all the above reasons, exploring the associations between occupants and their workplace environment and underpinning the mechanisms involved are the next challenge to achieving healthier and more productive workforce within the tropical region.

1.4. Research objectives

The main objectives of the present study are as follows:

a) To obtain the general knowledge on the effects of air temperature and outdoor air supply rate on perceptual responses, the intensity of SBS symptoms, and work performance of tropically acclimatized subjects in real offices performing their normal work (Chapter 3).
b) To investigate the effects of air temperature on perceptual responses, the intensity of SBS symptoms, the physiological biomarkers, and various work performance indices of the tropically-acclimatized people in the simulated office experiment, i.e. in a field environmental chamber (Chapters 4-5).
c) To investigate the effects of outdoor air supply rate on perceptual responses, the intensity of SBS symptoms, the physiological biomarkers, and various work performance indices of the tropically-acclimatized people in the simulated office experiment, i.e. in a field environmental chamber (Chapters 4 and 6).
d) To model the progressive effects of indoor environment as determined by air temperature or outdoor air supply rate on work performance indices of tropically acclimatized subjects. These indices incorporate the relevant mechanisms of physiological and perceptual responses (Chapters 5-6).

2

LITERATURE REVIEW

One of the major reasons for concern in the office environment is that poor indoor environmental quality is believed to be having adverse impacts on health and reducing productivity. The latter occurs by causing lower work output, poor quality of work, lost working hours or days (due to sick leave and absenteeism), and negative effects on other indices of performance. However, office productivity as a function of indoor environmental factors such as thermal environment and indoor air quality has only recently begun to attract any interest on a regional and global scale as the result of changes in building practice and increased occupant awareness.

Figure 2.1 provides the basic constructs of an office worker's microenvironment. It highlights different mechanisms that can lead to an effect on an office worker's performance. The cognitive and information processing abilities of an individual under the pressure of external stressors in the indoor environment determine what level of performance can be achieved. In the present study, two major stressors of office work performance associated with indoor environmental conditions, i.e. the air temperature and provision of outdoor air, are investigated in the field studies as well as the laboratory experiments.

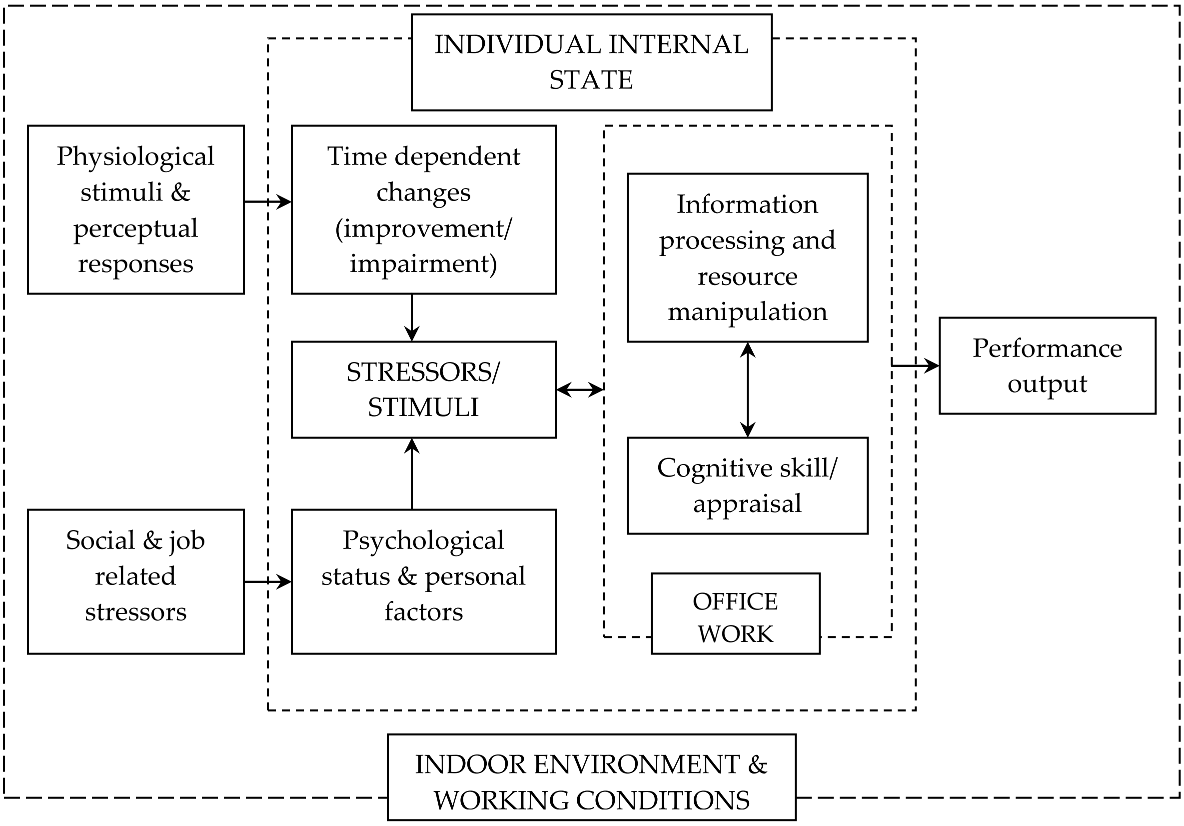

Figure 2.1 Model of interactions between office workers and the indoor environment

In the following sections, thermal environment (2.1) and indoor air quality (2.2) and other relevant aspects crucial to both parameters will be discussed. This is followed by reviews of past research that focused on studies relating the selected indoor environmental parameters to human performance (2.3). At the end of this chapter, the general factors affecting office workers' performance and the evaluation criteria are reviewed and discussed (2.4). It should be noted that the present study does not explore all the possible occupants' responses, especially not those that are purely psychological. Only a limited selection of factors affecting human performance is examined in the present study, concentrating on those that have been shown to be affected by the selected indoor environment variables.

2.1. Thermal environment

Thermal comfort is defined as "a condition of mind which expresses satisfaction with the thermal environment" (ASHRAE, 1992, ISO 7730, 1984). The word "thermal" expresses the condition "intended or designed in such a way as to help retain body heat" and "comfort" suggests the "capacity to give physical ease and well-being" (The American Heritage Dictionary, Pickett (ed.), 2000). In other words, thermal comfort is associated with subjective expression of satisfaction with the level of physical ease experienced in achieving a preferred state of bodily heat balance in the current environment. The definition implies that thermal comfort cannot be easily converted into some physical parameters but rather it is dependent on perceptual responses of the person's own physiological thermal balance. Geographically, people from different climates may prefer different thermal environments and have different expectations for thermal comfort due to their current and habitual state of adaptation or acclimatization and their ability to achieve an acceptable degree of physiological thermoregulation. This may indicate inherent differences of thermal environmental responses between people of different regions of the world. It has also been defined earlier that the Eastern concept requires comfort or well being to be achieved in terms of the serenity of the mind instead of just "physiological energy flow" (Chuen, 1991). Understanding the role of physio-psychological interactions in defining a thermal comfort, particularly among the tropical population, is needed.

In relation to perception, cognition and experience formed "layers" of influence over the perceived thermal comfort (Rybcynski, 1986). Heschong (1979) argued that thermal sense differed from all of other senses since thermal information was never neutral: "when our thermal sensors tell us an object is cold, it has already made us even colder" and that human sensors were more sensitive to changes rather than just noticing a steady state condition. Based on these definitions, it can be concluded that human thermal comfort is a function of the interplays between environmental condition, physiological characteristics, experience and expectation, and sensory effect. In view of these complexities, thermal comfort is commonly addressed via the thermal sensory mechanism, which is regarded as a more precise indicator.

In response to a thermal environment, the human body would attempt to maintain its thermal balance due to its homeothermic nature. This is achieved by some combination of the six parameters, i.e. air temperature, relative humidity, air movement, radiant temperature, metabolic rate and clothing type. Insufficient control over these parameters would normally lead to thermal discomfort. Symptoms such as cold hands and feet and physiological responses of discomfort and sweating can be associated with the level of body thermal balance. Other dimensions that affect thermal comfort are the duration of exposure, fluctuations of thermal sensory effects, and the behavioral responses initiated by the conscious mind (ASHRAE, 1992).

One of the benchmarks in thermal comfort studies was the development of an index, which combined thermal properties and behavioral responses to predict occupants' thermal sensation, i.e. the predicted mean vote, and its subsequent relationship with the percentage of a group expressing dissatisfaction with the thermal environment (Fanger, 1970). This model, however, was conducted on subjects acclimatized to the temperate climates, whom physiological characteristics differed from those of the tropical subjects. The acclimatization state and other external factors such as work rate, type of activities, social influence, etc, could increase the variance in the preferred thermal environment of the people from different climatic regions.

2.1.1. Human thermoregulation

The microclimate of a person exists within the boundaries of clothing, the surrounding air and on a larger scale, the workstation. The human physiological response to thermal environment may vary between individuals and within the same individual from one period to the next. The basic aim of physiological thermoregulation is to maintain the core temperature within very narrow limits close to 37°C. A greater variance and fluctuation of temperature is acceptable at the body surface, where temperatures are always lower than deep body temperature, usually maintained between 31 and 33°C. Surface temperature is a function of deep body temperature and the thermal environment and is determined by the heat balance mechanisms. Human thermoregulation varies between individuals and within each individual simply because body temperature is a distributed function which changes dynamically across the surface and within the body as immediate and long-term adjustments are made to a changing thermal environment and the changing rates of metabolic heat production in the body. In the long term, all the heat produced in the body must be dissipated to the environment. A small amount of heat storage or heat deficit may cause thermal discomfort, initiating behavioral changes that have the effect of restoring heat balance.

Thermoregulation to maintain body heat balance is achieved via several mechanisms. At any given time, this process of heat exchange with the environment was defined as (Burton, 1934):

$$S = M \pm C \pm D \pm R - E - W \tag{2.1}$$

where: S = Heat storage, either (+) for heat gain or (-) for heat loss of the body, M = Body heat production, C = Heat exchange by convection, D = Heat exchange by conduction, R = Heat exchange by radiation, E = Evaporative heat loss, and W = Rate of work accomplished.

The process of thermoregulation is controlled by the hypothalamus of the brain and/or input provided by the skin receptors in the sub-surface and the stimulation due to blood temperature. The skin receptors are very responsive to temperature and heat flow and are crucial for the control of various physiological heat balance mechanisms. The responsiveness was demonstrated in a laboratory study where seated subjects performing computerized tasks were asked to rate their thermal sensation while the temperature was gradually decreased or increased within 10 to 30°C over 90 minutes (Parsons, 2002). A higher mean air temperature for thermal neutrality was found in the reducing temperature step change in temperature of the same magnitude as a decreasing step change was voted more acceptable, as indicated on the thermal sensation scale (Knudsen and Fanger, 1990). In a neutral thermal environment, heat balance is normally maintained by regulation of blood flow. The blood flow increases as the microenvironment becomes warmer, in order to dissipate excessive heat through the skin and on to the immediate environment. The next step of thermoregulation as the temperature of the immediate environment becomes still higher or the rate of metabolic heat production increases during intensive work is sweating, which is the most efficient way to dissipate heat, as the evaporation of sweat absorbs latent heat. However, it should be noted that the rate of evaporation that is possible depends on the humidity of the surrounding air. Current technology and energy conservation require building practice in the tropics to accept "just acceptable" level of relative humidity that imply little difference in vapor pressure between the skin and the environment, and thus, prevent the effective heat loss by evaporation. In contrast to the processes related to heat exposure, during cold stress the human body can greatly increase its rate of metabolic heat production by the contraction of opposing muscle groups. This is known as non-shivering thermogenesis, which is a process that can increase in intensity until it eventually results in shivering in extremely low air temperatures or during prolonged exposure to a cold environment. In a moderately cool environment, the body responds by reducing heat flow to the skin to prevent heat loss.

2.1.2. Physiological (biomarkers) responses to the thermal environment

Two measures of cutaneous responses to various levels of temperature are discussed here. In the moderate range of thermal stress, body core temperature changes were unlikely to be large enough to evoke changes in thermal discomfort (Hardy, 1970) and because although body core temperature had been shown to vary slightly between acclimatized and unacclimatized subjects, it did not vary significantly between subjects exposed to similar environmental conditions (Adam and Ferres, 1954, Edholm et al, 1973). Thermal sensation associated with thermal stressors was best correlated with skin temperature as there are numerous very sensitive nerve endings (receptors) under the skin (Gagge et al 1937, Nielsen, 1969). Upon entering a thermal environment, skin receptors would sense the difference of temperature between the body and the environment and signal the hypothalamus to start either the process of vasodilation or vasoconstriction, to establish the appropriate cutaneous blood flow rate and the direction of heat flow. Under extreme thermal conditions, this mechanism may not be applicable and body temperature is environmentally driven. Under moderate thermal stress in the work environment, particularly during cold exposure, a transient reduction of skin temperature was expected as the cold receptors reduced blood flow to the skin (Hardy, 1961, Hensel, 1973). Wyon et al (1973a) demonstrated that the unweighted-mean skin temperature varied systematically with the amplitude and period of air temperature swing within 23-27°C. Small and rapid change about preferred air temperature seemed to affect the skin temperature whilst a large and slower change was followed by time-dependent variance in skin temperature in the absence of effect on skin temperature. The authors suggested that this indicated the difference in time constant of skin temperature response to the heat and cold.

Under moderate warm to hot conditions, the skin warm receptors would respond by initiating higher blood flow to the skin and the sweating mechanism, so indicators of skin moisture content also provide a good metric of the intensity of heat as an environmental stressor. It is also pertinent to note that in hot and humid climate, subjects are acclimatized to heat stress and are exposed to large variation of thermal environment from non-air conditioned, warm to hot outdoor to their working environment, which is generally on the cool side of thermal sensation. While the acclimatization to hot environment increases the people's ability to dissipate energy through the skin by sweat evaporation, the skin receptors are also adapted to the rapid transfer between the warm and cold receptors as they frequently move to and from the cooled, air-conditioned work environment.

The correlations between skin humidity indices and thermal comfort under various thermal stressors and occupant activity have been consistent (Berglund et al, 1985, Höppe et al, 1985, Toftum et al, 1998a). A 25% level of skin wettedness was normally perceived as thermally discomforting during sedentary work (Berglund and Cunningham, 1986). Therefore, occupants could almost accurately perceive their skin moisture level and factors that increase moisture evaporation from the skin, i.e. higher air velocity, lower air humidity, and low clothing insulation could significantly affect their thermal comfort.

When subjects are exposed to a continuous warm environment over a substantial number of days, they are likely acclimatized and become physiologically adapted to heat stress. In this case, they sweat more profusely and initiate sweating mechanisms faster in response to the onset of a heat stimulus. This is particularly true for people living in hot climate whose preferred level of thermal comfort is different from that of the inhabitants of cooler regions. For a given clothing ensemble and activity rate, subjects acclimatized to heat may prefer a slightly higher temperature, due to adaptation. Brierley (1996) investigated acclimatization to heat and found changes in human physiological responses, i.e. increased sweat rate, reduced heart rate, a smaller change in core temperature and greater tolerance of heat. However, the short 4-day acclimatization program did not significantly influence the thermal sensation of the subjects, suggesting that four-day acclimatization may be too short a time for true heat acclimatization to occur and to cause a shift in subjective preferences of thermal environment.

Gender differences in thermal comfort responses have been observed in studies employing temperate climate subjects. However, little is known on how the gender of tropical Asian subjects may influence their thermal response. For Caucasians, after both groups of gender reach a similar state of acclimatization following an exposure to moderate heat stress, internal body temperature and heart rate did not exhibit any differences. Using light clothing for optimum comfort, Olesen and Fanger (1973) showed that male and female mean skin temperatures did not differ significantly except for the local skin temperature at the feet, the measured foot temperature of female subjects being 2.1°C lower than that of the male subjects. However, female subjects sweat consistently less than male (Wyndham et al, 1964, Weinman et al, 1966). A local discomfort study reported in Parsons (2002) showed that under cool condition (PMV= -2), female subjects reported a significantly cooler sensation than male subjects do, due to cooler hand temperatures.

In parallel to the effect of gender, there are relatively limited documentations regarding thermal adaptation acquired by the diverse non-Caucasian populations or races. Among the few studies carried out were for African Negroids (Wyndham, 1952), Australian Aborigines and Sahara Arabs (Strydom and Wnydham, 1963), Mexicans (Hanna, 1970), New Guinea people (Fox et al, 1974) and the Japanese (Ohara et al, 1975). Within the tropical Asian region, there are three major races in the population, the Chinese, Indians and Malays. Duncan and Horvath (1988) conducted a comprehensive physiological study on the three races in Malaysia and found that heat acclimatization caused physiological strain as shown by the elevated heart rate, sweat rate and body temperature. However, comparing across races, only a minor difference in circulatory response was found in the Malay subjects. They further concluded "differences in heat response based on ethnicity would be difficult to demonstrate in populations with similar anthropometric, cultural characteristics, similar fitness levels and climate history". Another comparative study between Chinese and American also revealed that Chinese subjects were more tolerant to warm environment but less to the cool as compared to American subjects (Tao, 1994). In another study, Nakano et al (2002) reported no difference in thermal neutrality between Japanese subjects acclimatized to hot and humid environment and the temperate subjects. However, there was indication of a preference to higher temperature (~0.6 to 0.7 ºC) in the Japanese subjects. The suggestive evidences supported the understanding that tropically acclimatized people responded differently than people acclimatized to the temperate climate.

Under moderate thermal stress, measures of skin temperature are the most often-used indicators of thermal perceptions. However, due to the lack of any direct physiological indicators of cognitive activity, skin temperature cannot provide much insight into any plausible mechanism for the effects of the thermal environment on work performance, particularly in tasks requiring such diverse abilities as mental performance and manual dexterity. Naturalistic and non-invasive techniques using saliva analysis to indicate the enzymatic/ hormonal changes in the neuroendocrine and nervous systems as they respond to moderate thermal stressors are therefore extremely useful as simpler and more direct measures of the mental and cognitive state of a person performing different kinds of work. The techniques used in molecular biology are useful not only to provide objective correlates of internal responses but also for their sensitivity in detecting even the slightest hormonal fluctuations. These advantages have led to an upsurge in the use of biomarkers in occupational toxicology and in epidemiological studies, especially in the characterization of the most stressful occupations (Vainio, 1998, Tabak, 2001).

Stress-related factors that produce physiological effects activate the hypothalamus-pituitary-adrenocortical (HPA) axis of the neuroendocrine system and the sympatho-adrenomedullary (SAM) axis of the sympathetic nervous system, which together act as the principal components in the stress response systems. Much attention has been focused on the activation of the HPA axis as indicated by the episodic secretion of salivary cortisol that is provoked by psychological variables, such as mood, anxiety and fear and such factors as pain, fatigue and sleep deprivation (Kirschbaum and Hellhammer, 1989, Schulz et al, 1998, Biondi and Picardi, 1999, Morgan et al, 2000), whereas the second mechanism that involves activation of the autonomic (sympathetic) nervous system followed by the release of catecholamines (e.g. norepinephrine) into the blood has only been elucidated recently, providing better understanding of the psychobiological responses to stress, which affects not only the neuroendocrine system but also the locus ceruleus of the nervous system. When released into the blood, catecholamines increase heart rate, blood pressure, breathing rate, muscle strength, and mental alertness. They also reduce the amount of blood reaching the skin and increase blood flow to the major organs (such as the brain, heart, and kidneys). Several studies have demonstrated that salivary α-amylase is a good indicator of the activation of the sympathetic nervous system. Chatterton et al (1996) and Chatterton et al (1997) showed that salivary α-amylase concentration increases with the norepinephrine level in plasma, which indicates higher adrenergic activity under conditions of stress, whether physical and psychological. Rohleder et al (2004) confirmed that salivary α-amylase is elevated during psychological stress, while Skosnik et al (2000) showed that the performance of an attention task, i.e. negative priming, was affected by mild psychological stress that led to a significant increase in salivary α-amylase.

Most applications of salivary biomarkers have sought to establish the physiological nature of stress responses related to psychological, behavioral, work fatigue and cognitive functioning pathways and states induced by various external stimulations. Bohnen et al (1990) reported that subjects with a higher cortisol level after performing a four-hour continuous mental tasks exhibited decreased attention. Cortisol level was not only affected during long-term work but also during shorter periods of work. A short-term stress situation, in which subjects worked on VDU-related tasks demanding high speed and accuracy, significantly increased the cortisol level and was associated with higher heart rate, blood pressure and respiratory rate (Schreinicke et al, 1993).

In other studies by Aubets and Segura (1995) and Kivlighan et al (2005), performance competitiveness was reported to significantly elevate salivary cortisol levels even before the competition and to further increase them at the end of the event, whereas physical activities (without competition) also increased salivary cortisol but to a lesser extent. Negative anticipation of high workloads and of prolonged physical fatigue appeared to adversely affect stress level and cognitive functioning. Sleep-deprived and continuously active subjects undergoing a brief military simulation exhibited a degradation of vigilance, reaction time, memory and reasoning, accompanied by a deterioration of mood, e.g. fatigue, depression and tension (Lieberman et al, 2005). In this study, the highest level of cortisol was obtained before the subject underwent the tasks, while extensive training and experience as protective mechanisms against an overwhelming HPA activation were offered as an explanation of the lower level of cortisol that occurred after the tasks. Roy (2004) also suggested that given the capability to develop adaptive behavior towards stressors, HPA activation could either be maintained or decreased. Furthermore, less well-trained young subjects, as reported by Opstad (1994), showed a significantly higher cortisol level with intense training than without it. The association between negative affect and salivary cortisol was also seen during a public speech task in comparison with relaxing video screening (Buchanan et al, 1999, Zonnevylle-Bender et al, 2005). Negative affect increased during the speech but decreased when subjects' viewed the video, trends reflected by the observed fluctuations in cortisol concentration. Bollini et al (2004) suggested that positive subjective perception caused by having control over the stressors could lead to reduced cortisol levels.

In an office setting, indoor environmental parameters may naturally be considered as one of the source of stress. The application of salivary biomarkers to reveal the mechanisms relating thermal stressors to work performance is suggested by several studies. Higher body core temperature and lower plasma cortisol and melatonin were positively correlated with increased performance and better subjective alertness within the daily circadian rhythm (Monk et al, 1997). During thermal stress, subjects may exhibit a departure from thermal neutrality, which could be objectively detected by the above biomarkers. Chatterton et al (1996) investigated the concentration of salivary α-amylase under various stress conditions, namely physical exercise, written examinations and short exposures to extreme heat and cold. Salivary α-amylase levels were increased following exercise and the written examination. Exposure to heat for 40 minutes at c.a. 66°C progressively increased salivary α-amylase, whilst a rapid increase was seen during a 40 minutes exposure to cold (4°C). Thus, during exposure to both work- and thermal-related stress, salivary α-amylase may serve as a measure of the adrenergic activity of the sympathetic nervous system. Likewise, Hennig et al (1994) demonstrated an increase in cortisol levels during exposure to heat at 52°C in comparison to 28°C and that the effect could be suppressed by administering haloperidol to block the dopamine effect caused by dehydration in the heat.

2.1.3. Behavioral and sensory responses to the thermal environment

Thermo-behavioral responses are guided by the physiological states (Hensel, 1981). As the response to thermal stimuli, occupants would actively attempt to achieve and maintain thermal comfort. This is achieved by means of actively adjusting their position or body posture relative to heat/ cold sources, the clothing attires and/or the activity level. Under more extreme exposures, occupants may also be prompted to seek alternative environment. In other words, thermal stimuli causing thermal discomfort, of which behavioral change is difficult to resist voluntarily and when control of thermal conditions is unavailable, is often determined by intense thermal sensation.

Thermal sensation is a subjective measure of how a person feels thermally when he/ she is present in a preset micro-environmental condition. The integration of various thermal parameters affects the body thermal state and is sensed by the person through the thermo-sensory nerve endings, which leads to thermal sensation. This mechanism is the basis for the predicted mean vote (PMW) index of occupant’s thermal sensation (Fanger, 1970). For the same reason, thermal sensation also serves as the correlate for physiological indicators of thermal environment, i.e. the cutaneous responses. Thermal sensation is time-dependent (Nicols, 2004) and is influenced by acclimatization, gender, experience and memory recollection of past thermal stressors, and transient changes of thermal conditions (Parsons, 1993).

An important thermal comfort determinant is the clothing attire, which defines the additional thermal insulation to the skin surface, usually expressed as the clo value (Gagge et al, 1941). The clothing attire is one of the external instrument and part of human microenvironment through which a person may be able to reach and maintain the body thermal equilibrium or the preferred thermal sensation. The more permeable the clothing the higher the amount of heat energy released via skin moisture to the air cavity between the skin surface and clothing fabrics and subsequently dissipated to the surrounding air by evaporative control (Holmer, 1989).

The metabolic heat production is the next determinant of thermal comfort, which is expressed in terms of met. The metabolic rate for typical sedentary office works was estimated at 1.2 met or equivalent to about 70 W/m^2 (Brager et al, 1994). The amount of energy secreted by the body was dependent on the activities of a person and its distribution was regulated by the thermoregulatory system (Burton and Edholm, 1955). The negative association between air temperature and activity (metabolic) rate further suggested that subjects might deliberately reduce their activity to counteract warmer environments (Rowe, 2001). The alteration of activity rate to accommodate for the less than optimum comfort level was also known as one of the adaptive behavioral strategies (Humphreys and Nicol, 1998, Nicol and Humphreys, 2002). The PMV model estimates that effect of a change of 0.1 met of activity rate on thermal sensation is equivalent to that of a 1.0°C change of air temperature, indicating that a slight increment of activity rate may produce sensible thermal effects.

2.2. Indoor air quality

The building industry has witnessed the fast advancement in the technology of air conditioning, which allows vast areas to be air conditioned with innovative means of operation and control strategies. These improvements together with the application of new building materials and the intensive use of electronic equipment have increased, in parallel, the awareness of indoor air quality problems (Mendell and Fine, 1994) and the growing international interest about public health and comfort (Spengler and Moschandreas, 1982). Greater concerns have emerged during the past few decades in the well-developed nations such as the USA, several European countries, and only recently within the Asia Pacific region. Concerted studies on the characterization of the indoor air constituents inhaled by the occupants and its adverse effects on health, particularly to those at risks or having higher susceptibility are still in the progress.

Among the chief concerns for indoor air quality in the tropics are the starvation of outdoor air provision due to energy conservation and the high outdoor air relative humidity leading to higher risks of microbial infestation. These are in addition to the global concerns of the effects of the indoor air contaminants generated from the outdoor air intake, the air distribution system, the office appliances and the occupants themselves. Other concerns involve poor air filtration and insufficient maintenance.

The operation of air conditioning system determines the indoor air temperature, relative humidity as well as the concentration and transport of air pollutants. Since its applications in offices, air conditioning has contributed enormously to the workforce productivity through the facilitation of office activities by means of controlling and maintaining room air enthalpy within comfortable range. At this point, it is also worthwhile considering what implications the air conditioning strategies have brought to the workplace's air quality. The "deep" building design to cater for greater space demands inevitably causes pollutants built-up within the created indoor premises. Thus, one of the main objectives of the air conditioning system is to provide the ventilation needed for reducing the indoor air pollution to an acceptable level.

The effort to define the acceptable indoor air quality is still confronted with the lack of clear associations between indoor air parameters and various occupants’ responses. At the current stage of research, perceptual responses such as perception of air quality and the reported prevalence or intensity of SBS symptoms largely define occupants’ responses to indoor air quality. This is fundamentally because people trust their eyes and nose to sense their surrounding environment, and undoubtedly, the sensory system provides the first warning to the occupants of any annoying or harmful substances in the air. The effects of any exposures to the breathing system, the eyes, and the skin could range from perceptible differences from background air quality to the reported symptomatic health risks and behavioral responses. Fanger (1988) showed that occupant’s perception of the indoor air quality relied on the olfactory and chemestesis mechanisms and the perceptual response was influenced by thermal properties of the inhaled air (enthalpy) as demonstrated by Fang et al (2004). Despite the fact that buildings rarely exhibited apparent problems, occupants often reported building-related illnesses, which had been linked with air conditioning, ventilation, humidification, building materials, office appliances, renovations and even the psychosocial factors (Mendel, 1993, Menzies and Bourbeau, 1997, Jones, 1999).

2.2.1. Sick Building Syndrome (SBS) symptoms

Sick building syndrome is a situation in which occupants of a building experience from health matters that seem to be relate to duration spent in the premise without invoking any specific illnesses. This could further result in work distractions that culminate in absenteeism (Preller et al, 1990). There is still limited knowledge about causes of symptoms reported in non-industrial environment such as office buildings, schools, and residences. The World Health Organization (1983) defined that for any reported symptoms to be regarded as “sick building syndrome”, several conditions must be observed, as follows:

- mucous membrane irritation of eyes, nose and throat should be one of the most frequent expressions,
- symptoms involving lower respiratory airways and internal organs should be infrequent,
- no evident causality should be identified in relation to occupant sensitivity or to excessive exposure,
- symptoms should appear frequently in the building or part of it, and
- a majority of occupant reports the symptoms.

SBS was also described as phenomenon experienced by those working in the climate-controlled buildings with characteristic periodicity increasing with intensity during prolonged exposures and resolving rapidly on leaving the environment (Molina, 1989). Moreover, in a review based on 529 investigations conducted from 1971-1988 by the National Institute of Occupational Safety and Health (NIOSH), inadequacy of ventilation was found to be the primary contributor to the building-related problems and the occurrence of SBS symptoms (Seitz, 1989). This prompted the needs for evaluating the building practice in the tropics and its impacts on occupants since minimum ventilation has been commonly adopted to conserve energy.

In a crossover trial study, Jaakkola et al (1994) reported that adopting 70% air recirculation of the ventilation system caused SBS symptoms and perception of poor air quality as compared to no air recirculation. In their study, the office workers from two buildings recorded these responses through personal diaries. Some uncertainties, however, were introduced in the study design as the comparisons were based on two groups of sample populations from different buildings. In another investigation using blind intervention approach, Menzies et al (1993) reported no significant correlation between two ventilation rates and the prevalence of SBS symptoms. The authors further suggested that the results could be confounded by the uncontrolled indoor environment parameters such as room air temperature, relative humidity, and air velocity among the work premises of the four office buildings. Occupants who reported SBS symptoms also rated their indoor environmental quality as unacceptable. As the surrogate indicator of ventilation rate and pollutants generated by occupants, the indoor carbon dioxide level above outdoor concentration had been identified as a good predictor of several SBS symptoms such as sore throat, nose blocked, chest tightness, and wheezing with odds ratio per 100ppm carbon dioxide ranging from 1.2 to 1.5 (Apte et al, 2000).

Turiel et al (1983) compared an existing problematic building with low outdoor air supply to the control building and found the significantly higher eyes, nose and throat symptoms in the low outdoor air supply rate. In a comprehensive review, Seppänen et al (1999) reported that higher SBS symptoms prevalence was the result of insufficient ventilation and that this was particularly consistent for ventilation rates below 10 l/s per person. Among the other factors associated with increased prevalence of SBS symptoms were pollution sources, types of ventilation, and poor spatial design. In addition to outdoor air supply rates, Sundell et al (1994) reported that the presence of office equipment such as the photocopiers and the ventilation system operating hours were significantly correlated with the prevalence of SBS symptoms. Several studies have shown that SBS symptoms may continue to decrease with increased outdoor air supply rate up to 25 L/s per person and this effect was accompanied with improvements of the perceived air quality. Nevertheless, further increase of outdoor air supply rate was associated with higher eyes-related symptoms and mucosal irritation (Sundell et al, 1994, Jaakkola and Miettinen, 1995, and Nordstrom, 1995).

The mixed implications of increasing outdoor air supply rate suggest that the presence and concentration of air contaminants do not depend entirely on one factor, i.e. the outdoor air supply rate. In the conjunction with other parameters such as the introduction of ozone from the outdoors (Weschler et al, 1991), the emission and desorption of volatile organic compounds from: indoor surface materials (Won et al, 2001), ventilation filters (Clausen, 2004, Bekö et al, 2006), office appliances (Leovic et al, 1996), and personal computers (Bakó-Biró et al, 2005), an exceedingly high ventilation does not always measure up as the compelling approach for improving indoor air quality. The specific indoor air processes (indoor chemistry) leading to such adversarial results on occupants have only recently been identified (Wolkoff et al, 1999, Weschler, 2000, Clausen et al, 2002, Weschler, 2004a,b, Tamás et al, 2005). The lack of understanding of these reactive processes could therefore be the reason that up to 50% of occupants still consider the indoor air quality to be unacceptable and 20% or more occupants frequently reported SBS symptoms despite the absence of any identifiable problems of indoor air quality as consistently reported by Hedge, 1989, Skov et al, 1990, Mendell, 1991, Zweers et al, 1992, Mendell et al, 1996, Seppänen et al, 1999.

The statistically significant associations of the air conditioning application with SBS symptoms were much more frequent than a mere coincidence and within-subjects studies ensure that they were not likely to be of the consequences of personal-, job- or other building-related factors (Seppänen and Fisk, 2002). There were fewer reports on the SBS symptoms within the naturally ventilated buildings, while the SBS symptoms, such as headache, fatigue, and mucosal-related symptoms, prevailed in the mechanically ventilated or air conditioned premises (Mendell and Smith, 1990, Jaakkola et al, 1994, Mendell et al, 1996).

Exposures to either single or multiple indoor air contaminants at various concentrations have also been shown to affect the occurrences and the intensities of one or more SBS symptoms (Mølhave et al, 1982, Mølhave et al, 1986, Norbáck et al, 1990, Kjaergaard et al, 1991, Iregren et al, 1993, Brinke et al, 1998, Pan et al, 2000, Kjaergaard et al, 2004). Mølhave et al (1982) measured the emissions of VOCs from 42 commonly used building materials and showed that 82% of the detected compounds were potential irritants to the mucous membranes, 25% were suspected carcinogens, and 30% have odor threshold below the measured concentrations. Mølhave et al (1986) employed a mixture of 22 compounds detected from the previous study at three levels of total concentration, i.e. 0, 5, and 25 mg/m^3 and reported significant increase of intensity of air quality, odor, difficulty to concentrate, and mucous membrane irritation with concentrations. Based on the same mixture of compounds and concentrations, Kjaergaard et al (1991) subsequently reported that in addition to worsened irritation with exposures to VOCs, objective measurement indicated reduction in lung function and increment of polymorphonuclear leucocytes in the tear fluid and these effects were stronger in the subjects previously suffering from SBS symptoms. The sensitivity of normal subjects to the exposure to a specific type of VOC, the methyl isobutyl ketone or MIBK commonly found in organic solvents on the SBS symptoms associated with the central nervous system was also demonstrated by Iregren et al (1993), suggesting the negative implications on health and possibly on work performance, particularly during the longer exposures. In the school environment, higher concentrations of volatile organic compounds were related to chronic SBS symptoms while respirable dust caused new incidences of SBS symptoms (Norbáck et al, 1990). Weschler (2004a,b) reported the formations of radicals and reaction by-products facilitated by the chain-like reactions among the unsaturated volatile organic compounds, oxidants (ozone), and nitrogen dioxide. The formation of these contaminants represents the complex indoor chemistry processes occurring continuously in the room air. The indoor chemistry products are often present in the very low concentrations but may cause greater health effects than any of the volatile organic compounds in their original chemical structures. Furthermore, Tamás (2005) and Bekö (2006) showed that as the results of the ozone-initiated processes, perceived air quality was significantly degraded. The presence of oxidized products such as from the R-limonene-ozone and isoprene-ozone reactions exhibited the airways irritation in mouse bioassay study (Wilkins et al, 2001) and caused increase in eye blink rate and irritation in human study (Klenø and Wolkoff, 2004). Having said that, the indoor carbon dioxide as the bio-product of occupants, when present at high concentration, has also been shown to elevate eyes irritation intensity (Hempel-Jørgensen et al, 1997). Similarly, exposures to airborne dust were also related to sensory irritation (eyes tear film stability) and odor perception (Pan et al, 2000, Shusterman, 2001).

Personal and individual characteristics (Stenberg et al, 1994, Hedge et al, 1995), gender (Stenberg and Wall, 1995, Brasche et al, 2001), psychological (Berglund and Gunnarsson, 2000) and psychosocial phenomena may confound direct associations between building factors and SBS symptoms as is initially suggested by WHO (1983). Furthermore, Mendell (1993) reviewed studies related to health-related symptoms and found that only 5 out of 37 building/occupancy risk factors were consistently linked with SBS prevalence. Increment in prevalence of symptoms among office workers with high level of physical and mental stress including work-related psychosocial problems showed that many SBS symptoms might be stress-related (Ooi et al, 1999). A range of epidemiological criteria could also be inferred for the causal relationship between work stress and health related symptoms (Susser, 1991).

2.2.2. Physiological (biomarkers) responses to indoor air quality

Questionnaires devised to record the intensity of SBS symptoms are generally used to obtain the health status of occupants following any changes to the air quality. However, it has been shown that the psychosocial environment of the workplace may also influence this subjective measure. It is believed that biomarkers of the nervous system activation and the immune function could provide the objective indicators. In addition to the physiological measures of stress or activation of the HPA and SAM axis described in section 2.1.2, the other biomarker associated with the immunological system, i.e. the sIgA, is discussed in this section.

Few studies have examined how moderate indoor air quality stress caused by the presence of indoor air pollutants affect any specific biomarkers. Inhalation of carbon dioxide of up to 35% in total inhaled air may induce neurovegetative activity and even anxiety (Griez et al, 1990, Perna et al, 1994), due to the priming of the HPA axis and subsequently increase the plasma cortisol level (Argyropoulos et al, 2002). At a much lower concentration, Woods et al (1988) also reported a slight increase in salivary cortisol following inhalation of 7.5% carbon dioxide. Nasal fluid biomarkers were used as indicators of the effects of indoor air pollutants on school children by Norbäck et al (2000). They found that the presence of airborne yeast in the classrooms was associated with higher eosinophil cationic protein and lysozyme in samples from the children, which may be indicative of an inflammatory response.

Another relevant biomarker, the salivary secretory immunoglobulin A (sIgA), is a convenient indicator of the status of the immune system. Measurement of this parameter is thought to be indicative of the functional status of the entire mucosal immune system (Mesteck, 1993). Levels of sIgA have been used as a biomarker of job stress level. Increased job stress (Henningsen et al, 1992, Evans et al, 1994) and other stressful life events (Phillips et al, 2005) suppressed immunoglobulin secretion and led to a significant decrease of the sIgA concentration. However, positive stress effects such as successful adaptation to situational demands may overcome the immunosuppressive effects seen earlier and so lead to increases sIgA levels (Zeier et al, 1996). In the tropics, some preliminary work on the relationship between work-related stress and sIgA concentration and secretion rate has been conducted and the findings showed that female nurses who perceived higher levels of work-related stress had significantly lower levels of sIgA concentration and secretion rate compared to nurses who perceived lower levels of stress (Ng et al, 1999).

2.2.3. Sensory and perceptual responses to indoor air quality

Human sensory performance serves as a powerful tool in the detection of indoor air contaminants. The olfactory system plays the important role of perceiving the air quality while the chemethesis could be partly responsible for the effects on the reported intensity of SBS symptoms. These sensory effects, i.e. olfaction and chemesthesis, tend to overlap and influence each other (Cain and Murphy, 1980, Engen, 1986, Green et al, 1990, Cain et al, 2005). Under normal conditions, the sensory response would be initiated by the perception of odors through the olfactory receptor cells, whilst the irritation would develop after longer exposures. Fanger (1988) introduced the application of "olf" and "decipol" as units for the characterization of indoor air quality. These units were referenced to the total pollution generated by a standard person and the measurement employed trained-panels' olfactory senses as the final arbiter (Bluyssen et al, 1989). Since then, the relationships between acceptability, perceived air quality (decipol), percentage dissatisfied, sensory pollution load (olf), and the ventilation rate, have been established (Gunnarsen and Fanger, 1992, Clausen, 2000).

Knudsen et al (1998) reported the dose-response relationships between the concentration of indoor air pollutants (dilution factor) and the acceptability to air quality (or percentage dissatisfied with air quality). They showed that the coefficient estimates (gradients) of the function between dilution factor and acceptability varied for different building products. Carpet was consistently worst in terms of percentage dissatisfaction disregards of the dilution factor, while sealant's effect varied with dilution factor. Wargocki (2001) reported the log-linear trend of the dose-response relationship between the concentrations of a mixture of 22 common indoor organic pollutants and the acceptability of air quality. Furthermore, the ratings of each exposure were found to be repeatable when reassessed by the same observers in several sessions separated by 1-3 weeks. In these studies, sensory system was used to determine the "discomfort level" of indoor air quality. Wargocki (2001) further suggested that intervening variables influencing perception of air quality should be investigated. These variables included psychophysical measures of odor intensity and the level of irritation; and other personal-related factors (Klitzman and Stellman, 1989, Haghighat and Donnini, 1999).

In parallel to aforementioned effects of indoor air pollutants on perceived air quality, several studies have reported the evidences of negative impacts of exposure to irritation levels and the prevalence of SBS symptoms. Hudnell et al (1992) exposed subjects without past records of SBS symptoms to the mixture of 22 VOCs according to Mølhave et al (1986) definition for the common indoor VOCs composition. Using potentiometer ratings, significant differences were noted between the clean air and the VOCs exposures in the combined eyes, nose and throat irritation. The result was subsequently confirmed by subjective questionnaires, which results showed that irritation, headache and drowsiness increased with the exposure. The effects on irritation were in accord with previous findings by Mølhave et al (1986). Furthermore, odor intensity was also higher during VOCs exposure, although results from the mid- to post-exposure indicated a decline of 30% of perceived odor, suggesting adaptation. They concluded that time course functions of irritation and odor response were mediated by different mechanisms, i.e. the trigeminal and olfactory nerves, respectively. This may explain why the irritation level increased while perceived odor decreased over time.

Thermal environment influences perceptions towards indoor air quality. This is because people experience thermal climate via not only the skin thermo-receptors (Toftum et al, 1998a) but also the conditioning of mucous membrane in the upper respiratory tract (Toftum et al, 1998b). Cain et al (1983) reported a study on odor perceptions to the indoor air with and without tobacco smoke. The study was conducted at four combinations of air temperature ranging from 20.0 to 25.5°C and relative humidity from 50 to 70%. They found that air temperature/ relative humidity of 25.5°C/70% would exacerbate the odor intensity. Reinikainen et al (1997) demonstrated that room air with humidification was perceived as more odorous and stuffier and therefore, less acceptable, although the air humidity was below 40%Rh. In another study, Berglund and Cain (1989) suggested that during the episodes of normal exposures to indoor air pollutants, perceived air quality may be overwhelmed by the influence of air temperature and relative humidity. The study also showed a positively linear correlation and stronger effect between perceived air quality and air temperature than the relative humidity. Lower acceptability of air quality in relation to moderately high air temperature was caused by the effect of warm discomfort in the respiratory tract due, in part, to insufficient evaporative and convective cooling of the mucous membrane (Toftum et al, 1998b). In their study, one Centigrade of air temperature change had the same effect to the acceptability of air quality as 120Pa change in water vapor pressure. Concerning thermal sensation, one Centigrade of air temperature change would have the same effect as a 230Pa change in water vapor pressure. Based on linear proportionality, it was concluded that air temperature effect on acceptability of air quality was approximately half the effect on thermal sensation during immediate assessment by the subjects. In attempt to determine relative impact of thermal load on perception of indoor air, Clausen et al (1993) compared the magnitude of effects of various indoor environmental variables on the same scale and concluded that a 1°C shift of operative temperature produced the same effect on thermal comfort as a 2.4 decipol change in perceived air quality.

Furthermore, it has been reported that higher air enthalpy caused higher emission rates of chemical compounds from indoor sources/ materials and thus, could also affect the perception of indoor air quality. Both effects and their interactions were investigated carefully in a series of study conducted in environmental chamber using the specially designed test system called CLIMPAQ, exploring both immediate and longer term whole-body exposures (Fang et al, 1998a) as well as facial exposure (Fang et al, 1998b). In both studies, air polluted with either single or a mixture of pollutants was introduced to the subjects at different combinations of air temperature (18-28°C) and relative humidity (30-70%). While the effects on materials' emission rate were expected, the very large effects of temperature and humidity on the perception of air quality were not. In their results, even clean air was perceived as having a lower air quality when air was either hot or humid. Furthermore, perceived air quality can be maintained constant by reducing air enthalpy from 45 to 35 kJ/kg to counteract the negative effect due to a decrease in fresh air provision from 10 to 3.5 L/s/p. These findings highlighted that occupants' final evaluation to their indoor environment or more specifically the air quality is a function of synergistic relationships of thermal properties and constituents of the air.

2.3. Effects on work performance

Fitts and Posner (1973) suggested that for understanding of any effects on human performance, a conceptual framework in studying these associations had to be first available and that this was largely the problem underlying the difficulty in interpreting many results arising from studies on human performance. Many studies on thermal effects on work performance have been conducted since then, however, Parsons (1993) reiterated that despite the identification of various plausible mechanisms leading to performance changes, many factors related to these mechanisms have yet to be verified or understood. The studies of how and to what extent the indoor air pollution could interfere with the level of work are even more limited. Until recently, the majority of studies relating air pollutants and human responses targeted a specific type of pollutants such as carbon monoxide, particulates, ozone, and other chemical exposures, which is rarely the case in any indoor environments. These studies were initiated by the growing public outcries that subsequently prompted the governmental and international agencies to introduce regulations and controls over some airborne chemicals known to modify health and performance. This was despite the lack of definite conclusions as to the concentrations of these chemicals at which precise or predictable effects may appear (Horvath and Drechsler-Parks, 1992). The progress of research works in establishing associations that are more definite and supported by investigation about the effect mechanisms have been enormous in the past decade or so. Several landmark studies and reviews are reported in the following sections. These reports have considerably addressed and contributed to the conceptual frameworks of the effects of thermal environment and indoor air quality on the office work performance.

2.3.1. Overview of IEQ effects on productivity

Based on the literatures, Fisk and Rosenfeld (1997) suggested that there were at least four major links relating the indoor environment and the health and productivity. These links are a) infectious diseases, b) allergies and asthma, c) sick-building health symptoms, and d) the direct impacts of indoor environmental quality on human performance. They developed the crude estimate of the productivity gains arising from improved indoor environments. The results projected a remarkably large economical return. On annual basis, productivity gains of US6 billion to US19 billion dollars from reduced respiratory disease, US1 billion to US4 billion dollars from reduced allergies and asthma,US10 billion to US20 billion dollars from reduced sick building symptoms, and US12 billion to US125 billion dollars from direct impact on work performance were estimated. Benefits of improved indoor environmental quality exceeded the various cost factors by a factor of 18 to 47.

Djukanovic and Wargocki (2002) reported the cost-benefit analysis based on the quantitative associations between improved indoor air quality and productivity gain as previously reported in Wargocki et al (2000a). In a follow up report, Wargocki and Djukanovic (2003) extended their estimations by considering the life-cycle costs of upgrading investment in an office building in addition to the annual energy cost and initial cost of HVAC system. Their analysis predicted an annual benefit that exceeded 10 times the energy and maintenance costs arising from improved air quality by means of increasing the outdoor air supply rate. The conventional discounted payback time of upgrading investments and costs was estimated to be less than 2.1 years. In economical sense, these studies and detailed analysis have provided strong expressions for the global movements towards better indoor environments.

Wyon (1996) provided a review with focus on the impact of indoor environmental variables on human performance and productivity and described the plausible causative mechanisms involved. He concluded that individual performance may be affected by a range of intervening factors such as motivation, well-being, subjective comfort, SBS symptoms, overcrowding, visual and acoustic distraction, and the physical environmental variables and postulated that the lack of individual control to thermal climate elevated the prevalence of SBS symptoms, which were associated with decreased work performance, increased absenteeism, and thus, adversely affected overall productivity. Direct effects of thermal environment on various performance tasks were discussed together with the effects of the indoor air contaminants related to ventilation and filtration strategies on SBS symptoms and industrial work performance. He further articulated that "practical difficulty of manipulating any one aspect of air quality in isolation is perhaps the reason that so few systematic studies of indoor air quality" and later suggested a progressive approach to investigate the mechanisms relating indoor environmental variables and the occupants' performance.

Seppänen and Fisk (2004) proposed macro conceptual models for estimating the economical impacts of the indoor environmental factors through various hypothetical and established pathways. The model illustrated how changes in the indoor environmental quality not only incurred initial investment and the operational and maintenance costs but also potentially benefited various human responses (Fisk and Rosenfeld, 1997) and eventually promoted financial gains by reducing medical cost, lowering sickness absenteeism, improving work performance, lowering employees turn over, as well as reducing operational and maintenance costs with fewer occupant complaints.

In addition to the preponderance opinion of the direct benefits of better indoor environment, others have suggested that occupants' satisfaction may be the important intermediate variable in this positive association (Lorsh and Abdou, 1994a). Surveys undertaken by Kroner et al (1992) showed that a satisfactory and new working environment was responsible for a drop from 46% to 4% of the workers feeling dissatisfied to their workplace and for an increase from 13% to 75% of the workers expressing satisfaction. The satisfaction factor was also shown to be higher in office workers with increased work productivity. An optimum of 15% loss or gain of turnover in a typical office organization could be attributed to design, management and operation of indoor environment (Leaman and Bordass, 1999). It was suggested that personal control, prompt response to occupants' feedback, and system design catered to the office activities were necessary to achieving healthy, comfortable, and productive offices.

2.3.2. Impacts of thermal environment on occupants' performance

It is obvious that hot and cold exposures affect work performance (Pilcher et al, 2002). However, there is still a limited understanding of how the occupant-thermal climate interface could result in performance-oriented outcomes (Lorsch and Abdou, 1994b) and this is particularly true to the office settings of the tropical region. While physiological measures provide an accurate account of thermal stress on individuals, it does not necessarily mean impairment of mental performance. This is because the complex cognitive performance of office works requires that integration among mental abilities, physical, and behavioral responses be achieved optimally (Enander, 1989). This optimum level, however, varies from one task to another. It is therefore insufficient to design and operate the air conditioning system within the boundaries of thermally acceptable conditions. Recent reviews have indicated that even moderate thermal stress could affect work performance (Mendell and Heath, 2005, Seppänen and Fisk, 2005, Wyon and Wargocki, 2005). Moreover, some studies have shown that thermal conditions leading to comfort may not yield optimum performance (Pepler and Warner, 1968, Meese et al, 1982).

Mendell and Heath (2005) reviewed studies associated with occupants' performance, attendance, and health effects in the schools, offices, and laboratory settings environment. The focus of their review was the students' academic performance and based on this account, they highlighted two main concerns, i.e. the likeliness of environmental deficiencies due to chronic funding shortage and the higher susceptibility of the children to some air pollutants than the adults did. They further underlined the apparent lack of studies on children in the schools, while more progress have been shown in the studies involving working adults.

Seppänen and Fisk (2005) performed meta-analysis on 150 assessments from 26 studies on effects of air temperature and performance. This analysis yielded a curvilinear relationship. The slope and its 90% confidence interval seemed to suggest that air temperature up to 23.0°C potentially benefited work performance while further increment beyond 24.0°C could lead to decrease in performance, suggesting that cooler room air temperature, particularly between 20.0-23.0°C should be achieved for better office productivity. Despite the uncertainty in the derived estimations, the authors noted that the use of such relationship would have practical benefit to building design and operation.

Wyon and Wargocki (2005) reviewed the evidences and proposed various mechanisms of how room air temperature could affect workers' performance. In the warmth or moderate heat stress, SBS symptoms were exacerbated and arousal level was reduced presumably due to lowering of the metabolic rate to avoid sweating. Both effects had been shown to affect work performance. Workers with SBS symptoms performed slower in a standardized computer task and made more errors in another task (Nunes et al, 1993) while lower mental arousal had been shown to reduce concentration and work performance (Pepler and Warner, 1968, Wyon, 1969, Wyon, 1974) but improve task requiring lower optimum arousal such as memory-related tasks (Wyon et al, 1979) and creative thinking (Wyon, 1996). In the moderate cold, the authors suggested that mental arousal may be elevated and therefore enhanced tasks requiring higher level of optimum arousal, while thermal conditions leading to cold discomfort (below thermal neutrality) would affect performance through its distracting and de-motivating effects as well as the lowering of manual dexterity.

Mäkinen et al (2006) recently reported a study on cold exposures. Although the experimental condition in the cold (-10.0°C) was uncommon for the office environment in the tropics, it is worth noting that the negative effects of cold exposures were related to physiological changes and reduced thermal sensations and that this resulted in longer response time and lower efficiency of simple reaction time tasks. The authors concluded that simple cognitive tasks could be prone to thermal distractions. On the other hand, cold exposures were found to improve work accuracy. The authors attributed this effect to the higher mental arousal as indicated from the elevated body core temperature. Provins et al (1973) had described the associations between cold exposure and mental arousal previously. Langkilde et al (1978) demonstrated that subjects worked slower at 21°C as compared to 24°C but became faster at 18°C in the simulated component skills. This finding supported the postulation that room air temperature resulting in cool thermal sensation increased thermal stimulation and elevated arousal level.

Under heat exposure, Allnutt and Allan (1973) postulated that thermal discomfort induced by skin receptors and sweat evaporation would negatively affect work accuracy whereas further changes to body core temperature would influence the speed of work. Sundstrom (1986) showed that prolonged heat exposure caused higher error rates in mental tasks and that this was even more pronounced for tasks requiring coordination between visual and hand movement, which was common to office work such as text typing. Job satisfaction and the amount of effort exerted were also found to be dependent on the environmental conditions. Workers would tend to spent more time on informal breaks during thermally uncomfortable exposures, which would eventually cause productivity loss (Drake, 1990).

Subjects performing under similar thermal state exhibited no changes in mental performance (Wyon et al, 1975). This study was conducted at two clothing levels, i.e. 0.6 clo and 1.15 clo, each in combination with room air temperature that resulted in thermal neutrality. Within the thermal comfort region, the self-perceived effort, mental arousal, level of fatigue remained indifferent, and thus, mental performance was maintained. On the contrary, when exposed to two different temperatures, i.e. 20°C and 24°C, without the means to maintain thermal neutrality such as clothing adjustment, subjects performed better in the slightly cool than the slightly warm condition for text typing task (Wyon, 1974). The author offered two explanations: subjects were more aroused and thus type faster in the colder condition and/or subjects typed slower to lower metabolic rate in the moderate heat. Hygge (1991) also highlighted the application of arousal mechanism on the effects of moderate heat exposure. Complex mental performance seemed to follow a curvilinear relationship with increasing temperature. Performance of well-learned tasks was lowest at approximately 27.0°C. On the contrary, tasks that required relax situation were best around the same temperature. Taking these effects together would result in similar inverted U-shaped postulated by arousal theory.

2.3.3. Impacts of indoor air quality on occupants' performance

Although reports on the relationships between workers' performance and the air quality are hard to obtain, it seems obvious that the office workers and thus their productivity are sensitive to conditions of poor indoor air quality (Abdou and Lorsch, 1994). This is first evident from occupants' perceptions about their work environment and productivity. Based on office surveys, Woods et al (1987) reported that a considerable 17% and 26% of occupants working in enclosed space and open plan offices, respectively, associated their productivity with the indoor air quality and subsequently, Woods (1989) mentioned that increasing productivity of 20% of the workforce could be achieved by improving the indoor air quality of offices.

Wyon (2004) and Wyon and Wargocki (2005) reviewed the studies on the effects of indoor air quality on work performance from both the laboratory studies to the real office settings. There were strong evidences that poor indoor air quality adversely affected office work performance, which could result in 6-9% reduction. The author reiterated that there existed a positive decelerated curvilinear relationship of performance increment as the function of outdoor air supply rate and that performance decrement was related to percentage of dissatisfied of air quality following a linear function. The occurrence of SBS symptoms, particularly headache intensity and difficulty to concentrate, in the event of performance decrement was also highlighted as a plausible intervening effect of the poor indoor air quality.

Milton et al (2000) demonstrated that poor air quality affected productivity via the mechanism of negative health effects. In a large-scale case study using the blind intervention approach, they collected the epidemiological information on occupants' sick leave and absenteeism while the outside air supply rate was varied. The study involved a significantly large number of participants, i.e. 3720 people, from 40 buildings. These offices were owned and operated by a single company, i.e. the Polaroid Corporation. This would minimized the confounding related to work- and management-related factors. The analysis took account of many individual parameters such as age, gender, seniority, hours of non-illness absence, shift, ethnicity, and type of job. The authors concluded that there was significant association between occupants' sick leave and low provision of fresh air and that the cost of providing additional ventilation would be more than offset by the savings from reduced sick leave, apart from other benefits for the overall cohort of workers.

The relationship between health and productivity was also demonstrated by Nunes et al (1993) who administered two neurobehavioral tests on 47 office employees. The study concluded that workers with SBS symptoms required additional 7% longer period or 30% higher error rates in accomplishment of a neurobehavioral test. They concluded that workers with two or more frequent symptoms would suffer a 3% performance decrement. Likewise, Leinster and Mitchell (1992) showed that the prevalence of building-related symptoms negatively affected worker's productivity, while Hall et al (1993) reported that mucosal symptoms accounted for 18% of total variance in the self-reported productivity of 3000 office workers.

Wargocki et al (1999) and Wargocki et al (2000) reported one of the first series of studies that demonstrated direct impacts of common office pollution source and outdoor air supply rate on work performance in the well-controlled laboratory settings. In the first part of the randomized experiments, 20 years old carpet was a selected as the pollution source. In the second experiment, outdoor air supply rate was altered between 3, 10, and 30L/s/p. The study demonstrated that the presence of carpet caused SBS symptoms and reduced perceived air quality although the occupants did not perceived the difference in odor intensity. The presence of carpet further led to a reduction in the performance of office work of approximately 6.5%. This study had been replicated in another similar experiment conducted in the northern Sweden and the results showed a uniquely similar findings (Lagercrantz et al, 2000).

In the second experiment, the indoor air quality levels were altered by changing outdoor air supply rate from 3, 10 to 30 L/s/p (Wargocki et al, 2000). Increasing outdoor air supply rate significantly improved perceived air quality as well as the performance of the simulated office works. In summary, the authors concluded that "the positive correlation between the air quality, as perceived by occupants, and the performance of typing ($P<0.005$), addition ($P<0.07$) and proof-reading ($P<0.08$) indicated that performance would increase on average by 1.5% when proportion dissatisfied with air quality is reduced by 10% in the range of air quality causing 25-70% to be dissatisfied". Short-term effects on SBS symptoms were described as the causative factors in the negative effects on performance.

More recently, Bakó-Biró et al (2004) reported the effects of personal computers (PCs) with CRT monitors on perceived air quality, SBS symptoms, and productivity in offices. The study was conducted with the similar set-ups as those of Wargocki et al (2000) in the randomized experimental design. Five groups of six female subjects were exposed to room air with or without pollutants emitted from the PCs. There was significant effect of PCs on the perceived air quality of the occupants but this effect was not accompanied by noticeable difference of neither the odor intensity nor the SBS symptoms. The author argued that the exposure period was considerably too short for the development of any observable effects on the intensity SBS symptoms. Based on the subjective ratings of air quality, the sensory pollution load in the presence of PCs and the monitors was estimated to be about 3.5 olf (equivalent to 3.5 times the sensory pollution load from a standard person). More importantly, the study demonstrated that in the presence of PCs and CRT monitors, subjects performed significantly slower (~9.0%) on text processing performance.

2.4. Work performance factors

Tasks handling in office works constitute many basic as well as acquired skills developed over time, such as language processing, arithmetic skill, creative thinking, and analytical abilities. This is not to mention that other universal skills such as visual acuity, physical responses, and even social skills play important roles in a worker's performance. The typical sedentary office works generally constitute organized sequences of mental tasks with feedback system, e.g. in typing an article, one would have to perform reading, execute short-term memory, control movements of the eyes and hands through the central nervous system, then back to reading and so on. At some points, these activities would start to overlap and may even be executed simultaneously. Moreover, they are organized in the goal-oriented manner. In the text-typing, the goal is to re-type an article as fast and accurately as possible. In real office settings, workers' tasks are not clearly defined and often involved a myriad of intertwined and complex tasks. Any direct evaluations of the indoor environmental parameters on overall performance in such setting would be very difficult and likely confounded with various external parameters. The understanding of how the basic performance factors (subliminal level) are affected by either thermal environment or indoor air quality parameters is therefore crucial in characterizing and estimating the impacts of overall office performance. The following section discusses various basic mechanisms that are commonly associated with mental performance evaluations, which determine workers' ability to accomplish their daily tasks productively.

2.4.1. Arousal

The concept of mental arousal underlines the understanding of "optimal stress" in human performance. This further suggests the possibility of irrelevant environmental stimuli, which may be less preferred from individual comfort perspective but could be beneficial for enhancing the work performance. The arousal mechanisms are initiated through the activation of the brain by various stressors or stimuli. In the present study, these are the indoor environmental variables. Subsequently, the autonomic nerves activities, together with the intensified diffuse impulses, cause the rise of mental alertness and responsiveness (Davies and Krkovic, 1965).

The levels of arousal cause different implications on various tasks. The oldest formulation of this idea in the area of performance research, the Yerkes-Dodson law, suggested that the optimal level of irrelevant stimulation increases as the level of task difficulty decreases. For example, one may perform better when exposed to more stimuli, such as noise, higher or cooler temperature, and so on for common and repetitive tasks, whilst under serious work requiring more concentration, external or intensified stimuli may hamper performance. In other words, the optimum arousal level varies from one task to the others. This is best shown in the Figure 2.2.

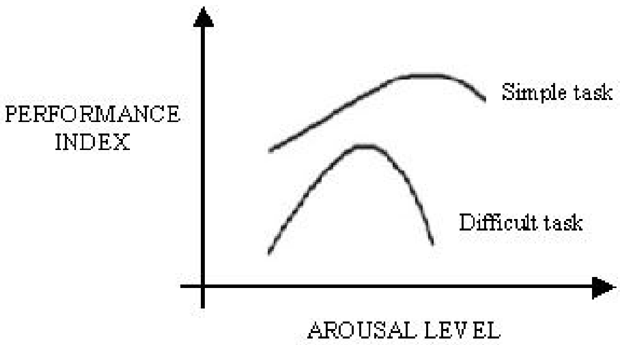

Figure 2.2 Performance index as the function of arousal for different task difficulties (the Yerkes-Dodson law)

Under low-arousing stimuli, drowsiness, sleepiness, and the lack of attention are some of the reasons for impairment of performance. When task difficulty is a variable, the inverted-U shape of arousal hypothesizes that there is an optimum level of performance and the optimum is lower for more difficult task. Understanding of arousal theory is particularly useful in explaining antagonistic interactions where one environmental factor cancels out the effect of other factor.

2.4.2. Attention/ concentration

Attention is an important basic function for office performance, which refers to the workers' ability to maintain awareness and to focus on a specific task while screening out other stimuli or potential distracters. In addition to other basic cognitive abilities, attention/ concentration are required for optimum performance on essentially all cognitive tasks. Attention is further divided into immediate and sustained attentions. Under moderate environmental stressors, workers may continue to perform simple tasks that require immediate attention, but may have difficulty to sustain their concentration during longer exposure (also termed as concentration endurance). Sustained attention level would inevitably influence the accuracy as well as the speed of work, and thus, the overall mental performance (LaBerge, 1995).

2.4.3. Creative thinking

Performance in the office works is not only determined by the quantity of work but also its quality, which in office settings often depends on creativity of the worker. The explanation to creative thinking ability is not simple and difficult to predict accurately due to so many factors contributing to expression of creativity, some are personal factors, and others are psychosocial and environment-related. It is not uncommon that individual differences in cognitive skills are attributed to creativity, which is why studies on human performance must be designed to cater for this possible confounding. A common approach around this problem is the application of repeated-measures approach in the experimental design.

Creative thinking enforces the workers to use and manipulate the knowledge and information from various sources. The role of knowledge and information in postulating ideas could be observed, for example, in open-ended thinking task. The answers to question such as "what are the uses of a pen?" are obviously influenced by one's knowledge. In this case, creativity measure of an individual lies in how the basic knowledge is developed into new ideas. Therefore, in order to avoid bias due to individual differences, measuring creativity using this approach should employ simple and easily recognizable objects.

2.4.4. Speed and accuracy tradeoffs

In human performance studies, the speed of work is one of the common measures of performance. Reaction times, movement times, search duration, and many other time-related measures have been used to attain information on the speed of work. Accuracy has been defined as freedom from error in discrete tasks (Drury, 1999) and measures of accuracy must be preceded with a clear definition of the error criteria in the performance evaluation (Rasmussen, 1986). The speed and accuracy tradeoff recognizes the trends in any information-processing performance (Wicklegren, 1977). The tradeoff suggests that, within the capacity of a person, increased speed of work would eventually compromise the accuracy and vice versa.

Nevertheless, not all tasks exhibit the speed and accuracy tradeoff. In some cases, accuracy is the inherent function of the quality of data presented for a specific task. This is even more obvious for quality discrimination tasks (also termed as data-limited tasks) in which accuracy is superior (Norman and Bobrow, 1979). A complex and challenging office task with time-consuming processes could be categorized as data-limited task. In the studies related to office performance, the simpler, quantifiable, and well-defined cognitive and mental tasks are preferred.

3

EFFECTS OF AIR TEMPERATURE & OUTDOOR AIR SUPPLY RATE IN THE FIELD STUDIES

3.1. Introduction

It is a challenging task to be able to characterize and quantify office work since the dynamic interactions involved in a particular office work are very complicated. Office workers perform high-level workload involving the use of multiple component skills, such as mental ability, cognition skill, muscular dexterity, etc. Most offices have a dynamic working environment and workers perform multitasks with almost no fixed criterion depending on the nature of the task. There is also significant variance in workload and performance, which give rise to difficulty in the evaluation of the workers on the same performance scale. Therefore, some criteria for real office work to be amenable for studies on the impact of indoor environmental quality on worker performance are the availability of measures or indicators of productivity, having multi-component skills in nature, possibility for blind intervention study, and availability for data logging of the performance measures.

The above criteria could be obtained, most reliably, from a call center, where high-level office work is performed. The office workers are dealing with customer or inquirer directly. Their tasks also involve the use of computer system to extract information and provide feedbacks to the customers. Sophisticated computer programs are commonly used to direct incoming calls, record call durations, and sometimes, record the audio conversations. Selection of the call center for field investigation eliminates common problems encountered in field studies, such as difficulty in finding a fixed performance indicator of workers due to variance of office work, irregularity in working schedule and other bias due to other work-related factors not associated with indoor environmental quality. Activities in the call center provide a good paradigm for many other kinds of multitasking and, unlike other office work, are routinely timed with great accuracy.

Niemela et al (2002) reported the effect of air temperature on the performance of call center operators in two call centers in Finland based on combined observational and intervention approach during summer. The performance criterion used was number of calls handled divided by the active working hours averaged over a month. The criterion was termed labor productivity. Subsequently, they computed the relative difference in mean monthly labor productivity. The task handled by operators in the first call center was number inquiries whereas the task in the other call center was not mentioned. The results of the study suggest a productivity reduction between 5-7% when temperature exceeded 25ºC. Some limitations to this study were noted as follows: the study was not performed using a balanced experimental design in testing the hypothesis. Any observed differences could have been due to pre-existing group differences. There existed a high air temperature variance during the experiment for each temperature settings, greater than 5.5ºC, indicating a lack of control of air temperature.

Wargocki et al (2004) performed a primary study on the combined effect of outdoor air supply rate and the presence of either old (filters used for 12 months) or new filters. The experiment was conducted in 2x2 replicated field study in a call center in Denmark. Four transits/ interventions were explored over 9 weeks experimental period, i.e. used to new filters at low outdoor air supply rate, new to used filters at high outdoor air supply rate, low to high outdoor air supply rate with new filter, and high to low outdoor air supply rate with used filter. The study reported inherent systemic variability in the average talk-time data obtained from the operators. This variability is associated with number of calls received, time of day, and number of operators, working concurrently. The analysis on weekly talk-time averages revealed that increasing the outdoor air supply rate when a new filter was in place reduced talk-time by 6% while changing the filter from used to new while keeping outdoor air supply rate high reduced talk-time by 10% at $P<0.05$ (one-tailed).

Another intervention study performed in the call center of a health maintenance organization indicated that call center operators (registered nurses) completed the calls faster when outdoor air supply rate was highest, i.e. above the level suggested by ASHRAE Standard 62, however the association between talk performance and ventilation rates was not significant or monotonic (Federspiel et al, 2004). Increased desorption of air pollutants from filters due to higher face velocities at higher ventilation rates was suggested as the explanation to the lack of strong association. Another result showed that the operators worked slower on wrap-up tasks (follow-up activities after concluding a conversation) when air temperature was high, i.e. above 25.4ºC, which is compatible with the results of earlier study by Niemela et al (2002).

This chapter reported the study conducted in three call centers in the tropics, Singapore. The effects of air temperature and outdoor air supply rate on subjective responses and office workers' performance were investigated in a 2X2 repeated-measures experimental design over nine weeks. The experiment was balanced for testing of main effects of air temperature and outdoor air supply rate. The office workers, whose primary task was to answer customer inquiries through the phone, were tropically acclimatized office workers. Their perceptions of indoor environmental parameters and the intensity of sick building syndrome (SBS) symptoms were collected through questionnaires every week, while the call handling performance data (i.e. talk time) was continuously recorded. Principal component analysis was subsequently carried out on the subjective data. This analysis extracted several factors (in the present study termed as the subjective factors) from coherent subsets of data. The main effects of air temperature and outdoor air supply rate on the subjective responses and call talk time were analyzed using the repeated measures statistical procedures.

3.2. Objectives and hypotheses

The objectives of the study in the call centers are as follow:

a) To define the impact of air temperature and outdoor air supply rate on call center operators' performance,
b) To determine the impact of air temperature and outdoor air supply rate on workers' perception of thermal comfort and other indoor environmental variables, acceptability of air quality and the incidence of SBS symptoms, and
c) To identify plausible mechanisms that link air temperature and outdoor supply rate with call center operators' performance in the tropics.

Derived hypotheses for objective a):

1) Increasing indoor air temperature at constant outdoor air supply rates reduces performance of call center operators by increasing call handling duration.
2) Increasing outdoor air supply rate at constant air temperature settings improves performance of call center operators by reducing call handling duration.

Derived hypotheses for objective b):

1) Increasing indoor air temperature adversely affects thermal comfort and reduces acceptability of air quality, increase sweating and thermal sensation; and reduces intensity of cold hand and cold feet symptoms and elevates neurobehavioral-related symptoms.
2) Increasing outdoor air supply rate improves acceptability of air quality, reduces intensity of neurobehavioral-related and other general symptoms.

3.3. Methods

3.3.1. Selection of call centers

Three call centers in Singapore were approached for their participation in the study. They were given a presentation and a proposal seeking consent for accessing the productivity database and conducting interventions to the indoor air conditions. Following the non-disclosure agreement with the call centers, hereafter, they will be referred to as Call center A, Call center B and Call center C. The call center operator will be referred to as Customer Service Officer or CSO.

The following were the main selection criteria for the call centers:

a) Availability and suitability of productivity measures in the call centers for the present study,
b) Number of permanent CSOs working in the call center,
c) Attendance and schedule of the CSOs,
d) Type of inquiries handled and the level of complexity of these inquiries.
e) Capacity of the air conditioning system to achieve desirable air temperature at an increased outdoor air supply rate.

The performance metrics used in this study was the talk time of the CSOs. The measured talk time was defined as the duration between the start and the end of a phone conversation between customer/ inquirer and the CSO excluding the hold time. Hold time was defined as the duration in which the conversation was put on hold through the phone system by the CSO. The call handling data was available through automated call distribution system in the pre-formatted versions and was accessible to the investigator with special permissions.

Table 3.1.Selection criteria for the call centers

	Call center A	Call center B	Call center C
Productivity metrics	Productivity Index (PI) as the function of number of attended calls and active hours recorded by the ASPECT™ automated call distribution (ACD) computer program. Further combined with average call handling time.	Based on preformatted reports, average call talk time and number of concluded calls were used as metrics.	Queuing time and the corresponding queuing time were the primary metrics (real-time monitoring). Talk time duration served as secondary measures (daily performance monitoring).
Number of CSOs	71 (permanent: 28, part time: 43).	A collective 227 permanent CSOs from four sections.	52 (permanent: 50, part time: 2).
Attendance and schedule	Permanent staff works on weekdays and Saturday between 08.00am and 17.00pm. Annual leaves were planned with the call center manager taking into consideration the peak call seasons.	Weekdays' and alternate Saturdays' schedule: 08.00am – 16.00pm or 09.00am – 17.00pm or 10.00am – 18.00pm. Annual leaves were planned with administration supervisors at least one month earlier.	Permanent staff works only during the weekdays, Monday to Friday, between 08.30am and 18.00pm. Annual leaves were taken with consent from the manager.
Type of inquiries	Main task: Dealing with inquiries on computing tax, filing and payment related matters. Other tasks: administrative works.	Section 1: Billing statement inquiries, section 2: Corporate contracts services. Section 3: Public phone directories, section 4: Mobile phone services. Other tasks: none.	Section 1: General member services such as accounts checking, investment matters, insurance options, etc, section 2: Schemes for employer or corporate. Other tasks: preparing official letters for the customers.
Capacity of air conditioning system	Lowest air temperature achievable with outdoor air supply rate kept at 18-22L/s/p (calculated based on actual occupancy) was 21.0-21.5°C (outdoor air temperature: 29.0-32.0°C). Air distribution system: VAV (fan frequency was locked during experiments). Filters were maintained prior to experiments.	Lowest air temperature achievable with outdoor air supply rate kept at 10-12L/s/p (calculated based on actual occupancy) was 20.0-21.0°C around the center and 22.7-24.0°C near the perimeters of the building (outdoor air temperature: 31.0- 33.5°C). Air distribution system: VAV (fan frequency was locked during experiments). Filters were replaced prior to experiments.	The office workstations were distributed along the four perimeters of the building, giving rise to non-uniform thermal stratification due to solar radiation. During overcast day, the lowest achievable air temperature was 22.4-23.7°C. Upgrading of the air handling unit and balancing was necessary (carried out in June 2004). Minimum achievable air temperature was 21.2-22.8°C (outdoor air temperature: 29.0-31.0°C, outdoor air supply rate: 7-8L/s/p). Air distribution system: CAV. Filters were replaced prior to experiments.

Each of the call centers employed different productivity metrics in determining the performance of the CSOs. In Call center A, the use of indicator: number of calls/ cases concluded within the active time online, was intended to elevate the service level of the CSOs by minimizing customer waiting/ queuing duration. This assessment was subsequently matched with average call handling time of each CSO to determine their overall speed of work. Here, the call handling time was the sum of the talk time and the wrap-up time. The latter measured the time during which a CSO performs follow-up tasks for the previous call and thus was temporary inactive from receiving call. Similar strategies to maintain service level was employed in Call center C, which monitored the queuing duration of incoming calls and the talk time. In Call center B, the talk time and number of completed calls were used to evaluate performance. Although it seemed that each of the call centers had their own approach in evaluating performance, the basic currency used here was the same, i.e. time/ duration, or more specifically, the speed of work or average time spent on the phone to solve an inquiry.

A reasonable sample size was available in each call center. The number of participants in Call center A was smallest, i.e. 26 CSOs, but still corresponded to 80% power to detect a difference of 0.25 mean difference (effect size: 0.60, α: 0.05, S.D.: 0.5, two-tailed t-test) (Machin et al, 1997, Zar, 1984). The sample sizes in Call centers B and C were substantially larger, i.e. more than 40 CSOs for each call center sections. These call centers employed permanent staff for the daily operation. The tasks performed in these call centers varied from simple inquiries such as phone directory search to the more complex ones such as handling payable tax cases. As the inquiries grew in complexity, more diversity in questions and longer handling time were expected, which could increase the uncertainties in the data. Nevertheless, as revealed by the managements, their monthly productivity reports showed that the variances were reasonably small within a group of officers/ operators because customers generally inquired on standard matters, which the CSOs were trained for and acquainted with.

Another criticism to selecting the call center in establishing the relationships between indoor environmental parameters and workers' performance is that better performance is not always associated with measurable outcomes such as the duration of case handling. Quality of work arguably presents greater impact in some office settings. Furthermore, Tuten and Neidermeyer (2002) reported that, in call center settings, optimism level and conscientiousness interactively affected work performance. Thus, in the present study, quality of service had to be controlled and assured. In order to achieve this, the call center managements applied various existing means, such as, but not limited to, audio recording, online customer feedback system, customer surveys, regular monitoring by supervisors, and attractive incentive schemes. The possibility of confounding was further reduced by the fact that most of the CSOs are professionally trained and well experienced in handling their tasks/ inquiries. This suggestion supports the proposition that shorter talk time could serve as an indicator of improved performance and therefore of overall productivity, without necessarily compromising the quality of work.

3.3.2. Description of call centers

3.3.2.1. Call center A

Call center A served the public on individual income taxation inquiries. There were 28 permanent customer service officers (CSOs), of whom, 26 CSOs participated in the study, including two male participants (age: 27-45 years, mean: 33). They were all non-smokers and none of them was asthmatic. The CSOs received a significant amount of intensive trainings and in-house courses. All the participants in the study had been working in the call center for at least 5 years. They were required to perform administrative tasks in addition to dealing with customers' inquiries on taxation matters such as computing and filing tax returns, information on what constitutes income and expenses as well as tax relief and rebates.

The CSOs worked full day from Monday to Saturday. The official working hours for each day was approximately eight hours (08.00am - 05.00pm). They did not work in shifts since the call center operated during normal office working hours. However, there was the half an hour staggered lunch period to maintain the service level, in which some CSOs would have their lunch starting from 11.30am, 12.00noon or 12.30pm. The data used in the analysis was taken from recorded talk time between 8.30am-11.00am and 02.00pm-04.30pm. The study was performed between August-October 2002 during the off-peak season to avoid possible confounding due to higher call volume, as highlighted in Wargocki et al (2004).

The call center was located on second floor of a 22-storey building located at the fringe of the Central Business District. The area of approximately 275 m^2 which houses the call center was served by an air handling unit. As the office adopts an open plan concept, interzonal air mixing between this area and other adjacent rooms could not be avoided. The location where participating CSOs were situated was, however, sufficiently distant from the boundaries to other rooms, and thus, the interzonal air mixing did not alter the intervention settings. Moreover, the call center area was kept under positive air pressure at all time during operation. Measured air temperatures and tracer gas concentrations were used as verification. The outdoor air supply was mainly contributed via louver dampers fixed to one side of the AHU room. The outdoor air was brought in directly from the outdoor by means of negative pressure created by the supply air fan of the AHU and mixed with the recirculated air in the AHU room before passing through the filtration system and cooling coil. In order to maintain the supply air volume, the frequency of supply air fan was kept constant at 45Hz. The air temperature set point prior to the experiment was 22.0ºC and outdoor air supply kept at approximately 7-9 L/s per person (based on actual occupancy). The electrostatic filters were serviced three months prior to the experiment and the fin surfaces of the cooling coil were cleaned a month before the experiment. Monthly checking of the air handling units was conducted according to the building maintenance schedule.

Figure 3.1 depicts a typical workstation of the call center. Each workstation was equipped with one computer with 17" CRT monitor and an extra computer with 15" CRT monitor for the purpose of parallel data search and system back-up. The luminous environment was rather dim but at 340±25 lux (N=8) was within the recommended level for an office setting (300 lux, CIBSE, 1993). The background noise level measured with the presence of occupants but without intermittent noise generated by incoming calls and phone conversations was approximately 32±4 dBA (N=8). All occupants of the call center wore uniform clothing with light cotton jacket (clothing insulation: 0.64-0.72 Clo, mean: 0.67).

Figure 3.1. Typical workstation in Call center A

3.3.2.2. Call center B

Call center B provided services for a major telecommunication company. Four selected sections/ groups of CSOs was included in the study (Table 3.1.), with detailed number of CSOs as follows: public phone directory 54 CSOs, billing statement inquiries 56 CSOs, mobile phone services 48 CSOs, and corporate contracts services 69 CSOs. These CSOs were well-trained and acquired substantial amount of experience over a minimum of two years in dealing with customer inquiries (age range: 23-39 years, mean: 27). None of them were asthmatic (based on medical records) or smoker (as told by the call center supervisors). For the present study, the four sections were considered independently due to group-related differences. CSOs from each section were trained and specialized for its own service, in other words, the CSOs from one section would not be able to handle or answer inquiries from other sections. Moreover, as the level of task complexities increased across different sections, the level of skills and educational backgrounds required from various sections also differed accordingly.

Call center B was located in a relatively new building, approximately 6 years in operation. The call center occupied the 12th floor of a medium-rise 14-storey building. Over 350 personnel occupied the large landscape office space (approximately 2000m^2 net area). A section of the call center is shown in Figure 3.2. All participants in the experiment were female, which also accounted for 95% of the total workforce of the call center division. The eight-hour work schedule from Monday to Saturday also included one-hour lunch break and another two fifteen-minute breaks. The study commenced in January 2003 and ended in March 2003.

Four air-handling units served the call center area due to its vast space. The air distribution system used variable air volume system to deliver the air to the occupants through linear diffusers. In order to supply constant amount of air to the occupied zones, the fan speed was locked at 40Hz, while chilled water flow rate through the coil had to be manually adjusted to achieve the desired room air condition. The normal air temperature set point was 24.0ºC. New panel absorber filters were installed three months before the commencement of the study and maintenance and checking of the air handling units were carried out monthly during the weekends. All the CSOs in the call center, including their supervisors, wore non-uniform clothing attires. In general, they wore light cotton blouse or shirt and skirt or light trousers. The estimated clothing value of the CSOs was within the range of 0.37-0.39 Clo (mean: 0.38).

Figure 3.2 shows the typical office layout of Call center B. The unconventional layout system allowed the CSOs to communicate better and encourage teamwork. The overall design of the office was intended to improve the occupants' satisfaction and productivity. Each workstation was equipped with a 15" CRT monitor. Average measured illuminance level was 420±40 lux (N=12). The average background noise level contributed by air conditioning system and the electronic equipment was 36±6 dBA (N=12).

Figure 3.2 Typical workstation in Call center B

3.3.2.3. Call center C

The services provided by the CSOs in this call center were crucial as the government-related service to the workforce. Customers would normally inquire on the schemes available for the service, the rules and regulations, the amount and modes of payment as well as the status of their account. In addition to their main task of dealing with customer inquiries, they also prepared official letters to relevant customers, sending forms and occasionally, administrative tasks assigned by their supervisors. The total number of CSOs participating in the study was 50 permanent staff from the first section (refer to Table 3.1 for detail) as agreed with the call center management. They worked daily from 08.30am to 06.00pm with one-hour lunch break between 12.00noon and 01.00pm. As in Call center A, the CSOs also took their lunch in shifts, starting from 11.30am, 12.00noon or 12.30pm. The data used for analysis was extracted from 09.00am-11.00am and 02.00pm-05.30pm. The call center maintained a consistent call volume throughout the year except during the periods when the government announced new scheme or project, which would generate a much higher incoming call frequency. The study was conducted between November 2003 and February 2004, within which no new scheme or project was introduced.

Call center C was located in a high-rise building within the Central Business District, occupying an approximate area of 600m^2 on the 15th floor. Two air-handling units located in the building core served the call center. Each air-handling unit served approximately half of the center and full-height partition walls physically separated the two zones to minimize interzonal mixing. The air conditioning system employed was the constant air volume system. The panel media filters were replaced three months prior to the experiments.

The office environment comprised of conventional workstations with full height (1.70m) partitions, arranged in double rows along the perimeters of the building. The average illuminance level was measured as 480±30 lux (N=6) and background noise level without intermittent noise from the incoming calls and conversations was approximately 40±2 dBA (N=6). Occupants in the call center wore uniform cotton shirt and skirt and occasionally, the office light jackets (estimated clothing insulation without jacket: 0.43-0.47 Clo, mean: 0.45).

3.3.3. Selection of parameters and conditions

Two nominal air temperature set points were selected, 22.5°C and 24.5°C. Both conditions were tested prior to the experimental period for two weeks in all the call centers and were within the tolerance limits of the occupants. It is pertinent to note that the preliminary study of air temperature interventions had indicated some thermal-related complaints from the occupants. In Call center A, when air temperature was raised to 25.5°C or lowered to 21.5°C, many occupants reported negative feedback to the building property managers. The same also applied in Call center B and Call center C, particularly when air temperature reached 21.0°C.

The second parameter was the fresh air provision or the outdoor air supply rate per person. It has been generally accepted that higher amount of outdoor air supply rate would lower or dilute the accumulated pollutants in the indoor environments. As the operating ranges of outdoor air supply rates in the three call centers varied, it was not possible to have the same intervention settings for this parameter. The air conditioning system designs and strategies differed for each building according to the operation needs and guidelines when the building was constructed or renovated. It was decided to maintain a minimum of two-fold increase of outdoor air supply rates from the current ventilation operation while the air temperature setting was maintained at either 22.5°C or 24.5°C.

Table 3.2 lists the selected settings for each call center. Call center A had the lowest outdoor air supply rate settings while Call center C had the highest settings, approximately three times higher than those of Call center A. The air temperature settings were maintained at the same levels for the three call centers.

Table 3.2. Air temperature and outdoor air supply settings

Parameters	Call center A	Call center B	Call center C
Temperature 1 (T_1) (°C)	22.5	22.5	22.5
Temperature 2 (T_2) (°C)	24.5	24.5	24.5
Outdoor air supply 1 (V_1) (L/s/p)	9.0	6.0	3.0
Outdoor air supply 2 (V_2) (L/s/p)	18.0	12.0	6.0

3.3.4. Experimental plan

The two main approaches of field studies are the observation and intervention study. The first approach is commonly used in data collection of existing conditions. Many studies on SBS symptoms were conducted using this approach to understand the existing status of building operations and the impact on occupants' health status and perceptual responses. The second approach is usually used to explore the influence of selected conditions on occupants or to test the effectiveness of various conditions/ parameters. The latter approach also provides a sound comparative study of various indoor environmental settings. Hence, it was adopted for the investigation in the call centers. Single blind interventions were conducted, in which the occupants were kept blind to the interventions. However, they were aware of the monitoring of the indoor environmental parameters such as air temperature and other gaseous pollutants.

The experiment was carried out as a 2X2 balanced repeated-measure design, in which each of the combinations of two room air temperatures (T_1 & T_2) and two outdoor air supply rate settings (V_1 & V_2) were achieved and maintained for one week. Only one parameter was modified for each intervention every Saturday. A total of nine consecutive weeks were required to complete the sequences for all possible combinations and transits. The first week (W1) was added in order to achieve the balanced experiment for testing of the main effects of air temperature and outdoor air supply rate. In other words, all eight transits, i.e. directional changes of a parameter, were carried out. On the other hand, since the length of proposed schedule of experiment was restricted by the call center management, the order of presentation by which the changes occurred could not be fully balanced, e.g. increasing air temperature at lower outdoor air supply rate appeared once at the beginning while the opposite occurred only at the end of experiment. The detail experimental plan is illustrated in Figure 3.3.

Long-term or acute health effects were not the target of the present study. Such study would usually require a longer exposure time and monitoring period. On the other hand, weekly interventions were considered sufficient to alter any short-term health effects, i.e. the intensity of SBS symptoms, or perception towards indoor environmental variables; and to observe any immediate to short-term exposure effects on the call handling performance. The selection of weekly intervention also suited the requirement by the call center management to keep the monitoring as short as possible to minimize interruptions to the daily operations. More importantly, the participants, in this case the CSOs could be avoided from experimental fatigue, which could affect the overall results of the study.

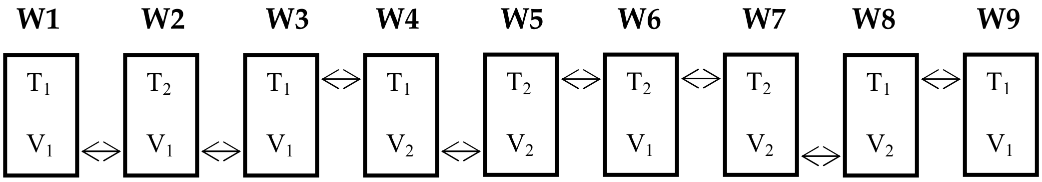

Figure 3.3 Experimental settings (week 1 (W1) - week 9 (W9))
Note: T_1= lower air temperature, T_2= higher air temperature,
V_1= lower outdoor air supply rate, V_2= higher outdoor air supply rate.

3.3.5. Measurements of various indoor air parameters

In each call center, an initial walkthrough was performed to determine the locations of measurement according to the floor area, office layout, occupant density, and air distribution strategy. Thus, the number of measurement points varied between the three call centers. Both continuous and instantaneous measurements were conducted in each selected location.

3.3.5.1. Physical parameters

The average air temperature and relative humidity in the call center were recorded continuously at the indoor locations and the return and supply air locations in the air handling unit (AHU) room by using the portable HOBO™ mini logger from Onset Computers Ltd. The device has an accuracy level of ±0.5°C. The preset measurement or data logging interval was 5 minutes. During the weekends, these data loggers were collected and stored data were downloaded to a computer for further analysis. In addition to the continuous measurement, Kanomax Climomaster™ was also deployed for instantaneous measurement on Thursdays, once in the morning and afternoon at the same locations. This portable instrument was also used to record the air velocity at various heights, i.e. 0.60m and 1.10m above floor level.

3.3.5.2. Chemical gaseous parameters

The chemical gaseous parameters were measured continuously using the Brüel&Kjær™ Multi-gas monitor type 1302 connected to Brüel&Kjær™ Multi-point sampler and doser type 1303 system. In principal, this instrument used real-time Photo Acoustic Sensor (PAS) quantification method to characterize the concentration of selected pollutants in the sampled air from the indoor locations as well as return air, supply air and outdoor air points located in the AHU rooms. The air was sampled via a 3mm (inner) diameter Legris™ tubes to the multipoint sampler of the system and subsequently, quantified by the multianalyzer and finally, data was stored directly in a computer.

Four selected pollutants, commonly found in the indoor environment i.e. carbon monoxide (CO), carbon dioxide (CO_2), formaldehyde (HCHO), and Total Volatile Organic Compounds (TVOC ref. toluene), were measured.

3.3.5.3. Ventilation parameters

Carbon dioxide levels served as good indicator of the amount of outdoor air introduced to the occupied spaces. The recorded carbon dioxide levels were initially used to adjust the outdoor air damper openings in attempt to achieve various outdoor air supply rates. Initially, a more detailed ventilation parameters measurement was conducted using the tracer gas pulse injection method to obtain the ventilation characteristics of various zones in the office premises, however, due to technical constraints in executing this method in the field studies, subsequent measurements were carried out using the concentration-decay tracer-gas technique weekly. The INNOVA™ system was used to measure the concentration of Sulfur hexafluoride (SF_6) tracer gas over time. The concentration decay over time was computed as air exchange rate per hour (ACH), which later determined the total amount of outdoor air supplied per person based on actual occupancy.

3.3.5.4. Biological parameters

Single stage Andersen sampler containing either Tryptic Soya Agar (TSA) plate for bacteria or Potato Dextrose Agar (PDA) plate for yeast and molds was used to collect the air sample using a pump at the rate of 14.8 L/min at two vertical levels, i.e. the occupant's breathing level and the supply air (near supply air paths discharged from the diffusers to the measurement locations). In the AHU room, measurement was carried out at the outdoor air intake and the main supply air duct.

Collected samples on the TSA and PDA plates were transported to the laboratory for incubation. The incubation period for bacteria samples was 48 hours whereas for yeast and molds was 120 hours. Bacteria samples were incubated at constant temperature of 37.0°C, while yeast and molds samples were stored at room temperature, i.e. 25.0°C.

3.3.5.5. Dust particulate level

GRIMM™ dust monitor 1.105 was used as portable instrument to measure dust particulate level at the selected locations indoors. Volumetric weight of dust particulate at various sizes, i.e. 1 μ, 2.5 μ, 10 μ and the total suspended particulate matter was recorded every minute and averaged over 10 minutes interval.

3.3.6. Survey methods

Interviews with the call center management were carried out during the presentations and preliminary meetings to collect basic information necessary for the selection of the call centers. A devised questionnaire was subsequently distributed to the CSOs to obtain their subjective responses. The questionnaire comprised of visual-analog (VA) scales (horizontal continuous scales) for the recording of occupants' perceptions of various indoor environmental parameters and intensity of SBS symptoms, which was modified from assessments of anxiety, alertness, mood, and quality of sleep and was earlier introduced for sub clinical symptoms associated with SBS symptoms by Wyon (1992). Several vertical scales were also devised to obtain occupants' responses on thermal comfort, thermal sensation, acceptability of air quality, and perception of odor and irritation.

These continuous scales were designed to circumvent problems associated with verbal reports and had been demonstrated to be a useful tool for the rating of subjective responses. These are straight lines, anchored by two ends, which represent the minimum and maximum extremes of the variable to be rated. Respondents, i.e. the CSOs, were required to mark the line at a point corresponding to their estimates of the variable. Upon marking by the respondent, the length of the segment on each scale from one end to the marking point by the respondent was measured by digitizer and converted into numeric value.

The full set of questionnaire, supplemented in Appendix A, included perceived thermal comfort, thermal sensation, sweating intensity, acceptability of air quality, perceived odor and irritations, general perceptions of the indoor environment, intensity of SBS symptoms, and the self-assessed effort and productivity. The CSOs participated in weekly surveys every Thursday morning and afternoon for nine consecutive weeks. The surveys were conducted from 10.00am to 10.30am for morning sessions and 03.00pm to 03.30pm for the afternoon sessions. Communications were also established between the investigators and the call center operators to explain the purpose of the surveys and the importance of receiving their completed questionnaires. The process was kept anonymous by asking the CSOs to provide their phone extension numbers and the login identification numbers instead of their names or initials.

Participants generally spent between 5-10 minutes for each survey. Interruptions in the filling up process were observed due to incoming calls. The interruption could not be avoided as the CSOs were required to prioritize the call center service. Moreover, the calls were routed by the automated call distribution (ACD) system to the designated trunking or extension, requiring the available CSO to respond immediately.

3.3.7. Call performance metrics

The automated call distribution (ACD) programs logged several performance metrics. These data were recorded from each successful communication between the customer/ inquirer and the CSO. As noted earlier, each call center adopted different productivity metrics and thus, the structure of computed and pre-formatted data output in the performance analysis of each call center differed substantially from one another. In Call center A, talk time data was available as daily averages and further used deriving the productivity index, whereas in Call centers B and C, talk time data was available as half hourly and hourly averages, respectively. Number of calls handled by each CSO was evaluated in Call center B, while the length of queuing time was reviewed in Call center C by the supervisors. For the purpose of further analysis, only daily talk time averages based on selected duration of the day were used in each call center.

The recorded talk time were taken from incoming calls (from customer to the CSO). All outgoing calls, transferred calls and in-house calls between CSOs were excluded from the analysis and all incoming calls were further sieved for outliers. The most resourceful personnel to conduct the data sieving process was the CSO who handled the cases directly, however, the checking process could be time consuming and not practical. Thus, the supervisors were consulted and whenever possible, the outliers were excluded. Some of the pre-formatted reports have already included data sieving procedures in generating the performance metrics. These outliers included, but were not limited to, very long calls involving special cases, which involved more than one CSOs or involved a supervisor, and very short calls, which indicate wrong call destination or early terminated call.

3.4. Data analysis

Sequentially, the analysis can be summarized as follows:

a) Quantifying thermal parameters and indoor air quality determinants (objective measurements) to ensure that the experimental conditions were sufficiently achieved and maintained.
b) Testing effects of air temperature and outdoor air supply rate on subjective responses from weekly surveys.
c) Performing principal component analysis on the subjective responses to obtain subjective factors and deriving factor scores for each subjective factors.
d) Testing effects of air temperature and outdoor air supply rate on factor scores derived in c).
e) Investigating the relationship between average talk time and number of concluded calls.
f) Testing effects of air temperature and outdoor air supply rate on average talk time.
g) Identifying the plausible mechanisms between subjective factors and average talk time as the function of air temperature and outdoor air supply rate settings.

3.4.1. Analysis of subjective data from questionnaire

The completed questionnaire was converted into numerical data through the use of GTCO Roll-up™ digitizer. The numerical data for each scale was rescaled to interpretable scores based on the following coding:

1) Perception of thermal comfort scale: from "very comfortable"= (1) to "just comfortable/ just uncomfortable"= (0) to "very uncomfortable"= (-1).
2) Acceptability of air quality scale: from "clearly acceptable"= (1) to "just acceptable/ just unacceptable"= (0) to "clearly unacceptable"= (-1).
3) Perception of odour scale: from "no odor"= (0) to "slight odour"= (1) to "moderate odour"= (2) to "strong odour"= (3) to "very strong odour"= (4) to "overpowering odour"= (5).
4) Irritation scales: from "no irritation"= (0) to "slight irritation"= (1) to "moderate irritation"= (2) to "strong irritation"= (3) to "very strong irritation"= (4) to "overpowering irritation"= (5).
5) Visual analog (VA) scales:
    i. Air warmness: from "too cold"= (0) to "too warm"= (100)
    ii. Air humidity: from "too humid"= (0) to "too humid"= (100)

   iii. Air stuffiness: from “air fresh”= (0) to “air stuffy”= (100)
   iv. Air stillness: from “high air movement”= (0) to “air still”= (100)
   v. Room darkness: from “too bright”= (0) to “too dark”= (100)
   vi. Room noisiness: from “too quiet”= (0) to “too noisy”= (100)
   vii. Room dustiness: from “office clean”= (0) to “office dusty”= (100)
   viii. Nose dryness: from “nose running”= (0) to “nose dry”= (100)
   ix. Intensity of blocked nose: from “nose clear”= (0) to “nose blocked”= (100)
   x. Intensity of flu-like symptom: from “no flu-like symptom”= (0) to “flu-like symptom”= (100)
   xi. Throat dryness: from “throat not dry”= (0) to “throat dry”= (100)
   xii. Mouth dryness: from “mouth not dry”= (0) to “mouth dry”= (100)
   xiii. Lips dryness: from “lips not dry”= (0) to “lips dry”= (100)
   xiv. Skin dryness: from “skin not dry”= (0) to “skin dry”= (100)
   xv. Eyes dryness: from “eyes not dry”= (0) to “eyes dry”= (100)
   xvi. Intensity of smarting eyes: from “eyes not smarting”= (0) to “eyes smarting”= (100)
   xvii. Intensity of aching eyes: from “eyes not aching”= (0) to “eyes aching”= (100)
   xviii. Intensity of gritty eyes: from “eyes not gritty”= (0) to “eyes gritty”= (100)
   xix. Intensity of cold hand: from “hand not cold”= (0) to “cold hand”= (100)
   xx. Intensity of cold feet: from “feet not cold”= (0) to “cold feet”= (100)
   xxi. Intensity of headache: from “no headache”= (0) to “severe headache”= (100)
   xxii. Ability to think clearly: from “head clear”= (0) to “difficult to think”= (100)
   xxiii. Dizziness: from “not dizzy”= (0) to “dizzy”= (100)
   xxiv. Feeling/ mood: from “feeling good”= (0) to “feeling bad”= (100)
   xxv. Level of fatigue: from “rested”= (0) to “tired”= (100)
   xxvi. Ability to concentrate: from “easy to concentrate”= (0) to “difficult to concentrate”= (100)
   xxvii. Level of depression: from “positive”= (0) to “depressed”= (100)
   xxviii. Level of arousal: from “alert”= (0) to “sleepy”= (100)
   xxix. Level of tension: from “relaxed”= (0) to “tense”= (100)
   xxx. Self-perceived effort: from “slight effort”= (0) to “strong effort”= (100)
   xxxi. Self-perceived productivity: from “not productive”= (0) to “productive”= (100)
6) Thermal sensation scale: from “cold”= (-3) to “cool”= (-2) to “slightly cool”= (-1) to “neutral”= (0) to “slightly warm”= (+1) to “warm”= (+2) to “hot”= (+3).
7) Sweating intensity scale: from “not sweating”= (0) to “slightly”= (50) to “extensively”= (100).

Next, the numerical data of subjective responses was sorted according to the week of experiment. For each CSO, responses from the same air temperature and outdoor air settings was further averaged for testing of the main effects. Since the measurement scale of the subjective responses did not represent, at least, an interval scale, a more conservative approach in the analysis was conducted using non-parametric procedures. The Wilcoxon matched-pairs signed-rank test was carried out to test the main effects of either air temperature or outdoor air supply rate on each subjective response and median scores were reported.

It was postulated that the subjective responses may represent similar underlying mechanism and thus, could be clustered to reduce dimensionality of the subjective responses (Willem and Tham, 2004). The principal component analysis was carried out to extract several factors from coherent subsets of data as described in Tabachnick (2001). In order to allow for correlated subjective responses, the data was subjected to principal component analysis with oblique rotation (oblimin, δ: 0-0.25). The two criteria for extracting the factors, hereafter termed as subjective factors (SF), were eigenvalues greater than one and the consistency of line gradients in the scree plot. Data variance explained by each SF was also reported. Each SF was derived from a cluster of subjective responses with varying weighting factors (also termed as factor loadings) on the SF. All factor loadings greater than 0.5 were presented in the observed pattern matrix (an output table showing clusters of subjective response under each SF).

In order to further quantify each SF, factor scores (hereafter termed as SF scores) were derived based on Equation 3.1 in matrix form. The output of this calculation yielded SF scores for each CSO on all subjective factors across the weeks. The non-parametric analysis for testing of main effects was subsequently carried out on the SF scores.

$$F = [\ Z \,.\, (A \,.\, R^{-1})\ ] \qquad (3.1)$$

where: F=factor scores for each SF, Z=standardized scores on subjective responses, A=pattern matrix of factor loadings, R=correlation matrix between subjective responses.

3.4.2. Analysis of talk time data

Daily talk time averages of each CSO as obtained from the ACD's pre-defined reports or requested from the call center management were initially sorted according to days of week for nine consecutive weeks across all participating CSOs. Mondays' data was excluded because the intended air temperature settings could not be achieved from the start of working hours. This was caused by the air conditioning system operation schedule which was shut down during weekends, from Saturday evening to Sunday, to conserve energy. The operation of air conditioning system on Mondays could also potentially alter the concentration of pollutants resulting in a different exposure level in contrasts to the other weekdays. Saturdays' data was also excluded from the analysis due to a lower service level or lower attendance. The decision to exclude performance data of Mondays and Saturdays was also based on psychological consideration that work motivation after and prior to weekends may differ from other weekdays. The first and last half an hour of the working days as well as lunch periods were excluded from the averaging process to account for settling down and adaptation period in the morning, fatigue or expectation to leave office in the late afternoon, and lower service level during lunch hours.

Average weekly talk time data sorted by air temperature and outdoor air supply rate settings was used in the main effects analysis. By using weekly average talk time, the analysis was in accord with the weekly intervention approach. It was also viewed as more reliable and accurate as systemic data pattern due to time of day or days of week, if any, and also data variance caused by personal characteristics, acclimation process, and other intermittent interruptions such as informal meetings would be minimized or "averaged out".

The unit of call volume of each CSO used in the analysis was total number of calls handled per day. It was sorted in a parallel method to the talk time data. The weekly data of both variables from all CSOs were subjected to a linear regression analysis to reveal relationships of call volume and talk time. As had been revealed by Wargocki et al (2004), the call center operators might attempt to conclude calls gradually faster with increasing call volume. If present, this effect would strongly and systematically influence talk time. The main effects analysis must therefore be adjusted for.

Repeated-measures linear mixed-effects model analysis (Singer, 1998, McCulloh and Searle, 2000) was carried out to test the main effects of air temperature and outdoor air supply rate on talk time performance metric, while adjusting for call volume effect when present. This was achieved by including the call volume parameter as covariate in the fixed effects component. Linear mixed-effects model was considered more robust than the general linear model ANOVA due to its capabilities to handle correlated data and unequal variances. It could also deal with partial missing data without necessarily eliminating other useful information (Krueger and Tian, 2004). The main outcome (dependent variable) of the model was talk time. The analysis modeled both the fixed effects (main effects) of air temperature, outdoor air supply rate and their interactions, while subjects' intra-individual variance was included as the random effects. Repeated-measures component in the analysis, i.e. the weekly intervention, was included in the model to adjust for correlated residuals within each person. The general expression for the linear mixed model was as follows:

$$Y = X\beta + Zb + \varepsilon \qquad (3.2)$$

where: Y= n-dimensional vector for the response variable, X= an $n \times p$ design matrix including covariates and terms associated with fixed parameters of the model, β= a p-dimensional vector of fixed parameters of the model, Z= an $n \times q$ design matrix for the random components of the model, b= a q-dimensional vector of random components (covariance matrix of random effects), and ε= an n-dimensional vector of residual error terms (covariance matrix for errors).

3.5. Results

3.5.1. Indoor environmental parameters

3.5.1. A. Results of objective measurements in Call center A

Table 3.3 summarizes the measured indoor environmental parameters in Call center A. Average room air temperatures indicated that the interventions were not able to maintain a difference of 2.0° Centigrade between lower and higher settings particularly in one case between weeks 4-5 where increasing air temperature resulted in an average difference of 1.1° Centigrade. It is pertinent to note that the call center was distantly located from fenestration areas and thus the thermal environment was not influenced by radiation or convection heat transfer. A two-fold increase of outdoor air supply rate between weeks 3-4 and 6-7 and vice versa between weeks 5-6 and 8-9 as estimated from tracer gas method corresponded well with carbon dioxide levels during steady state recorded in the afternoon hours. Except for carbon dioxide, measured gaseous contaminant levels were not affected by the changes of either air temperature or outdoor air supply rate. The same could also be applied to biological contaminants level and the volumetric weight concentration of particulate matters at any size ranges.

3.5.1. B. Results of objective measurements in Call center B

Results of Call center B measurement is tabulated in Table 3.4. Target room air temperatures were reasonably achieved and maintained, with relative humidity kept within 55-65%. The CSO clusters were located at the center of the office premise and thus the effects of thermal radiation and convection through the perimeter areas did not affect the thermal conditions experienced by the CSOs. The outdoor air supply rates estimated from tracer gas measurement suggested slightly lower than expected levels for both lower and higher settings. Nevertheless, despite the deviation of c.a. 1.0 L/s/p, the intended two-fold increase of outdoor air supply rate had been successfully obtained, which was further confirmed by carbon dioxide levels at both settings.

There was no influence of either air temperature or outdoor air supply rate interventions to the level of carbon monoxide and total volatile organic compounds concentrations. An almost consistent effect on formaldehyde concentrations were noticeable when outdoor air supply rate was increased. Doubling outdoor air supply rate eliminated the presence of formaldehyde in this call center. Bacteria count was higher when air temperature was set at 24.5°C, which could indicate more bio-effluents released from the occupant’s skin surface. Dust particulate matter at lower size range, PM 1.0, was elevated at higher outdoor air supply rate. The observed trend was less profound as the particulate size increased.

3.5.1. C. Results of objective measurements in Call center C

Table 3.5 describes the measurement results of Call center C. The measured air temperatures did not deviate substantially from the design air temperatures, except in week 6, in which air temperature dropped slightly below 24.0°C. Tracer gas measurements and measured carbon dioxide levels indicated a consistently higher outdoor air supply rate than the design settings. At lower setting, the outdoor air supply rate was kept at 4.8-5.8 L/s/p as opposed to 3 L/s/p, while at higher setting, the level was maintained between 7.1-7.8 L/s/p as opposed to 6 L/s/p design condition. Therefore, the changes between lower and higher outdoor air supply rates were less than the factor of two. Fluctuations in the measured gaseous contaminants other than carbon dioxide, bio-contaminant colonies counts, and dust particulate levels were not attributable to any interventions to either air temperature or outdoor air supply rate.

3.5.2. Perceptual responses and intensity of SBS symptoms

Tabulated results of main effects of air temperature and outdoor air supply rate on subjective responses for the three call centers are given in Appendix B. In Call center B, analysis was carried out and reported separately for each section participating in the study. In order to obtain a more precise interpretation of perceptual ratings by the CSOs, all results are expressed in terms of perceptual or symptom intensity median scores following the scale coding specified in section 3.4.1. Here, the results of main effect analysis are presented separately for each call center. Results of principal component analysis of the subjective responses and the main effects analysis of derived subjective factor scores from the three call centers are presented simultaneously.

Table 3.3 Targeted and measured indoor environmental parameters (Call center A)

Week no.	Target conditions		Measured parameters^													
			Thermal*			Vent.**	Gaseous contaminants				Biocontaminants[##]		Dust particulate[+]			
	Air temperature	Outdoor air supply rate	T	Rh	Vel.	O/A	CO_2[#]	CO*	TVOC ref. Toluene*	HCHO*	Bacteria	Yeast and molds	PM1.0	PM2.5	PM10.0	TSP
	ºC	L/s/p	ºC	%	m/s	L/s/p	ppm				CFU/m³		µg/m³			
1	22.5	9	22.4±0.4	63±3	0.12	9.8	701±30	0.84±0.32	1.76±0.20	0.04±0.03	82	35	1.7±1.7	2.4±2.0	10.2±4.3	32.9±19.5
2	24.5	9	24.1±0.4	60±3	0.10	10.2	669±38	0.61±0.16	1.80±0.21	0.04±0.03	22	25	2.8±0.5	3.4±0.6	11.5±2.5	35.4±12.4
3	22.5	9	22.7±0.7	65±3	0.18	9.7	724±67	1.09±0.18	3.00±0.47	0.21±0.15	69	22	1.6±0.9	2.0±1.0	6.6±2.5	19.9±6.6
4	22.5	18	23.0±0.4	65±2	0.15	21.8	542±56	1.13±0.32	3.29±0.74	0.39±0.47	40	12	2.1±1.1	2.4±1.2	6.1±2.0	16.1±6.2
5	24.5	18	24.1±0.4	63±3	0.09	22.2	565±65	0.93±0.20	3.04±0.63	0.27±0.40	196	9	3.7±6.2	4.2±6.7	9.7±7.1	24.0±12.7
6	24.5	9	24.2±0.7	65±5	0.09	9.2	706±24	0.81±0.26	2.93±0.50	0.24±0.21	66	76	0.3±0.2	0.6±0.3	3.3±1.1	11.3±5.2
7	24.5	18	24.1±0.3	73±2	0.06	20.5	555±24	1.21±0.23	2.97±0.35	0.20±0.12	73	52	1.8±0.1	2.2±0.1	6.0±1.3	19.1±7.5
8	22.5	18	22.3±0.8	68±2	0.12	22.8	534±46	1.11±0.21	2.94±0.68	0.29±0.34	82	64	1.1±0.2	1.6±0.3	8.4±2.3	29.6±12.3
9	22.5	9	22.5±0.5	67±3	0.06	9.4	756±36	1.07±0.09	2.70±0.40	0.26±0.11	95	79	0.5±0.3	1.1±0.5	11.1±8.2	44.9±41.2

Note: ^: measurement data collected from five locations; *: results averaged over four days (Tuesday-Friday) between 09.00-12.00 and 14.00-17.00; **: results based on one-time pulse injection tracer gas method, calculated using actual occupancy rate; [#]: results based on steady state condition achieved in the afternoon hours, c.a. 14.30 between Tuesday-Friday; [##]: results based on average of morning and afternoon one-time sampling procedure, counted after specified incubation period; [+]: results based on average of morning and afternoon ten-minute measurements.

Table 3.4 Targeted and measured indoor environmental parameters (Call center B)

Week no.	Target conditions		Measured parameters^													
			Thermal*			Vent.**	Gaseous contaminants				Biocontaminants##		Dust particulate+			
	Air temperature	Outdoor air supply rate	T	Rh	Vel.	O/A	CO_2#	CO*	TVOC ref. Toluene*	HCHO*	Bacteria	Yeast and molds	PM1.0	PM2.5	PM10.0	TSP
	ºC	L/s/p	ºC	%	m/s	L/s/p	ppm				CFU/m³		μg/m³			
1	22.5	6	22.3±0.6	54±3	0.14	5.4	1128±99	0.35±0.04	1.25±0.36	0.05±0.02	220	16	0.7±0.1	1.2±0.1	10.5±5.7	38.2±19.6
2	24.5	6	24.6±0.6	58±5	0.13	5	1151±109	0.47±0.07	1.27±0.31	0.02±0.01	394	30	1.5±0.5	2.2±0.8	10.1±3.0	32.8±11.2
3	22.5	6	22.4±0.5	55±3	0.11	5.8	1206±122	0.50±0.11	1.19±0.17	0.01±0.00	157	31	2.4±0.1	2.9±0.2	11.1±2.2	39.0±10.5
4	22.5	12	22.2±0.5	56±2	0.20	10.9	846±55	0.52±0.09	1.06±0.17	nd	249	35	3.7±0.2	4.2±0.2	10.1±2.0	29.5±11.1
5	24.5	12	24.1±0.5	64±3	0.17	11.2	848±33	0.50±0.04	1.15±0.29	0.01±0.00	306	69	2.1±0.1	2.6±0.1	9.1±2.4	31.1±9.7
6	24.5	6	24.0±0.4	61±2	0.09	5.6	1048±37	0.60±0.11	1.13±0.20	0.01±0.00	270	53	1.7±0.6	2.0±0.6	5.5±1.1	16.0±6.2
7	24.5	12	24.1±0.2	65±4	0.12	12.1	818±59	0.57±0.07	1.02±0.18	nd	240	73	3.2±0.1	3.7±0.1	10.0±1.4	31.8±13.8
8	22.5	12	22.7±0.6	58±3	0.16	11.6	821±51	0.56±0.04	0.89±0.12	nd	171	49	4.7±0.3	5.3±0.4	11.8±2.2	31.8±10.2
9	22.5	6	22.7±0.2	61±3	0.10	5.4	1110±79	0.71±0.28	1.06±0.17	0.01±0.00	197	38	1.9±0.4	2.3±0.5	6.6±2.1	23.2±9.8

Note: ^: measurement data collected from eight locations; *: results averaged over four days (Tuesday-Friday) between 09.00-12.00 and 14.00-17.00; **: results based on one-time pulse injection tracer gas method, calculated using actual occupancy rate; #: results based on steady state condition achieved in the afternoon hours, c.a. 14.30 between Tuesday-Friday; ##: results based on average of morning and afternoon one-time sampling procedure, counted after specified incubation period; +: results based on average of morning and afternoon ten-minute measurements; nd: not detected.

Table 3.5 Targeted and measured indoor environmental parameters (Call center C)

Week no.	Target conditions		Measured parameters^											
			Thermal*			Vent.**	Gaseous contaminants				Biocontaminants$^{\#\#}$		Dust particulate^{+}	
	Air temperature	Outdoor air supply rate	T	Rh	Vel.	O/A	$CO_2^{\#}$	CO*	TVOC ref. Toluene*	HCHO*	Bacteria	Yeast and molds	PM10.0	TSP
	ºC	L/s/p	ºC	%	m/s	L/s/p	ppm				CFU/m^3		μg/m^3	
1	22.5	3	22.2±0.6	59±3	na	5.7	1140±57	0.46±0.13	2.36±0.37	0.05±0.03	106	13	5.7±4.1	16.0±5.6
2	24.5	3	24.4±0.4	65±2	0.15	5.1	1184±70	0.33±0.09	2.33±0.38	0.05±0.02	110	16	3.9±2.5	7.3±3.3
3	22.5	3	22.2±0.2	66±1	0.18	4.9	1225±41	0.55±0.08	2.09±0.23	0.03±0.02	92	15	6.9±4.8	18.5±7.9
4	22.5	6	22.5±0.4	62±3	0.14	7.5	983±56	0.36±0.06	2.47±0.12	0.05±0.03	70	36	3.7±2.6	7.6±3.8
5	24.5	6	24.3±0.5	64±3	0.18	7.1	1015±38	0.33±0.10	2.18±0.02	0.07±0.02	129	25	3.3±1.4	11.2±5.1
6	24.5	3	23.8±0.5	60±1	0.16	5.0	1161±42	0.41±0.08	2.52±0.12	0.05±0.02	57	2	2.7±1.2	6.7±3.6
7	24.5	6	24.4±0.5	57±6	0.15	7.8	942±33	0.39±0.05	2.97±0.25	0.06±0.03	99	6	4.8±1.4	13.8±5.3
8	22.5	6	22.6±0.5	59±2	0.13	7.6	967±29	0.45±0.08	2.34±0.14	0.01±0.03	78	11	3.7±1.1	9.8±4.3
9	22.5	3	22.5±0.8	62±5	0.15	5.8	1133±52	0.37±0.09	2.72±0.39	0.04±0.03	82	15	7.1±3.1	24.9±19.0

Note: ^: measurement data collected from five locations; *: results averaged over four days (Tuesday-Friday) between 09.00-12.00 and 14.00-17.00; **: results based on one-time pulse injection tracer gas method, calculated using actual occupancy rate; $^{\#}$: results based on steady state condition achieved in the afternoon hours, c.a. 14.30 between Tuesday-Friday; $^{\#\#}$: results based on average of morning and afternoon one-time sampling procedure, counted after specified incubation period; $^{+}$: results based on average of morning and afternoon ten-minute measurements; na: not available.

3.5.2. A. Survey results of Call center A

Effects of either air temperature or outdoor air supply rate on thermal comfort and acceptability of air quality did not reach formal significance based on the Wilcoxon matched-pairs signed-rank test. In other words, the overall perception of thermal comfort and air quality were not affected by the interventions. Given the freedom to adjust their clothing by putting on or off their office uniform jacket, occupants in Call center A seemed to be able to maintain their thermal comfort level despite a small but consistent shift of the thermal sensation. There was no significant impact of air temperature on perceived odor, irritation of the eyes or the nose. Nevertheless, there existed a trend of lower intensity of irritation of the eyes, nose and throat at higher air temperature, with the last-named being statistically significant at P<0.007 (Table 3.6).

Thermal effects on subjective responses were characterized by significant changes in thermal sensation, sweating intensity and the intensity of cold hand and cold feet symptoms. Figure 3.4 shows the shift, c.a. 0.6 on thermal sensation scale towards the warmer side, when air temperature was increased (P<0.005). The small magnitude of change hovering near thermal neutrality may be the reason for the insignificance influence of the change of air temperature on overall thermal comfort. There was also significant change in sweating intensity in the expected direction (Figure 3.5). Higher air temperature resulted in more sweating as perceived by occupants. Cold hand and cold feet symptoms were elevated at lower air temperature. In parallel to thermal sensation response, the differences caused by interventions to air temperature on both symptoms were small. At higher air temperature, perceptions of general indoor environmental parameters, namely air warmness (P<0.0002), humidity (P<0.0009), stuffiness (P<0.03), stillness (P<0.0007), and room darkness (P<0.04), were worse (Table 3.6). Occupants also experienced more dryness of the throat (P<0.09) and the mouth (P<0.05) and felt more sleepy (P<0.09) at the higher air temperature.

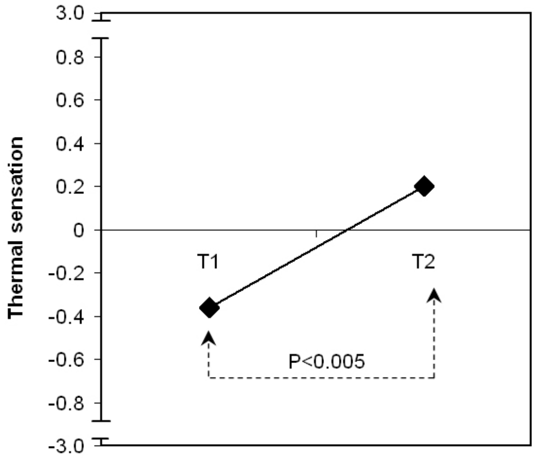

Figure 3.4 Thermal sensation as the function of air temperature in Call center A.

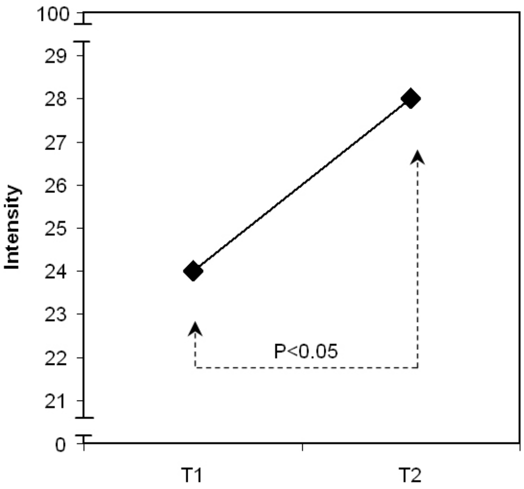

Figure 3.5 Sweating intensity as the function of air temperature in Call center A

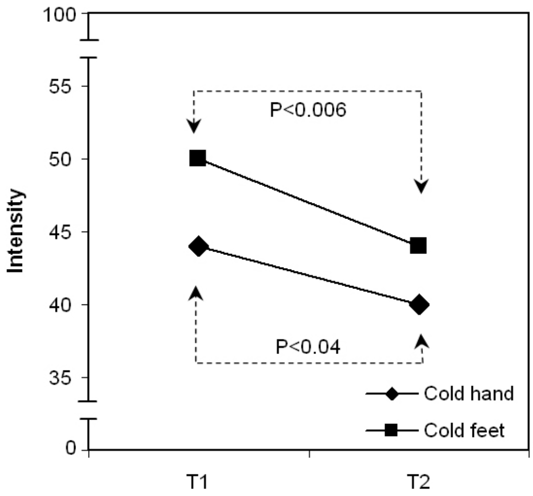

Figure 3.6 Intensity of cold hand and cold feet symptoms as the function of air temperature in Call center A.

Table 3.6 Effects of air temperature on perception towards general indoor environmental parameters and intensity SBS symptoms in Call center A with significance level (P) at <0.10.

Perceptual and SBS symptoms responses	Intensity score		Statistics	Scale description
	T_1	T_2	P	
Perceived throat irritation	0.85	0.80	<0.007	0: no irritation - 1:slight irritation - 2: moderate irritation - 3: strong irritation - 4: very strong irritation - 5: overpowering irritation
Air warmness	42	49	<0.0002	0: too cold - 100: too warm
Air humidity	40	47	<0.0009	0: too dry - 100: too humid
Air stuffiness	45	51	<0.03	0: air fresh - 100: air stuffy
Air stillness	48	55	<0.0007	0: high air movement - 100: air still
Room darkness	44	48	<0.04	0: too bright - 100: too dark
Throat dryness	43	54	<0.09	0: throat not dry - 100: throat dry
Mouth dryness	50	55	<0.05	0: mouth not dry - 100: mouth dry
Level of arousal	51	57	<0.09	0: alert - 100: sleepy

Note: mean T_1 = 22.6°C, mean T_2 = 24.1°C

There was no significant impact of the outdoor air supply rate interventions on acceptability of air quality, perceived odor and irritation of the eyes, nose and throat, although there was a consistent trend towards improvement, i.e. less perceived odor and irritation, at higher outdoor air supply rate. Occupants also tended to perceive their room as less dusty (P<0.07) at the higher outdoor air supply rate. Two neurobehavioral-related symptoms, namely the ability to think clearly (P<0.03) and dizziness (P<0.08), were affected by level of outdoor air supply rate in a positive direction (Table 3.7). It is also pertinent to note that other neurobehavioral-related symptoms, i.e. intensity of headache, level of fatigue, ability to concentrate, level of depression, level of arousal (higher), and level of tension, generally improved with more outdoor air supply provision. However, these results did not reach statistical significance. Negligible change for scales related to thermal perceptions such as overall thermal comfort, thermal sensation, and intensity of cold hand and cold feet symptoms following the interventions to outdoor air supply rate suggested no influence of thermal conditions on the effects of outdoor air supply rate.

Table 3.7 Effects of outdoor supply rate on perception towards general indoor environmental parameters and intensity SBS symptoms in Call center A with significance level (P) at <0.10.

Perceptual and SBS symptoms responses	Intensity score		Statistics	Scale description
	V_1	V_2	P	
Room dustiness	46	44	<0.07	0: office clean - 100: office dusty
Ability to think clearly	33	31	<0.03	0: head clear - 100: difficult to think
Dizziness	26	25	<0.08	0: not dizzy - 100: dizzy

Note: mean V_1 = 9.6 L/s/p, mean V_2 = 21.8 L/s/p

3.5.2. B. Survey results of Call center B

Effects of air temperature on perceptions and intensity of SBS symptoms from four sections (groups) in Call center B were in good agreement with each other. There was no significant influence of air temperature on thermal comfort perception and the intensity score averaged around "just comfortable" (intensity: 0.12-0.16) for both air temperature settings. Likewise, there was minimum impact on perception of odor and irritation with some exceptions. CSOs from Section 2 experienced increased irritation of the eyes (P<0.04), nose (P<0.05) and throat (P<0.09) at higher air temperature, whereas those from Section 1 perceived more odor (P<0.06) and throat irritation (P<0.09) at higher air temperature.

All sections in Call center B consistently perceived the air as warmer, more humid and stuffy and the air movement as lower at higher air temperature, all at P<0.01 (Figure 3.7). Intensity change was greatest for air warmness scale indicating a direct effect of air temperature on occupants' perception. The fact that occupants' response on air warmness fell within c.a. 25-60 on the 0-100 scale may indicate that room air temperatures both at 22.5°C and 24.5°C set-points were felt to be in the cooler region. This postulation was confirmed by occupants' ratings of thermal sensation, which remained below thermal neutrality (Table 3.8). The results also suggested that occupants were able to remain closer to thermal neutrality at 24.5°C set-point, while at 22.5°C they felt slightly cool.

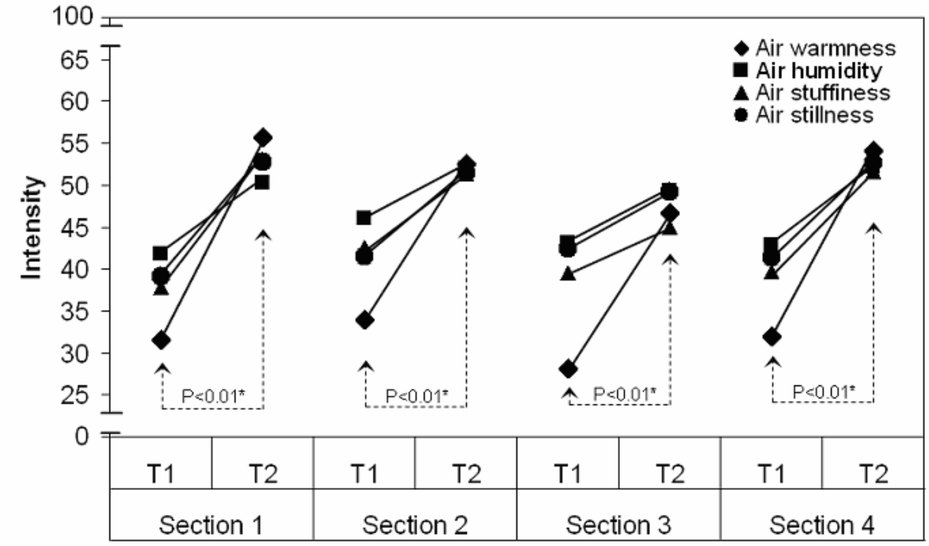

Figure 3.7 Perception towards indoor air parameters as the function of air temperature in Call center B.

Note: * = significance level applicable to all scales, mean T_1 = 22.5°C, mean T_2 = 24.2°C

The effects of air temperature on perceived air humidity, air stuffiness and air stillness were observed as secondary effects of air temperature interventions. There was no apparent reason for the change in perceived air humidity from objective measurements on air humidity, which showed reasonably small fluctuations across the weeks. It is therefore likely that occupants' perception on air humidity was correlated with their cutaneous response, i.e. evaporative heat loss through the skin, which could be observed through the sweating intensity scale. With room air perceived as less stuffy at lower air temperature, thermal cooling sensation through the inhaled air stream seemed to play an important role in improving perception of air freshness. However, the improvement did not yield any observable impact on acceptability of air quality. The thermal cooling effect at lower air temperature also influenced draft sensation. There was no increase in the total supply airflow rates to the occupants throughout the experimental period since the supply air fan was locked at constant frequency. This further ruled out the possibility of confounding due to air velocity changes in at the occupied zone altered by fluctuations in supply air volume as evident from air velocity measurements.

Correspondingly, a lower room air temperature at 22.5°C set-point markedly increased intensity of cold hand (P<0.0001) and cold feet symptoms (P<0.0001); and a lower sweating intensity (P<0.0001) in parallel to occupants' inability to maintain thermal neutrality resulting in the slightly cool thermal sensation. These observations, in view of thermal comfort response, practically implied that occupants did not require a thermal neutral state in order to remain thermally comfortable.

Table 3.8 Effects of air temperature on thermal sensation and intensity SBS symptoms consistent across different sections in Call center B (P <0.10).

Perceptual and SBS symptoms responses	Intensity score												Scale description
	Section 1			Section 2			Section 3			Section 4			
	T_1	T_2	P	T_1	T_2	P	T_1	T_2	P	T_1	T_2	P	
Thermal sensation	-1.1	-0.40	<0.0001	-0.64	-0.39	<0.04	-1.47	-0.72	<0.0001	-1.1	-0.15	<0.0001	-3: cold -- 0: neutral -- +3: hot
Sweating intensity	25.5	34.7	<0.0001	27.6	34.9	<0.0001	17.8	32.6	<0.0001	22	41.3	<0.0001	0: no sweat - 100: extensive sweating
Intensity of cold hand	63	38	<0.0001	54	42	<0.0001	67	46	<0.0001	54	35	<0.0001	0: hand not cold - 100: cold hand
Intensity of cold feet	63	30	<0.0001	51	40	<0.0001	62	47	<0.0001	60	37	<0.0001	0: feet not cold - 100: cold feet

Note: mean T_1 = 22.5°C, mean T_2 = 24.2°C

Increased outdoor air supply rate was envisaged to improve acceptability of air quality and reduce intensity of SBS symptoms. Across the four sections participating in the study only Section 2 registered significantly better thermal comfort (P<0.02) with higher temperature, which trend was also seen in Sections 1 and 3, and more acceptable air quality (P<0.03). This trend showed that increasing outdoor air provision not only affected perception of air quality, as expected, but also potentially improved perceptions related to thermal environment. Such observation could also be related to perceived cooler air (all sections), less humid air (Sections 2-4), higher air movement (all sections) and lower sweating intensity (all sections) when outdoor air supply rate was increased or c.a. doubled from 5.5 to 11.5 L/s/p.

Positive effects of having a higher outdoor air supply rate on perceived irritation (Table 3.9) were also seen in Section 2 by means of reducing eyes ($P<0.05$), nose ($P<0.006$), and throat irritation($P<0.0002$). Nose irritation was significant affected in the same direction in Sections 3 ($P<0.002$) and 4 ($P<0.03$), while in Section 1 the same trend was found. Adding to that, air stuffiness was significantly reduced with higher outdoor air provision for all sections. Also at higher outdoor air supply rate, occupants' perceived their office cleaner (less dusty) and reported a lower intensity of blocked nose, flu-like, mouth dryness, lips dryness, eyes dryness, aching and gritty eyes symptoms. CSOs from Section 2 also experienced significantly lower intensity of headache ($P<0.03$) and level of depression ($P<0.0008$); and better ability to concentrate ($P<0.009$), ability to think clearly ($P<0.02$), and feeling/ mood ($P<0.0003$).

These findings essentially emphasized the crucial impacts of increasing outdoor air supply rate on occupants' perception. Interestingly, although lowering air temperature has been shown to affect the perception of air quality, it has never been shown before that increasing outdoor air provision would have any influences on thermal-related perceptions, suggesting that improved indoor air quality by means of increasing outdoor air supply rate could have some influence on general perceptions of the indoor environmental parameters, including thermal-related parameters.

Table 3.9 Effects of outdoor air supply rate on acceptability of air quality, perceived irritation and intensity SBS symptoms across different sections in Call center B ($P <0.10$).

Perceptual and SBS symptoms responses	Intensity score												Scale description
	Section 1			Section 2			Section 3			Section 4			
	V_1	V_2	P	V_1	V_2	P	V_1	V_2	P	V_1	V_2	P	
Acceptability of air quality	0.24	0.23	ns	0.18	0.21	<0.03	0.20	0.18	ns	0.33	0.24	ns	+1: very acceptable; 0: just acceptable/ just unacceptable; -1: very unacceptable
Perceived nose irritation	0.52	0.33	ns	0.54	0.38	<0.0002	0.71	0.50	<0.002	0.55	0.54	<0.03	0: no irritation - 1:slight irritation - 2: moderate irritation - 3: strong irritation - 4: very strong irritation - 5: overpowering irritation
Perceived eyes irritation	0.66	0.40	ns	0.56	0.48	<0.05	0.70	0.60	ns	0.55	0.50	ns	
Perceived throat irritation	0.63	0.45	ns	0.65	0.48	<0.006	0.74	0.60	<0.04	0.56	0.58	ns	
Air stuffiness	47	42	<0.03	48	45	<0.0001	46	43	<0.05	47	44	<0.008	0: air fresh - 100: air stuffy
Room dustiness	42	41	<0.03	45	44	<0.03	49	49	ns	43	41	<0.03	0: office clean - 100: office dusty

Note: mean V_1 = 5.5 L/s/p, mean V_2 = 11.5 L/s/p

3.5.2. C. Survey results of Call center C

Table 3.10 shows that both thermal comfort and acceptability of air quality responses were significantly affected by air temperature. At higher air temperature, the CSOs felt more thermally comfortable ($P<0.008$). For the same condition, they also perceived the air quality to be better ($P<0.003$). Increasing air temperature also significantly elevated sweating intensity ($P<0.0002$) and tended to increase thermal sensation. However, a clear evidence of impact of air temperature on other thermal perceptions was not observed. In contrast to the positive implications of having higher air temperature on perception, the CSOs in Call center C reported the increase of dryness symptoms intensity such as nose ($P<0.006$), throat ($P<0.05$), and skin dryness ($P<0.04$).

Table 3.10 Effects of air temperature on perception towards general indoor environmental parameters and intensity SBS symptoms in Call center C with significance level (P) at <0.10.

Perceptual and SBS symptoms responses	Intensity score		Statistics	Scale description
	T_1	T_2	P	
Thermal comfort	0.41	0.52	<0.008	+1: very comfortable; 0: just comfortable/ just uncomfortable; -1: very uncomfortable
Acceptability of air quality	0.47	0.60	<0.003	+1: very acceptable; 0: just acceptable/ just unacceptable; -1: very unacceptable
Nose dryness	56	69	<0.006	0: nose running - 100: nose dry
Throat dryness	50	58	<0.05	0: throat not dry - 100: throat dry
Skin dryness	51	59	<0.04	0: skin not dry - 100: skin dry
Sweating intensity	28	40	<0.0002	0: no sweat - 100: extensive sweating

Note: mean T_1 = 22.5°C, mean T_2 = 24.2°C

Outdoor air supply rates seemed to have mixed implications for subjective responses in Call center C (Table 3.11). Perceived odor level ($P<0.04$) and thermal sensation ($P<0.02$) were increased at higher outdoor air supply rate. Occupants also experienced higher intensity of aching eyes ($P<0.04$) and gritty eyes ($P<0.008$), increased level of fatigue ($P<0.05$) but reduced dizziness ($P<0.02$) and room noisiness ($P<0.03$) with higher outdoor air supply rate. The same condition also decreased both air warmness and stuffiness, at the cusp of formal significance ($P<0.08$).

Table 3.11 Effects of outdoor supply rate on perception towards general indoor environmental parameters and intensity SBS symptoms in Call center C with significance level (P) at <0.10.

Perceptual and SBS symptoms responses	Intensity score		Statistics	Scale description
	V_1	V_2	P	
Perceived odor	0.18	0.24	<0.04	0: no odor - 1:slight odor - 2: moderate odor - 3: strong odor - 4: very strong odor - 5: overpowering odor
Thermal sensation	-1.31	-1.05	<0.02	-3: cold -- 0: neutral -- +3: hot
Air warmness	51	47	<0.08	0: too cold - 100: too warm
Air stuffiness	52	49	<0.08	0: air fresh - 100: air stuffy
Intensity of aching eyes	42	49	<0.04	0: eyes not aching- 100: eyes aching
Intensity of gritty eyes	36	49	<0.008	0: eyes not gritty - 100:eyes gritty
Level of fatigue	50	54	<0.05	0: rested - 100: tired
Dizziness	35	31	<0.02	0: not dizzy - 100: dizzy
Room noisiness	50	48	<0.03	0: too quiet - 100: too noisy

Note: mean V_1 = 5.2 L/s/p, mean V_2 = 7.5 L/s/p

3.5.2. D. Derived subjective factors (SF) for each group of CSO (a principal component analysis)

The pattern matrixes (clusters of subjective response), the corresponding explained variances, and the factor loadings of the subjective factor (SF) for each group of CSOs are presented in Appendix C. A consistent and coherent structure of data clusters could be observed across the groups. At least five SFs, comprising of similar subjective responses, were extracted, namely:

a) intensity of neurobehavioral-related symptoms and self-assessed productivity (hereafter termed: *SF neuro-prod*),
b) perception of thermal environment and intensity of cold hand and cold feet symptoms (hereafter termed: *SF therm-coldsymp*),
c) intensity of dryness and breathing-related symptoms (hereafter termed: *SF dry-breathsymp*),
d) perceived odor and irritation(hereafter termed: *SF odor-iritn*),
e) perceived thermal comfort and acceptability of air quality (hereafter called: *SF comf-aq*).

In Call center A and Call center B Section 4, an additional cluster could be derived from subjective responses on f) perceived indoor environmental factors (hereafter termed: *SF ieq*). It is important to note that SF neuro-prod accounted for the most variance in the data, range: 31-38%, while other factors explained for less than 20% of the total data variance.

The main effects of air temperature on calculated SF scores are given in Table 3.12. Higher air temperature was consistently shown to have profound negative effects on SF neuro-prod ($P<0.05$), SF therm-coldsymp ($P<0.0001$), SF dry-breathsymp ($P<0.05$), and SF ieq ($P<0.0001$) in Call center A. Effects of air temperature on SF therm-coldsymp and SF ieq also confirmed results from the individual subjective responses. It appeared that perceptual responses dominate over other subjective responses in Call center A. Moreover, as the subjective responses were allowed to cluster, it is evident that neurobehavioral-related symptoms were significantly increased with air temperature, an effect not observed when individual responses of neurobehavioral-related symptoms were considered singly.

In Call center B, impacts of air temperature could be observed for SF therm-coldsymp across the groups of CSOs (Sections 1-4). Increasing air temperature appeared to marginally increase the perception towards thermal environment and intensity of cold hand and cold feet for all sections ($P<0.0001$). In Sections 1 and 2, higher air temperature led to higher SF odor-iritn at $P<0.04$ and $P<0.003$, respectively. The effects were previously observed on the individual responses of perceived odor and intensity of irritation (approaching formal significance) and the clustering of these responses exhibited a much stronger effect. Similar trend was also seen in Sections 3 and 4. In parallel to result of Call center A, environmental halo effect seemed to also play a dominant role in Section 4 of Call center B. With thermal environment being adversely affected at higher air temperature, the occupants also perceived other indoor environmental factors, such as noise, luminous intensity, and cleanliness to be negatively influenced.

In contrast to results from Call centers A and B, results of Call center C indicated a less profound impact of changing air temperature on the subjective responses. Furthermore, analysis of SF comf-aq factor score revealed that occupants in Call center C felt thermally more comfortable and experienced a better air quality at higher air temperature.

Table 3.13 shows the main effects of outdoor air supply rate on the extracted SFs across the call center groups. In Call center A, SF neuro-prod was significantly reduced at higher outdoor air supply rate (P<0.007). This finding followed the tendencies of the individual neurobehavioral-related symptoms although they did not reach statistical significance. There were no indications that interventions to outdoor air supply rate affected other SFs in Call center A.

The significant effects of outdoor air supply rate on different sections of CSO in Call center B were most consistent for SF therm-coldsymp and SF dry-breathsymp. As observed in the analysis of individual subjective responses, improved thermal-related perceptions would have contributed mostly to improved SF therm-coldsymp in Section 2 (P<0.0001), Section 3 (P<0.02) and Section 4 (P<0.0001). Adding to that, lower SF dry-breathsymp in Section 1 (P<0.01), Section 2 (P<0.02) and Section 4 (P<0.0002) at higher outdoor air supply rate also confirmed the reductions of dryness intensity and breathing-related symptoms observed previously. The analysis of SF scores for SF odor-iritn and SF comf-aq further suggested more benefits of increasing outdoor air provision as SF odor-iritn decreased for Section 1 (P<0.03) and Section 3 (P<0.002), while SF comf-aq improved in Section 1 (P<0.005) and Section 2 (P<0.02).

Analysis of subjective factor scores in Call center C did not yield any significant effects of outdoor air supply rate, except for SF therm-coldsymp (P<0.008). The result, again, indicated positive impact of outdoor air supply rate on thermal-related perceptions. The scattered effects of outdoor air supply rate on neurobehavioral-related symptoms from analysis on the individual symptoms did not converged to a significant effect on SF neuro-prod of Call center C when these responses were clustered because of the weak and contradictive effects of some reported symptoms.

3.5.3. Performance metric (talk time data)

Results of performance metric analysis are presented separately for each group of CSOs. Influence of call volume on talk time was first established to avoid any confounding and, if present, the analysis model was adjusted (section 3.4.2). The following section would focus on the main effects of air temperature and outdoor air supply rate on talk time as the measure of the CSOs' performance.

Table 3.12 Effects of air temperature on subjective factors' scores for all groups of CSO

Perceptual and SBS symptoms responses	Factor score#																		Score description
	Call center A			Call center B												Call center C			
				Section 1			Section 2			Section 3			Section 4						
	T_1^	T_2^	P	T_1	T_2	P	T_1	T_2	P	T_1	T_2	P	T_1	T_2	P	T_1	T_2	P	
INTENSITY OF NEUROBEHAVIORAL-RELATED SYMPTOMS & SELF-ASSESSED PRODUCTIVITY	-0.09	0.13	**	-0.02	0.02		-0.08	-0.02		0.12	0.04		-0.06	0.01		0.09	0.30		Higher score indicates higher symptoms intensity but lower self-perceived productivity.
PERCEPTION OF THERMAL ENVIRONMENT & INTENSITY OF COLD HAND AND COLD FEET SYMPTOMS	-0.34	0.29	***	-0.53	0.42	***	-0.43	0.27	***	-0.32	0.47	***	-0.33	0.54	***	-0.29	0.12		Higher score indicates perceived warmer, more humid and stuffy environment but lower cold hand and cold feet symptoms, except for Call center C where higher score means perceived cooler and fresher environment but higher cold hand and cold feet symptoms
INTENSITY OF DRYNESS & BREATHING-RELATED SYMPTOMS	0.06	-0.06	**	0.14	0.29		0.14	0.06		0.00	0.02		0.18	0.05		-0.10	0.06		Higher score suggests higher dryness and breathing-related symptoms intensity.
PERCEIVED ODOR & IRRITATIONS	0.05	0.08		0.32	0.22	**	-0.40	-0.28	***	-0.16	0.01		-0.12	-0.10		-0.22	-0.08		Higher score suggests lower perceived odor and irritations, except for Call center B Section 2 and Section 4, and Call center C where higher score indicates higher perceived odor and irritations.
PERCEIVED THERMAL COMFORT & ACCEPTABILITY OF AIR QUALITY	0.11	-0.04		0.05	-0.02		0.18	0.22		0.06	0.11		-0.12	0.01		-0.37	0.18	***	Higher score suggests better thermal comfort and acceptability to air quality.
PERCEIVED INDOOR ENVIRONMENTAL FACTORS	0.30	-0.28	***	-	-		-	-		-	-		0.01	0.08	***	-	-		In Call center A, higher score indicates better indoor environmental factors (less humid, less stuffy, brighter, less noisy, less dusty), whereas in Call center B Section 4, higher score suggests otherwise (room less bright, more noisy and dusty).

Note: *** denotes $0<P\leq0.01$; ** denotes $0.01<P\leq0.05$; * denotes $0.05<P\leq0.10$

^ : T_1 indicates lower air temperature (set-point= 22.5°C) and T_2 indicates higher air temperature (set-point= 24.5°C)

: derivation from Z-score (Tabachnick, 2001)

Table 3.13 Effects of outdoor air supply rate on subjective factors' scores for all groups of CSO

Perceptual and SBS symptoms responses	Factor score$^{\#}$																		Score description
	Call center A			Call center B												Call center C			
				Section 1			Section 2			Section 3			Section 4						
	V_1^	V_2^	P	V_1	V_2	P	V_1	V_2	P	V_1	V_2	P	V_1	V_2	P	V_1	V_2	P	
INTENSITY OF NEUROBEHAVIORAL-RELATED SYMPTOMS & SELF-ASSESSED PRODUCTIVITY	0.10	-0.12	***	-0.02	-0.06		0.04	-0.15		-0.06	0.04		0.05	-0.16		0.14	0.20		Higher score indicates higher symptoms intensity but lower self-perceived productivity.
PERCEPTION OF THERMAL ENVIRONMENT & INTENSITY OF COLD HAND AND COLD FEET SYMPTOMS	0.05	-0.07		0.09	0.05		-0.01	-0.20	***	0.10	0.01	**	0.13	0.01	***	-0.22	0.04	***	Higher score indicates perceived warmer, more humid and stuffy environment but lower cold hand and cold feet symptoms, except for Call center C where higher score means perceived cooler and fresher environment but higher cold hand and cold feet symptoms
INTENSITY OF DRYNESS & BREATHING-RELATED SYMPTOMS	0.03	0.06		0.29	0.19	***	0.20	0.08	**	0.00	0.03		0.29	-0.04	***	-0.07	-0.07		Higher score suggests higher dryness and breathing-related symptoms intensity.
PERCEIVED ODOR & IRRITATIONS	0.07	0.05		0.16	0.44	**	-0.33	-0.36		0.13	-0.19	***	-0.13	-0.09		-0.22	-0.01		Higher score suggests lower perceived odor and irritations, except for Call center B Section 2 and Section 4, and Call center C where higher score indicates higher perceived odor and irritations.
PERCEIVED THERMAL COMFORT & ACCEPTABILITY OF AIR QUALITY	0.06	-0.03		-0.09	0.17	***	0.07	0.16	**	-0.02	0.05		-0.02	0.02		-0.17	-0.15		Higher score suggests better thermal comfort and acceptability to air quality.
PERCEIVED INDOOR ENVIRONMENTAL FACTORS	0.00	0.03		-	-		-	-		-	-		0.03	0.00		-	-		In Call center A, higher score indicates better indoor environmental factors (less humid, less stuffy, brighter, less noisy, less dusty), whereas in Call center B Section 4, higher score suggests otherwise (room less bright, more noisy and dusty).

Note: *** denotes $0<P\leq0.01$; ** denotes $0.01<P\leq0.05$; * denotes $0.05<P\leq0.10$

^ : V_1 indicates lower outdoor air supply rates and V_2 indicates higher outdoor air supply rates

$^{\#}$: derivation from Z-score (Tabachnick, 2001)

3.5.3. A. Results of talk time analysis of Call center A

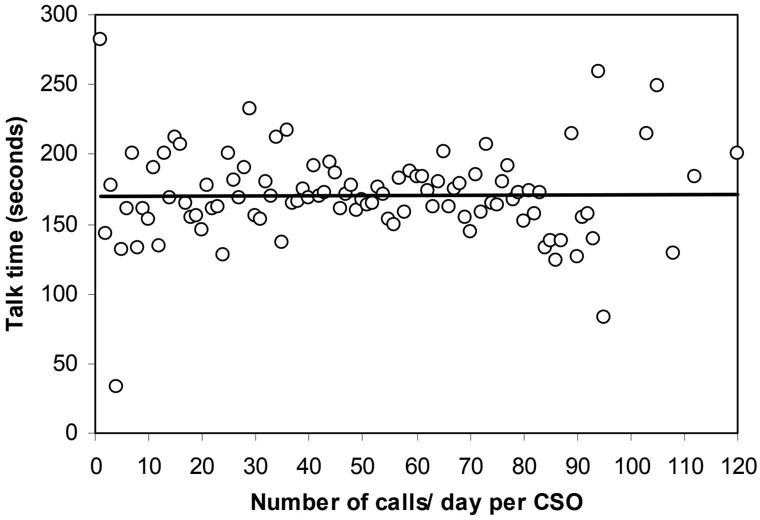

Figure 3.8 Talk time as the function of call volume in Call center A

Figure 3.8 shows that average talk time durations did not vary systematically with the number of calls received by each CSO on each working day. The talk time data in Call center A therefore required no further adjustment. The linear mixed model parameter estimates for effects of air temperature and outdoor air supply rate on talk time adjusted for correlated residuals of repeated measurements is summarized in Table 3.14. The interactions between air temperature and outdoor air supply rate suggested that the slope (estimates) of outdoor air supply rate differ depending on the air temperature (P<0.04). Both residual covariance parameters (AR1) were significant indicating that model variance explained by the repeated measurements was not negligible. Random effect variance estimate was also significant with estimates greater than residual variance (AR1 diagonal), suggesting that most of the variability unaccounted for by the fixed effects is due to subject-to-subject variations.

Table 3.14 Model parameter estimates of talk time data in Call center A

Parameter	Estimates	Statistics
Fixed effects		
Intercept	167	P<0.0001
Air temperature (T)	0.26	ns
Outdoor air supply rate (V)	8.79	P<0.02
Interaction (TxV)	-9.98	P<0.04
Random effects		
AR1 (diagonal)	405	P<0.0001
AR1 (rho)	0.22	P<0.04
Intercept (subjects)	664	P<0.003

Figure 3.9 shows the effects of air temperature and outdoor air supply rate on talk time (estimated marginal means). The significant interaction effects underlined that the main effects of either parameter was significant despite the estimate for air temperature being

non-significant. Reducing air temperature from 24.1°C to 22.6°C at lower outdoor air supply rate improved talk time by approximately 10 seconds or 5.7% ($P<0.004$). Reduction of 9 seconds or 5.1% in talk time was also attained when outdoor air supply rate was increased from 9.6 L/s/p to 21.8 L/s/p at higher air temperature ($P<0.03$).

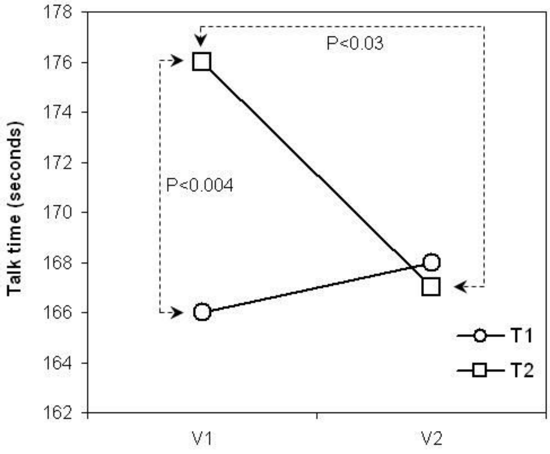

Figure 3.9 Effects of air temperature and outdoor air supply rate on talk time in Call center A
Note: interactions significant at $P<0.04$; mean $T_1 = 22.6$°C, mean $T_2 = 24.1$°C, mean $V_1 = 9.6$ L/s/p, mean $V_2 = 21.8$ L/s/p.

3.5.3. B. Results of talk time analysis of Call center B

The four groups of CSO in Call center B (Sections 1-4) required different amount of time to conclude a call on average due to their nature of tasks and inquiries. Thus, duration of call handling can be adopted as proxy indicator of task difficulty levels, safely assuming that longer duration on the phone indicated a more complex task or inquiry requiring more time and resources to deal with.

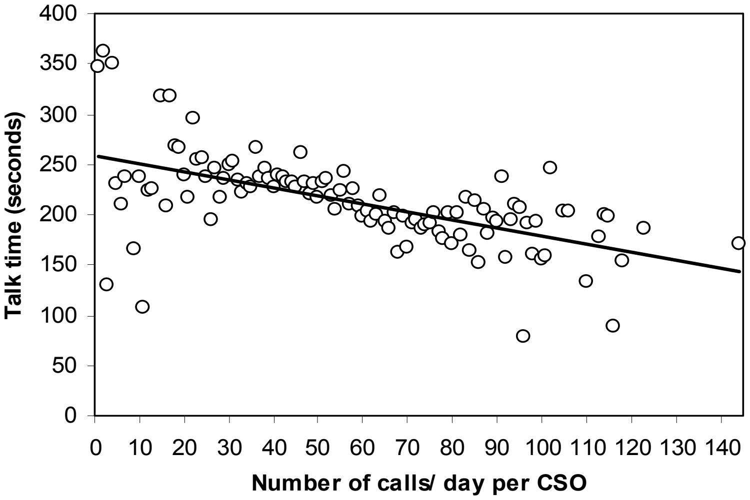

Figure 3.10 Talk time as the function of call volume in Call center B Section 1

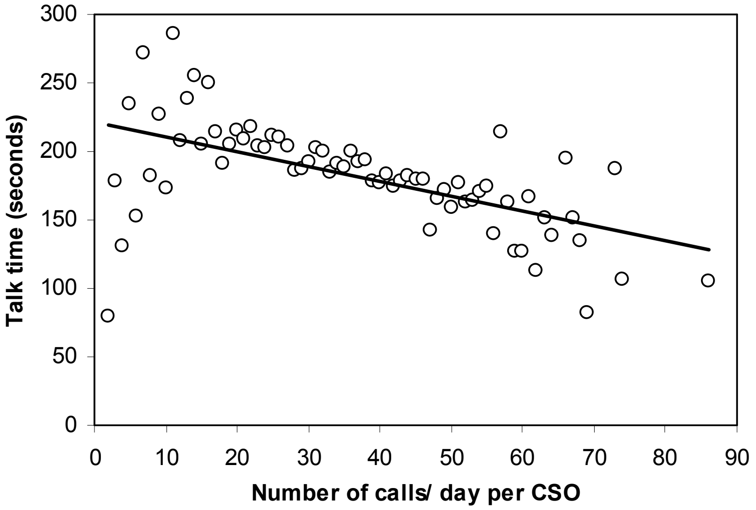

Figure 3.11 Talk time as the function of call volume in Call center B Section 2

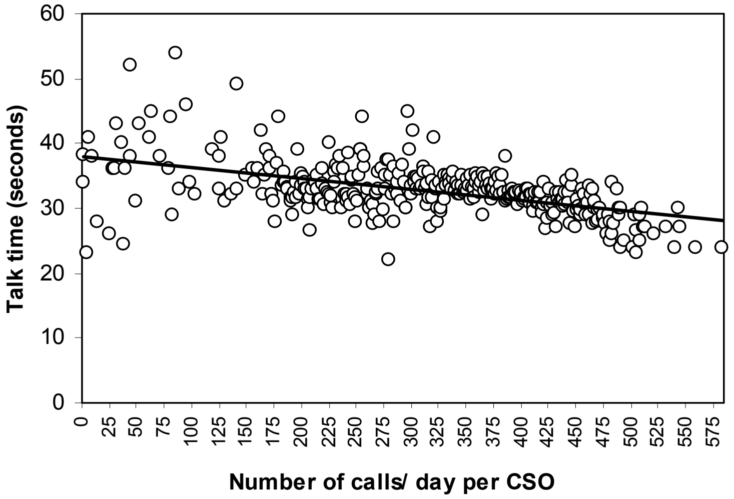

Figure 3.12 Talk time as the function of call volume in Call center B Section 3

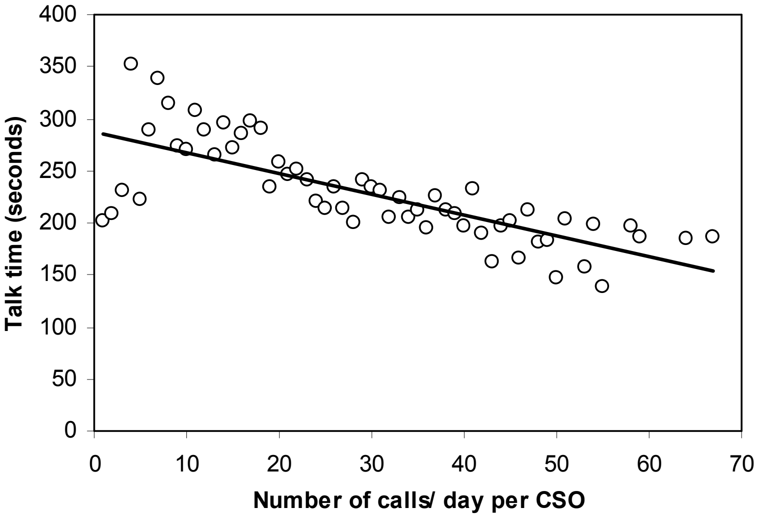

Figure 3.13 Talk time as the function of call volume in Call center B Section 4

Figures 3.10-3.13 unequivocally depict the influence of call volume on CSOs call handling performance with higher number of calls corresponded well with shorter talk time. The most profound effect could be seen in Section 4 where an increase of 10 calls per day could be associated with reduction in talk time by c.a. 16 seconds. The effect of call volume on talk time data thus presented potential confounding in the analysis and needed to be adjusted. The figures also indicated that Section 3 dealt with the least complex tasks, requiring talk time in the margin of c.a. 30-40 seconds, Sections 1 and 4 probably had the most complex tasks requiring talk time within c.a. 150-350 seconds and Section 2 somewhere in between with talk time ranging between 120-250 seconds. The range of talk time of various sections suggested that, as the task grew in complexity, chances were that customers would have a wider range of inquiries leading to greater variance in the data. In terms of call volume, it appeared that each CSO in Section 3 dealt with most number of callers, up to c.a. 550 calls per day, while Sections 2 and 4 handled the least number of calls, c.a. 80 and 70 calls per day respectively.

Summary of mixed model parameters of the four sections in Call center B is presented in Table 3.15. The influence of air temperature and outdoor air supply rate was evident in three sections in Call center B. Section 1 results indicated most profound main effects (P<0.0001) and interactions (P<0.002) of the two parameters on talk time. Effect of interactions of air temperature and outdoor air supply rate on talk time was also significant in Section 3 (P<0.009). On the contrary, there were negligible impacts of both parameters in Sections 2 and 4. Subjects' variability and residual covariance structure of repeated measurements were attributable to variance in the data unexplained by the fixed effects.

Table 3.15 Model parameter estimates of talk time data in Call center B

Parameter	Section 1		Section 2		Section 3		Section 4	
	Estimates	Statistics	Estimates	Statistics	Estimates	Statistics	Estimates	Statistics
Fixed effects								
Intercept	218	P<0.0001	236	P<0.0001	35	P<0.0001	258	P<0.0001
Air temperature (T)	23.61	P<0.0001	-7.87	ns	-0.64	ns	0.59	ns
Outdoor air supply rate (V)	24.26	P<0.0001	1.84	ns	2.23	P<0.0001	-3.62	ns
Interaction (TxV)	-26.81	P<0.002	1.7	ns	-1.77	P<0.009	11.98	ns
Call volume (covariate)	-0.4	P<0.01	-1.24	P<0.0001	-0.01	P<0.0001	-0.7	P<0.04
Random effects								
AR1 (diagonal)	1737	P<0.0001	1115	P<0.0001	8.73	P<0.0001	1819	P<0.0001
AR1 (rho)	0.07	ns	0.1	ns	0.04	ns	0.05	ns
Intercept (subjects)	842	P<0.0001	2015	P<0.003	3.40	P<0.003	3153	P<0.003

Increasing outdoor air supply rate from 5.5 to 11.5 L/s/p at higher air temperature reduced talk time by c.a. 24 seconds or 10.9% (P<0.0001), while increasing air temperature from 22.5°C to 24.5°C at higher outdoor air supply rate reduced talk time by c.a. 23 seconds or 10.5% (P<0.0001) for Section 1 of Call center B (Figure 3.14). The changes were marginally higher for the complex task in comparison to services provided in Call center A. However, other sections in Call center B, namely Sections 2 and 4, did not seem to be affected by any parameters.

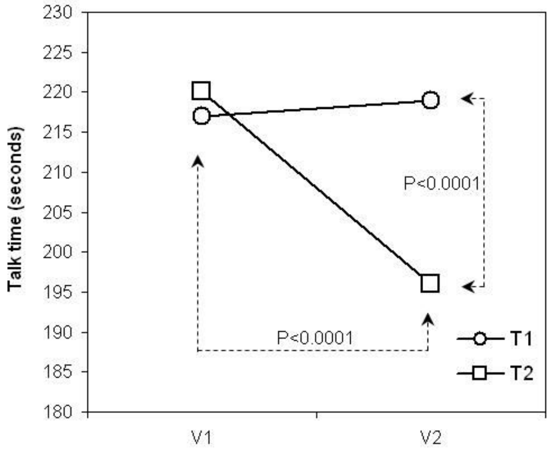

Figure 3.14 Effects of air temperature and outdoor air supply rate on talk time in Call center B Section 1

Note: interactions significant at P<0.002; mean T_1 = 22.5°C, mean T_2 = 24.2°C, mean V_1 = 5.5 L/s/p, mean V_2 = 11.5 L/s/p.

The changes associated with Section 3 were within the range of 1-2 seconds, which at face value may seem rather trivial. However, in the context of short calls, c.a. 30 seconds, the significant improvements may be beneficial to the CSOs' performance especially when they received up to 575 calls on average per day. Increasing outdoor air supply rate from 5.5 to 11.5 L/s/p at higher air temperature reduced talk time by c.a. 2 seconds or 6.0% (P<0.002), while decreasing air temperature from 24.2°C to 22.5°C at lower outdoor air supply rate reduced talk time by c.a. one second or 3.0% change in talk time (P<0.06) (Figure 3.15).

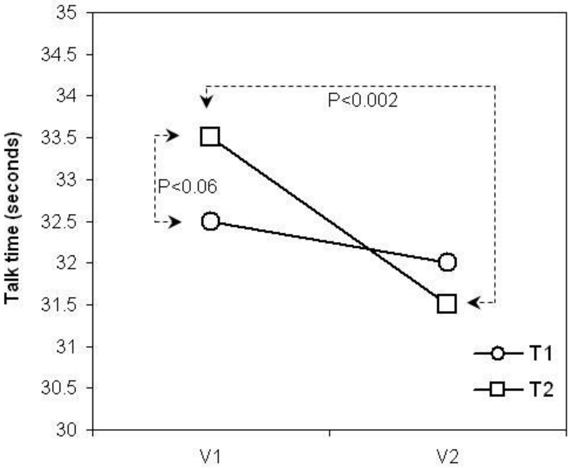

Figure 3.14 Effects of air temperature and outdoor air supply rate on talk time in Call center B Section 3

Note: interactions significant at P<0.009; mean T_1 = 22.5°C, mean T_2 = 24.2°C, mean V_1 = 5.5 L/s/p, mean V_2 = 11.5 L/s/p.

3.5.3. C. Results of talk time analysis of Call center C

Analysis of the CSOs' talk time data in Call center C was not adjusted for call volume since the data was not available to the investigators. Therefore, the data treatment and analysis resembled those of Call center A. Summary of mixed model analysis is shown in Table 3.16. The estimates of interaction effects of air temperature and outdoor air supply rate on talk time approached formal significance (P<0.07) and so was the fixed effects of outdoor air supply rate (P<0.07). The random components of the model also indicated that residual covariance structure related to repeated measurements and subjects' variability contributed to the data variance.

Table 3.16 Model parameter estimates of talk time data in Call center C

Parameter	Estimates	Statistics
Fixed effects		
Intercept	155	P<0.0001
Air temperature (T)	0.89	ns
Outdoor air supply rate (V)	6.08	P<0.07
Interaction (TxV)	8.00	P<0.07
Random effects		
AR1 (diagonal)	735	P<0.0001
AR1 (rho)	0.25	P<0.0001
Intercept (subjects)	1421	P<0.0001

Interactions effects suggested decreasing talk time with higher outdoor air supply rates, an effect profoundly observed at lower air temperature (Figure 3.15). Reductions of 6 and 14 seconds in talk time, or 3.7% (P<0.12) and 8.2% (P<0.003) change, were attained when outdoor air supply rate was increased from 5.2 to 7.5 L/s/p at 22.5°C and 24.2°C respectively. Likewise, increasing air temperature from 22.5°C to 24.2°C shortened talk time by 9 seconds or 5.3% only at lower outdoor air supply rate (5.2 L/s/p) (P<0.02).

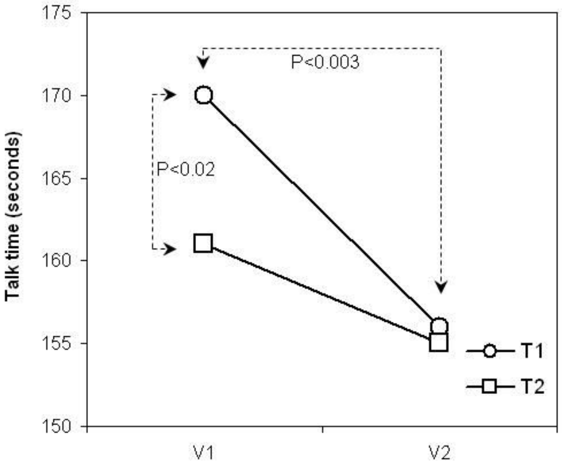

Figure 3.15. Effects of air temperature and outdoor air supply rate on talk time in Call center C

Note: interactions significant at P<0.07, mean T_1 = 22.5°C, mean T_2 = 24.2°C, mean V_1 = 5.2 L/s/p, mean V_2 = 7.5 L/s/p.

3.6. Discussions

The results of present field studies affirm that performance of call center operators, the CSOs, is affected by their thermal environment and the provision of fresh air introduced through the air conditioning system. This further implies that, in tropical context, air conditioning may be one of the key elements for improving office workers performance, and thus, the overall productivity of the company. Improvements of call handling performance and subjective responses, namely perceptions of the indoor environment and intensity of SBS symptoms, can be achieved by changing either parameter within the acceptable ranges stipulated by guidelines. In this regards, defining optimum conditions for performance becomes very crucial from workers' well-being and economical point of views.

Seppänen and Fisk (2004) underlined that one main strategy for improving human responses to the indoor environment is to increase ventilation rate, which decreases the prevalence of SBS symptoms and thus, number of sick leave days. While it is intuitive that increasing ventilation rate will lead to a better or more acceptable air quality and therefore, may lead to higher productivity, the direct impact of introducing higher outdoor air supply rate on worker's performance has only been established recently. Wargocki et al. (2000) demonstrated that increasing outdoor air supply rate to the occupied zones significantly improved component skills such as text typing, addition task and proof-reading. It is thus challenging to translate these indicators of work performance to the real office settings. In the present study, results obtained from three call centers in the tropics suggest that increasing outdoor air supply rate has the most consistent impact on the call handling performance. Moreover, the actual improvements are associated with the operating ranges of outdoor air supply rates following an exponential function (Figure 3.16). The result indicates that performance improvements due to increased outdoor air supply rate diminish exponentially at the higher range of outdoor air supply rates (R^2=0.99). This relationship is in accord with the results from laboratory study reported by Wargocki et al (2000). Their results suggested log-linear functions of text typing (R^2=0.99), addition (R^2=0.97) and proof-reading (R^2=0.98) across outdoor air supply rates ranging from 3, 10 to 30 L/s/p based on aggregates of speed and accuracy indicators. With the presumption that filtration system in each call center has been well-maintained, the positive effects of outdoor air supply rate are also consistent with a previous study conducted in a call center in the temperate climate, which studied the effects of outdoor air supply rates and filtration system (Wargocki et al, 2004). In their study, increased outdoor air supply rate from 2.5 to 25 L/s/p improved (reduced) talk time performance by 6% or equivalent to c.a. 0.3% change per L/s increment, which resembled performance improvement in Call center A. This observation seems to suggest a higher return of improving fresh air provision in the tropical context. Generally, operating range of outdoor air supply rates in office premises in the tropics are much lower than that of temperate regions due to energy usage concerns. It is therefore possible that "starvation" of fresh air provision propagates the effects of increased outdoor air supply rate to a higher order of magnitude.

Defining the associations between performance indicator and subjective responses may be encumbered by the myriad of SBS symptoms and perceptual responses; although some evidences of the potential relationships between ventilation and SBS symptoms, particularly the neurobehavioral-related symptoms, have been reported in recent research. In the field study of a large company, Milton et al (2000) demonstrated higher risk of short-term sick leave (another productivity indicator) in office premises with indoor environmental quality (IEQ) complaints, while Wargocki et al (2004) reported the decrease of several SBS symptoms, namely nose irritation and aching eyes, perceived better office cleanliness and general feeling, when outdoor air supply rate was increased, in parallel with improved talk time. In the field laboratory study, improvement strategy by increasing outdoor air supply rate significantly reduced the difficulty to think clearly and lowered intensity of fatigue (Wargocki et al, 2000). Also, based on the preliminary data from the present study, Tham et al (2003) reported a 19.5% reduction of headache intensity and 13.2% reduction in difficulty to think when outdoor air supply rates was increased by approximately 2.3 times. Other than these findings, evidence supporting possible causal links between subjective responses and work performance is subtle and hard to find. Considering the subjective responses with similar underlying mechanisms as a latent variable or a principal component may yield stronger and more consistent subjective response, which could result in better correlation with the performance indicator. Further analysis on the subjective responses have showed clusters of coherent data (subjective factor) capable of explaining up to 75% data variance cumulatively, with the neurobehavioral-related symptoms identified as the subjective factor that offers the highest explanation of the variance, c.a. 30% (Willem and Tham, 2004).

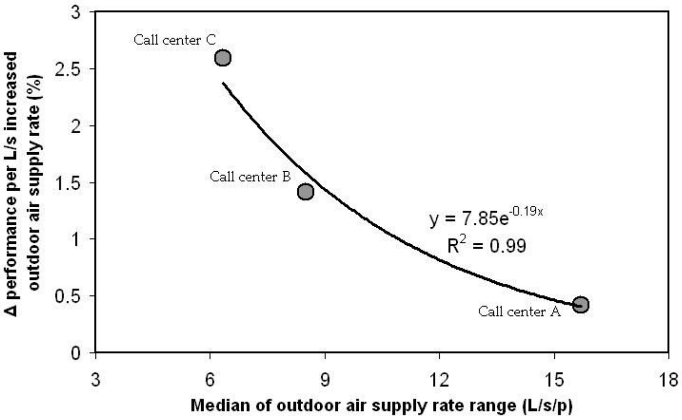

Figure 3.16 Changes in performance as the function of outdoor air supply rates in three call centers

The approach has successfully reduced the complexity arising from the vast number of questions in the survey. Subsequent analysis on the factor scores has further revealed the strong influence of outdoor air supply rate on subjective responses, which is consistent with the effects on performance. In Call center A, higher outdoor air supply rate significantly reduced SF neuro-prod indicating lower intensity of neurobehavioral-related symptoms and better self-assessed productivity, which would irrefutably lead to better performance as evident above. In Call center B Section 1, increased outdoor air supply rate was related to lower SF dry-breathsymp, lower SF odor-iritn and better SF comf-aq, all of which could be beneficial to workers' performance. In addition to positive influence of outdoor air supply rate on SF comf-aq, changing outdoor air supply rate seemed to have profound influence over SF therm-coldsymp in Call center B Section 3 and Call center C. Overall, the better perceptions and lower intensity of irritation and SBS symptoms at higher outdoor air supply rate were indicative of improvements of work performance.

Effects of air temperature on talk time, however, were not in the same direction of change across the three call centers. In Call center A and Call center B Section 3, decreasing air temperature reduced talk time by 5.7% and 3.0%, respectively, while in Call center C and Call center B Section 1, the same intervention increased talk time by 5.3% and 10.5%, respectively. Results of SF scores analysis generally suggested higher SF therm-coldsymp at higher air temperature indicating increased perceived air warmness, humidity and stuffiness but lower intensity of cold hand and cold feet symptoms. The effects could potentially explain the significant effects of air temperature on talk time performance in Call center A and Call center B Section 3. In Call center A, increase air temperature also elevated the intensity of neurobehavioral-related symptoms (SF neuro-symp) and worsened the general perceptions of indoor environmental quality (SF ieq). These adverse effects seemed to overcome the positive outcome of lower intensity of dryness and breathing-related symptoms (SF dry-breathsymp) at higher air temperature. Occupants in Call center C perceived thermal comfort and air quality as better with higher air temperature. This preference was consistent with the improvement of performance with increased air temperature. There was no apparent explanation for the improved performance in Call center B Section 1 with increased air temperature, which elevated both SF therm-coldsymp and SF odor-iritn, indicating worsened perceptions. Nevertheless, higher SF therm-coldsymp also indicated lower intensity of cold hand and cold feet symptoms. Referring to the analysis of individual responses of Call center B Section 1, it could be observed that increasing air temperature reduced cold hand and cold feet symptoms by c.a. 25 (40%) and 33 (52%) on the 0-100 scale, the most of the four sections in Call center B. Understanding the nature of work of this group of CSOs might further explain the reason for the improvement with increasing air temperature. In this section, CSOs received inquiries related to billing statements, charges and notices that were sent earlier to the customers' address. During each call, the CSO would have to first retrieve relevant database related to the customer inquiries and sometimes, to recalculate the bills through numeric pad or calculators. Although the amount of time spent on multitasking between conversing with customer and typing entries through computer keyboard was not recorded, these activities must have taken a substantial amount of time within the average talk time of c.a. 210 seconds. Wyon and Wargocki (2005) summarized in their review that "cold conditions lower finger temperature and so have a negative effect on manual dexterity". Improved cold hand and cold feet symptoms at higher air temperature may indicate better manual dexterity required in inputting information through the computer keyboard and thus, shortened the talk time. The fact that changing air temperature in one direction, i.e. increase or decrease, resulted in opposite impacts on call handling performance in two sections of the same call center (Sections 1 and 3) demonstrates that optimum conditions for performance in one group or task may not be applicable to others within the same premise.

Figure 3.17 depicts the comparison between calculated predicted mean vote (PMV) and the measured thermal sensation ratings from occupants in the three call centers. The calculated votes tend to predict thermal sensation slightly warmer than those rated by occupants. Major discrepancies could be observed at higher air temperature settings in Call centers B and C where occupants rated a much lower thermal sensation, suggesting that air temperature at c.a. 24.5°C did not substantially reduce the cooling sensation without the active means of adjusting the clothing insulation. On the other hand, occupants in Call center A were required to wear their uniform jacket, resulting in a higher clothing insulation. The perceived slightly cool thermal sensations at 22.5°C consistently observed in Call centers B and C could indicate departure from thermal neutrality. Therefore, as the surrogate indicator of ability to maintain body thermal balance, it is plausible that work performance could be adversely affected at the lower air temperature settings. The effects of increased air temperature, although still perceived within the range of slightly cool to neutral, provided slight relieve from the moderate cold stress at 22.5°C and this elevated worker's performance in Call centers B and C. Across the three call centers, thermal comfort parameters resulting in thermal sensation between neutral and slightly cool appeared to be more favourable for performance. In another call center study by Niemela et al (2002), a 5-7% decrease of productivity was reported when air temperature exceeded 25.0°C. However, they did not report subjects' thermal responses and no information on or estimation of thermal sensation was provided. They further associated the significant effects with the fact that some of the thermal conditions were outside the range of thermal neutrality of 21.0-25.0 in summer conditions. Although it is expected and evident that warm discomfort could negative affect productivity, this does not warrant nor imply the negligible impact of conditions within the range for comfort.

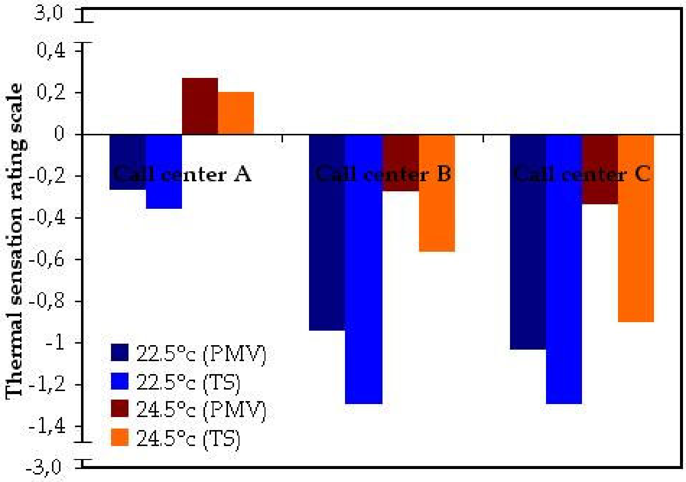

Figure 3.17 Comparisons of predicted PMV and subjects' thermal sensation (TS) votes in the three call centers at 22.5°C and 24.5°C

Interactions effects of air temperature and outdoor air supply rate on talk time were significant across the call centers, indicating that influence of both parameters, while significant when considered singly, was not independent of each other. Increasing outdoor air supply rate consistently occurred at higher air temperature (set-point: 24.5°C), with the exception in Call center C where the same change influenced talk time significantly at lower air temperature (set-point: 22.5°C). This indicates that the possible negative effect of thermal environment at 24.5°C set-point, as shown by SF therm-coldsymp in Call centers A and B and SF comf-aq in Call center C, could be offset by increasing outdoor air supply rate. Effects of air temperature on talk time appeared to be more dominant when outdoor air supply rate was kept at lower settings, with the exception of Section 1 of Call center B where effect of air temperature on talk time occurred at higher outdoor air supply rate. Likewise, looking at the effects of outdoor air supply rates on subjective factors, it is plausible that the preferred lower air temperature setting counterbalanced the adverse effects at lower fresh air provision and thus, improving performance, while at the higher outdoor air supply rates, the effects of increasing air temperature were minimum. Fang et al (1998b) postulated based on a series of laboratory experiments that decrease in the respiratory cooling effect may result in poor perceived air quality, leading to a less acceptable environment and impaired work performance. This postulation is in good agreement with the present results which show improved work performance by decreasing air temperature at lower outdoor air supply rate or, in other words, by adding "the cooling effects".

According to the above discussions, the present study has identified several plausible mechanisms that link air temperature and outdoor air supply rate with the performance of call center operators' as follows:

a) Modifications to room air temperature by c.a. 2.0 °C alter the intensity of neurobehavioral-related symptoms and/ or thermal-related symptoms-and-perceptions, indicating the physiological stress on the central nervous systems and/ or cutaneous responses, respectively, which could eventually lead to the impaired work performance.
b) Increasing outdoor air supply rates by factors of 1.5-2.0 improves neurobehavioral-related, breathing-related and dryness symptoms, reduces perceived odor and irritation; and promotes better perceptions of thermal comfort and acceptability to air quality. Consistent with a), the persistent effects on subjective responses suggests that the central nervous systems and health responses associated with breathing and mucosal systems may be partly responsible in mediating the effects on work performance.

3.7. Economical aspects

3.7.1. Benefits of increasing outdoor air supply rates

The productivity benefit of changing either air temperature or outdoor air supply rates was calculated based on Net Present Value (NPV) method. Singapore's economic indicator was used as input variables. This was available from Singapore Department of Statistics. The aim of this analysis was to estimate the productivity gains of the work performance improvements arising from increased outdoor air supply rate by adjusting for cooling energy costs and other economical parameters. To achieve this, data from a call center was used as the input variables in the analysis. Call center C was selected for the analysis to represent the range of outdoor air supply rates commonly found in the Tropics.

The overall cooling energy consumption was simulated using the DOE2.1B program based on Singapore weather data. The simulation parameters and results were obtained from Tham (1993). It is pertinent to note that the simulated multi-storey building has similar configurations to the building that houses Call center C with building services zone located at the core of the building and the occupied office areas at the perimeters of the building.

Table 3.17 shows the parameters used in the analysis. The calculated total cooling energy at 5.2 and 7.5 L/s/p outdoor air supply rates were 343.9 and 374.3 MWh/ year, respectively, or equivalent to c.a. 8.8% cost increment. The savings parameter assumed that at constant call volume, shorter talk time would mean better efficiency of the workers in handling cases and thus, the total number of workers could be reduced accordingly. The analysis was carried out based on improved talk time of 3.7% and 8.2% reported in section 3.5.3.C and NPV was calculated for a period of ten years.

Table 3.17 Parameters used in the cost-benefit analysis of performance change in Call center C related to increased outdoor air supply rate

Parameters	Amount		Unit (notes)
COSTS			
Cooling energy	343.93		MWh/ year
COP	4.5		
System efficiency	0.9		
Electrical consumptions	84.92		MWh/ year
Increased energy usage	8.8%		(5.2 to 7.2 L/s/p)
Electrical unit cost	0.195		SGD/ kWh
Cost increment	1457		SGD/ year
SAVINGS			
Number of workers	50		
Net salary of workers	1800		SGD/ month
Average talk time/ case	160		seconds
Reduced talk time	3.7	8.2	%
Number of workers required	48	46	
Salary savings	39960	88560	SGD/ year
ECONOMIC FACTORS			
Salary increment*	4		%p.a. for 10 years
Cost increment (inflation)*	1		%p.a. for 10 years
Corporate tax	20		%p.a.
Cost of capital	10		%p.a. return rate

Note: *:Singapore Department of Statistics (data from 2000-2004).

The cost-benefit analysis of improved fresh air provision over 10 years is shown in Tables 3.18 and 3.19 as the result of call handling performance improvements of 3.7 and 8.2%, respectively. The estimated profit arising from altering outdoor air supply rate in the small scale office could potentially yield a benefit within the range of c.a. SGD235,000-SGD532,000 for a period of ten years, which exceeded the costs by a factor of 16 to 36. The estimation is well within the predicted financial benefits from direct impacts of improving indoor environmental conditions suggested by Fisk and Rosenfeld (1997), who recommended a factor of 18 to 47. In addition to the direct estimate of productivity gain, their estimation also included the projected savings from the days of lost work and health care costs due to respiratory illnesses. Assuming that improved outdoor air supply rate in Call center C yielded similar benefits for long term exposure, the present result could be further increased by approximately four times, thus resulting in correspondingly higher economic gains.

3.7.2. Benefits of reducing room air temperature

To demonstrate the productivity gains of changing air temperature, results from work performance analysis of Call center A was used instead of those in Call center C. In the latter call center, increasing air temperature elevated work performance by reducing talk time, which would not incur additional costs by increasing cooling energy. In Call center A, decreasing air temperature from c.a. 24.1°C to 22.6°C improved call handling performance by 5.7%. The cost-benefit analysis was performed using the same parameters reported in section 3.7.1. Based on the energy simulation results, reducing air temperature by c.a. 1.5°C potentially increased cooling energy consumption by c.a. 13.0%. The analysis parameters were listed in Table 3.20 based on the simulated office building from previous analysis.

Table 3.18 Net present value analysis for ten cumulative years for Call center C as results of 3.7% improved performance

Calculation steps	Cumulative year										
	1	2	3	4	5	6	7	8	9	10	11
Salary savings	41558	43221	44950	46748	48617	50562	52585	54688	56876	59151	
Costs	-1472	-1487	-1501	-1516	-1532	-1547	-1562	-1578	-1594	-1610	
Net savings	40087	41734	43448	45231	47086	49015	51022	53110	55282	57541	
Tax		-8017	-8347	-8690	-9046	-9417	-9803	-10204	-10622	-11056	-11508
Net cashflow	40087	33717	35101	36542	38040	39598	41219	42906	44660	46485	-11508
Cost of capital	0,91	0,83	0,75	0,68	0,62	0,56	0,51	0,47	0,42	0,39	0,35
Present values	36442	27865	26372	24958	23620	22352	21152	20016	18940	17922	-4034

Net present value (10 years) : 235606 SGD

Note: Net Present Value (NPV) = the value obtained after adjusting for cash outflows and inflows of a capital investment projected by a chosen target rate of return or cost of capital. A positive NPV indicates that return from investment's cash inflows is in excess of cost of capital.

Table 3.19 Net present value analysis for ten cumulative years for Call center C as results of 8.2% improved performance

Calculation steps	Cumulative year										
	1	2	3	4	5	6	7	8	9	10	11
Salary savings	92102	95786	99618	103603	107747	112057	116539	121200	126048	131090	
Costs	-1472	-1487	-1501	-1516	-1532	-1547	-1562	-1578	-1594	-1610	
Net savings	90631	94300	98117	102086	106215	110510	114977	119623	124455	129481	
Tax		-18126	-18860	-19623	-20417	-21243	-22102	-22995	-23925	-24891	-25896
Net cashflow	90631	76174	79257	82463	85798	89267	92875	96627	100530	104590	-25896
Cost of capital	0,91	0,83	0,75	0,68	0,62	0,56	0,51	0,47	0,42	0,39	0,35
Present values	82391	62954	59547	56323	53274	50389	47659	45077	42635	40324	-9076

Net present value (10 years) : 531496 SGD

Note: Net Present Value (NPV) = the value obtained after adjusting for cash outflows and inflows of a capital investment projected by a chosen target rate of return or cost of capital. A positive NPV indicates that return from investment's cash inflows is in excess of cost of capital.

Results of NPV analysis is shown in Table 3.21. Reducing air temperature by approximately 1.5°C in a small-scale office building could provide productivity gain of more than SGD360,000 in ten years. The benefit of improving thermal environment as such exceeded the cost by a factor of 17, excluding other possible benefits related to better health-related outcomes.

It is obvious that opportunities to increase productivity gain by improving thermal condition and providing more fresh air markedly exceeded the costs for such changes, not to mention that increasing air temperature, which would eventually add to the savings, has also been shown to improve work performance. At this stage, it has been shown that not only plausible relationships between subjective responses and work performance exist as the results of modifying air temperature and outdoor air supply rate, but also the strong economical gain could justify the needs for investigations of the mechanisms involved. Detailed studies on these mechanisms conducted in the Field Environmental Chamber (FEC) are reported and discussed in Chapters 4-6.

Table 3.20 Parameters used in the cost-benefit analysis of performance change in Call center A related to decreased room air temperature

Parameters	Amount	Unit (notes)
COSTS		
Cooling energy	343.93	MWh/ year
COP	4.5	
System efficiency	0.9	
Electrical consumptions	84.92	MWh/ year
Increased energy usage	13.0%	(24.1 to 22.6 °C)
Electrical unit cost	0.195	SGD/ kWh
Cost increment	2153	SGD/ year
SAVINGS		
Number of workers	50	
Net salary of workers	1800	SGD/ month
Average talk time/ case	160	seconds
Reduced talk time	5.7	%
Number of workers required	47	
Salary savings	61560	SGD/ year
ECONOMIC FACTORS		
Salary increment*	4	%p.a. for 10 years
Cost increment (inflation)*	1	%p.a. for 10 years
Corporate tax	20	%p.a.
Cost of capital	10	%p.a. return rate

Note: *:Singapore Department of Statistics (data from 2000-2004).

Table 3.21 Net present value analysis for ten cumulative years for Call center A as results of 5.7% improved performance

Calculation steps	Cumulative year										
	1	2	3	4	5	6	7	8	9	10	11
Salary savings	64022	66583	69247	72016	74897	77893	81009	84249	87619	91124	
Costs	-2174	-2196	-2218	-2240	-2263	-2285	-2308	-2331	-2354	-2378	
Net savings	61848	64387	67029	69776	72635	75608	78701	81918	85265	88746	
Tax		-12370	-12877	-13406	-13955	-14527	-15122	-15740	-16384	-17053	-17749
Net cashflow	61848	52018	54151	56371	58679	61081	63579	66178	68881	71693	-17749
Cost of capital	0,91	0,83	0,75	0,68	0,62	0,56	0,51	0,47	0,42	0,39	0,35
Present values	56226	42990	40685	38502	36435	34479	32626	30872	29212	27641	-6221

Net present value (10 years) : 363446 SGD

Note: Net Present Value (NPV) = the value obtained after adjusting for cash outflows and inflows of a capital investment projected by a chosen target rate of return or cost of capital. A positive NPV indicates that return from investment's cash inflows is in excess of cost of capital.

4

GENERAL METHODS OF THE LABORATORY EXPERIMENTS

The chapter describes the methods used in the series of laboratory experiments. The experiments were designed to study the effects of air temperature and outdoor air supply rates on both environmentally-induced subjective perceptions and physiological responses as the plausible mediating parameters that could lead to changes in the performance of mental tasks (reasoning, creativity, concentration and arousal) and other simulated office works (addition, proof-reading and text-typing).

4.1. Experimental designs

The effects of air temperature and outdoor air supply rate defined the focus of the present study. The experimental conditions of both air temperature and outdoor air supply rate were expanded from two settings in the field studies to three selected conditions in the laboratory experiment, resulting in better evaluation of dose-response relationships between the independent variables and the measured parameters.

The experimental design was planned such that positive carry-over effects or learning, negative carry-over effects or fatigue/ boredom and other external confounding related to individual differences, when present, were minimized or balanced out. This was achieved by using the repeated-measures or within-subjects approach while balancing the experimental conditions introduced to the subjects (Montgomery, 2001). For three experimental conditions, counter-balancing approach was used, resulting in six permutations of possible sequences assigned to different groups of subjects, which would sufficiently balance the intercurrent effects such as familiarization with the procedures and learning on the performance measures. Detailed experimental design for the effects of air temperature and outdoor air supply rate are described in Chapters 5 and 6, respectively.

4.2. Subjects

Ninety-six subjects were selected and recruited from approximately 1100 applicants. These applicants were young adults and students of the National University of Singapore who responded to an online advertisement distributed through the campus intranet. The selection was based on health backgrounds (no chronic illnesses and allergic reactions), smoking habits (non smoker/ never smoker), initial performance test results obtained from the training session (computer literate and understanding of task instructions), interviews (self-motivation), and availability throughout the experimental period (commitment to fulfill attendance requirement). A summary of subjects' characteristics is provided in Table 4.1. The subjects were divided equally into six groups of 16 people with each group having an equivalent number of male and female participants. To satisfy the research ethics requirement, the subjects approved and signed the subjects consent form for their participations, which also specified the objectives and protocols of research. Three female subjects with history of childhood asthma agreed to participate and were included.

Prior to the start of experiments, subjects were given three training sessions within two consecutive weeks with each session lasted for four and a-half hours. They were not informed about the training sessions so that they would attempt to learn and perform the tasks seriously. The subjects wore typical clothing attires for office workers in the tropics, which generally consist of a) for male subjects: light cotton shirt with or without t-shirt, light trouser, men's briefs, light calf-length socks and shoes and b) for female subjects: light dress or blouse with skirt or light trouser, women's briefs, ankle-length socks and ladies shoes. Throughout the experiments, subjects were encouraged to adjust their clothing attires as and when necessary for achieving and maintaining thermal neutrality. In the moderate warm conditions, several subjects were observed removing their shirt and continued working with only light t-shirt. Under the moderate cold stress, the subjects were seen putting on additional clothing such as light sweater, jacket, or an extra shirt.

Table 4.1. Characteristics of 96subjects participating in the present laboratory experiment.

Subjects parameters	Gender	
	Male	Female
Number of subjects	48	48
Age (years)	22±1	21±1
Weight (kg)	68±5	55±3
Height (cm)	170±4	163±4
Calculated BMI	23.5±1.3	20.7±1.4
Mean Dubois Area (m^2)	1.78	1.58
Sleeping hours (hours)	6.0±2.0	6.5±1.5

4.3. Facility

The twin field environmental chamber (FEC) of the National University of Singapore was developed and constructed as part of the infrastructure requirement of the ongoing research program. Each of the chambers has an independent air conditioning system allowing various environmental set-ups to be tested simultaneously. For the purpose of the present study, the field environmental chamber no. 2 was consistently used throughout the setting up and experimental period between June-October 2004.

The longer axis of the room followed the northeast-southwest orientation. In order to minimize the solar radiation and heat conduction through the northeast fenestration area, particularly in the morning sessions, external shading device was installed along the northeast wall and aluminum sheets were fixed onto the outer side of the windowpanes, while movable blinds were installed on the internal side. All the other walls were adjacent to air-conditioned interior spaces, which were kept under isothermal conditions, and thus, thermal transfers were negligible. It is pertinent to note that the southwest facing wall consists of a substantial portion of 7.0mm full height glazing area separating the FEC from the adjoining control room of the FEC. The glazing system was useful for occasional monitoring of subjects activities in the FEC.

The air distribution system of the FEC, which was capable of switching between mixing, displacement, and under-floor ventilation system, adopted a closed air distribution system. For the present study, only mixing ventilation system was used while other modes were turned off throughout the experiment. Investigations for infiltrations to the air distribution system were carried out thoroughly during the FEC commissioning and identified air infiltrations were immediately rectified. Conditioned air was supplied to and exhausted from the FEC through the fully ducted system. In order to maintain total air flow rate to the chamber, the supply air fan was locked at constant frequency of 45Hz. Outdoor air was mixed with the re-circulated air and subsequently passed through the filtration system before being treated by the cooling and heating coil to the required set-point of air temperature and relative humidity, which were controlled by the central automated system. The conventional panel filters were not replaced or maintained within the period of experiments to maintain similar levels of pollution load contributed from the filter. This would ensure that future comparisons of results or pooling of data from the series of experiments would not be confounded by pollution load variations. The age of the used ventilation filter was equivalent c.a. 5 months usage under normal daily operating schedule. The conditioned-air was delivered to the chamber via six concentric air terminal devices with perforated panel at the outlet to ensure uniform air distribution or mixing and minimize the risk of non-uniform turbulence intensity. In controlling the room thermal parameters, room air temperature and relative humidity feedbacks were obtained from five pairs of thermostats for measuring air temperature and relative humidity located near the clusters of workstations and at the center of the room. These thermostats were suspended from the ceiling to occupant's height, i.e. 0.60m from the floor.

Figure 4.1 shows the schematic drawing of room set-up occupied by sixteen subjects in each experimental session. The dimension of the field environmental chamber is approximately 11.20m X 7.50m X 2.70m (length X width X height). The extra space area next to the entrances is designed for storing additional pollution sources required to realistically simulate the normal office pollution load in the study of the effects of outdoor air supply rate. This space was kept empty for during the study on the effects of air temperature. Curtain blinds were used to create the physical separation between the office space and the pollution space. It is worth noting that the indoor air quality in the room was designed to achieve Class 1 indoor air quality stipulated by ASHRAE (2004), i.e. with low contaminant concentration, low sensory-irritation intensity and inoffensive odor. Addition of carpet in the later experiment for outdoor air supply rate, however, may elevate pollution load and consequently other perceptual responses.

Sixteen new identical personal computers with flat screen monitors were set-up for the simulated office works. In view of the higher pollutant emission rates generated by newly operated personal computers, they were continuously operated for approximately 750 hours prior to the experiments. Two identical laser printers were also placed in the room and were kept idle for the present study to simulate normal office pollution load. These printers have been intensively used for more than 2 years in other office settings.

Figure 4.2 shows the general room conditions during the experiment. The field environmental chamber was divided in four sampling zones according to the four clusters of workstations. The illuminance level of the room and its uniformity was kept in accordance to CIBSE Code for interior lighting (CIBSE, 1993), whereas background noise levels were maintained according to ASHRAE recommendation for office settings (ASHRAE, 2003). The transparent sampling tubes for the measurement of gaseous contaminants, the thermistors for air temperature measurement and room thermostats for control system were installed in the room at the specified locations near the workstations of the occupants to have a more precise exposure measurement and control. All measurement equipments and data acquisition systems were kept in the adjoining control room, except for the physiological measurement devices, which must be placed in the room due to the specified tubing length for measurement accuracy.

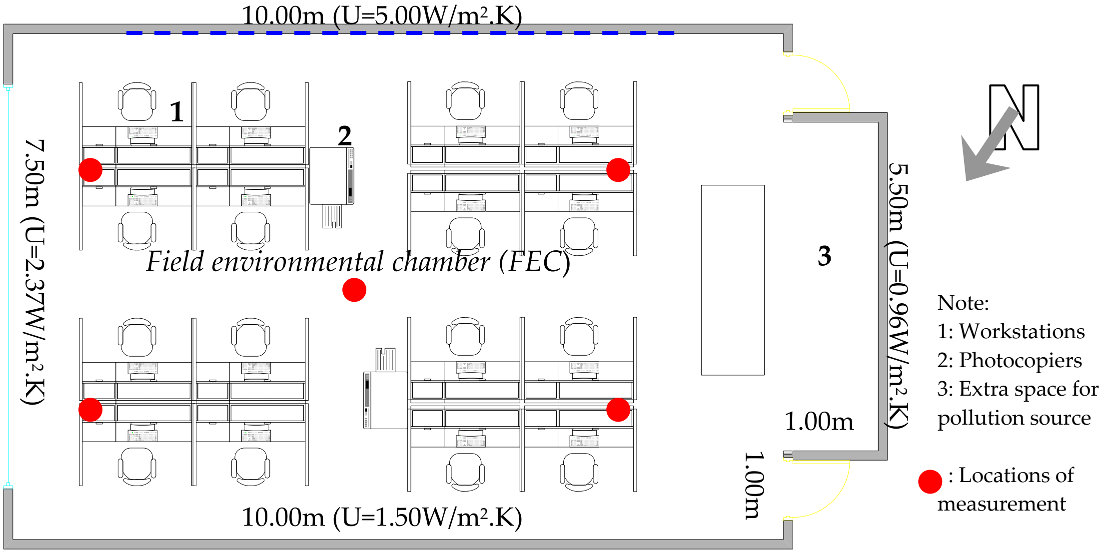

Figure 4.1 Schematic layout of the field environmental chamber

Figure 4.2 General room set-up of the field environmental chamber

4.4. Measurements

4.4.1. Indoor environmental parameters

The experimental parameter, i.e. the room air temperature, was measured continuously. Calibrated AT-series SeMitec™ thermistors with the accuracy level of ±0.3°C registered the air temperature data through the Agilent technologies™ 34970A series data acquisition module to a computer, while Honeywell™ thermostats with an accuracy level of ±2.0% were used to record and control the relative humidity in the FEC. The air velocity levels were measured once during each experimental session using the Kanomax climomaster™ with the accuracy at ±0.05m/s. Data from the physical parameters were collected from five locations in the room, at the vicinity of the clusters of workstations and at the center of the room.

Outdoor air supply rate was calculated based on air exchange rate obtained from SF_6 tracer gas decay profile measured by the Brüel&Kjær™ Multi-gas monitor type 1302 connected to Brüel&Kjær™ Multi-point sampler and doser type 1303 system, and recorded real-time using a computer. The calculation was made following equation 4.1. The same system was used to continuously measure chemical gaseous parameters, namely carbon monoxide (CO), carbon dioxide (CO_2), Formaldehyde (HCHO), and Total Volatile Organic Compounds (TVOC ref. Toluene).

$$\text{OA rate} = [(\ln C_2 - \ln C_1)/\ t] \times V_e \times 0.278 / n \qquad (4.1)$$

where: OA rate= outdoor air supply rate (L/s/p), C_2 & C_1= concentrations of SF_6 at time 2 and time 1 respectively (ppm), t= duration between time 1 and time 2 (hours), V_e= effective room volume/ estimated as: 90% of total room volume (m^3), n= number of occupants in the room.

Two GRIMM™ dust monitor type 1.105 was used as portable instrument to measure dust particulate level at the center of the room. One of the units was used to measure the volumetric weight of dust particulate, while the other was used as particle counter at various sizes. The interval of measurement was one minute and data was collected continuously. The direct sampling of microbial as described in section 3.3.5.4 was not conducted in the laboratory settings with the consideration that the noise generated by the sampling pump and the presence of the instruments could have influence on subjects' perceptions and work performance.

The noise level in the room was measured using the portable sound level meter while the illuminance was measured using Kicke™ digital light meter. Both parameters were measured once near the four clusters of workstations during the break in each experimental session to avoid any distractions to subjects' work.

4.4.2. Subjective responses

Throughout each experimental session, subjects were asked to complete two versions of questionnaire. The longer version was introduced in three surveys, upon entering the FEC, before the session break and prior to the final task of the session. The second version, which is a shorter version of the first one, was introduced twice during c.a. mid-time of the first and second halves of the session.

The first version consisted of perceptual aspects regarding 1) air quality, namely acceptability of air quality, perceived intensity of odor and irritations to the eyes, nose and throat, 2) thermal environment, namely thermal comfort, perceived body and inhaled air thermal sensations, 3) local thermal sensations at forehead, front and back sides of the neck, chest, back, upper arms, lower arms, hands, thighs, calves, and feet, 4) perceived indoor environmental parameters that included air humidness, stuffiness, and stillness, as well as perceived luminous environment, noise level and dustiness; and 5) self-assessed productivity and effort. The same version also required the subjects to indicate the intensity of SBS symptoms, i.e. 1) breathing system-related symptoms, namely nose dryness, level of blocked nose, flu-like symptoms and chest tightness, 2) eyes-related symptoms, such as eyes dryness, eyes aching, and watering eyes, 3) other dryness symptoms, namely throat, mouth, lips, and skin dryness, 4) thermal-related symptoms, such as cold hand and cold feet, 5) neurobehavioral-related symptoms, namely headache, thinking difficulty, dizziness, mood, fatigue, difficulty to concentrate, depression, alertness/ arousal level, and tension. In order to record the changes to subjects' clothing attires throughout the experiment, subjects were asked to provide information about their clothing in the checklist included in the first version of the questionnaires. The second version of the questionnaires consisted of the perceptual aspects on 1) and 2) above. It is also pertinent to note that subjects were not asked about their productivity or level of effort during the first survey (upon entering the FEC) as they have yet to start their tasks. A sample of the questionnaire could be found in Appendix D.

Subjective responses pertaining to perception of air quality and thermal environment were obtained from vertical continuous scale. Dichotomous acceptability of air quality scale used by Gunnarsen and Fanger (1992) and another equivalent scale for thermal comfort were introduced to subjects, who put a tick mark on each scale according to their perception at the moment. Each scale was divided in two regions of 40mm vertical lines contrasting the "acceptable/ comfortable" range to the "unacceptable/ uncomfortable". Perceptions of odor and irritations scales, 50mm in length, were assessed following the six-intensity-level scale first used by Yaglou (1955), while the seven-point (60mm) AHSRAE rating scale was used for both body and inhaled air thermal sensations.

The rest of the perceptual responses and intensity of SBS symptoms were devised using the visual-analog (VA) scale first adopted by Wyon (1992) for evaluation of sub-clinical symptoms and subsequently developed as the measure of intensity of SBS symptoms (Kildesø et al, 1999). The VA scale for assessing local thermal sensations consisted of 60mm continuous horizontal line, while the VA scale for the perceptions of indoor environmental parameters, self-assessed productivity and effort; and intensity of SBS symptoms used 100mm continuous horizontal line. Each scale was marked with two endpoints that represent the extreme points of the subjective response. The subjects were asked to give a tick within the scale according to their immediate perception and symptom intensity during the survey period. GTCO Roll-up™ digitizer was used to convert the distance between a standard endpoint of the scale to point ticked/ marked by the subjects and subsequently transferred and stored the distances in millimeter unit in spreadsheets in a computer.

4.4.3. Physiological responses

4.4.3. A. Cutaneous responses

Two subjects, one male and one female, were randomly selected from each group of subjects for the continuous skin temperature and sweat rate measurements. Prior to the experiments, the twelve selected subjects were briefed about the objective of measurements and the non-invasive procedures in addition to the tasks that they would be performing during each sessions. Brief descriptions of the skin measurements were also included in the subject consent form approved and signed by the subjects before the start of the experiments.

Skin temperatures were measured by calibrated ET-series SeMitec™ thermistors having the accuracy level at ±0.05°C (Figure 4.3). The type thermistor is also commonly used as sensor in digital thermometer and other medical appliances. Thermistors were affixed on the skin surface at five locations using thin dermiform tape: 1) forehead (at the center of forehead), 2) upper arm (c.a. 5cm below the armpit), 3) back (c.a. 15cm below shoulder), 4) hand (upper side of the hand, next to middle finger), and 5) foot (c.a. upper side of the foot, near ankle). In regards to concerns raised by Buono and Ulrich (1999) on elevated temperature of covered skin area, an initial measurement of covered vs uncovered thermistor on the hand surface did not yield significant difference of measured skin temperature. The interval of measurement was 30 seconds. Resistance data was recorded by the Agilent technologies™ 34970A series data acquisition module and subsequently converted into temperature readings. Each thermistor was carefully calibrated within the range of 30-40°C and calibration curve for each thermistor was used to convert measured values registered by the data acquisition system into skin temperature data.

The Q-Sweat™, a simple Trans Epidermal Water Loss (TEWL) device (Figure 4.4), was used to measure the moisture emitted from the skin surface. In principle, the system used room air that was drawn across a desiccant pack, which removed any moisture present in the room air. The dried air subsequently picked up any moisture found in the sweat emitted from the skin. The moisture was captured inside a capsule, where it was transported by airflow to the temperature and humidity measuring sensors. There, an accurate measure of the amount of moisture found within the moving air sample was made. The unit was capable of measuring sweat rate within the range of 0-1000 nl/min at the accuracy level of ±5%. The skin capsule, which covered an area of 5.06 cm^2 or volume of 3.614 cm^3, was fixed onto the skin of the subjects at the inner section of the upper arm with special cloth strap. The skin moisture sampling was carried out continuously to obtain the fluctuations of sweat rate profile across time.

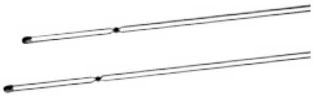

Figure 4.3 Skin thermistors

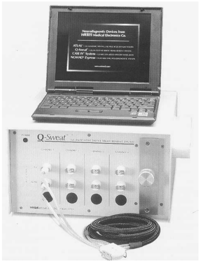

Figure 4.4 Trans Epidermal Water Loss device

4.4.3. B. Salivary biomarkers

Saliva samples were collected from all subjects in the afternoon sessions to avoid confounding with diurnal changes in the biomarkers' level. A non-stimulated passive drool salivary sampling procedure was used. This started with subjects rinsing their mouth with plain drinking water. Subjects were then asked to swallow or clear their mouth of any excessive saliva before they started to accumulate and expel saliva into a carefully labeled sampling tube over a period of 5 minutes, so that the sample represented all the saliva generated by their salivary gland during this period (Figure 4.5). A sampling tube and the cone collector are shown in Figure 4.6 (left). During this period, subjects were not allowed to drink or to swallow their saliva. Afterwards, the tube were tightly sealed, stored in a thermally insulated box with ice packs, and then transported to the laboratory for subsequent processing. The sampling was conducted at the beginning of the session, immediately after subjects entered the chamber, and towards the end of each experimental session, just before subjects left the chamber.

Figure 4.5 A female subject is shown expelling saliva to the sample tube

Before storing the samples in a freezer at -30°C to precipitate mucins, all samples were thawed and then centrifuged at 4°C for 10 minutes at 1500rpm. After the process, the clean and transparent portion of saliva liquid in the upper layer of the sample was withdrawn using a pipette and divided equally into five small vials (Figure 4.6 (right)), each with a capacity of 10ml and labeled according to the initial labeling. The pre-processed samples were then sorted and kept in a storage box labeled according to experimental session and the date and time of sample collection. As the storage period of the sample may influence the stability of the targeted enzyme markers, assays were conducted within three months from the time of sample collection, beyond which the samples were stored at -70°C to be available for sample re-assays.

Figure 4.6 Saliva sampling apparatus (sampling tube and collector-cone (left) and saliva sample in small vial for storage (right)

In the analysis procedures, the frozen samples were first thawed to room temperature and centrifuged and then subjected to immediate analysis. An Enzyme-Linked Immunosorbent

Assay (ELISA) method was used to determine salivary α-amylase, cortisol and secretory IgA (SIgA) concentrations. Each salivary biomarker was quantified by using a specifically designed assay kit, so the analysis procedure for each biomarker was different. Salivary α-amylase was determined using a kinetic immunoassay measurement that utilizes a chromagenic substrate, 2-chloro-p-nitrophenol, to activate spectrophotometrically measurable enzymatic reactions. Salivary cortisol was measured using the competitive immunoassay principle. Cortisol concentration was determined from the established inverse proportional relationship with the amount of bound cortisol peroxidase on a standard microtiter plate (Figure 4.7) after several stages of analysis and incubation. An indirect competitive immunoassay principle was used to capture the full range of salivary SIgA levels. As in Cortisol detection, SIgA concentration was determined from the inverse proportional relationship with the bound conjugate peroxidase on a standard microtiter plate after several stages of analysis and incubation. SIgA analysis as an indicator of immune system response (immunoglobulin level) was only carried out for experimental sessions examining the effects of outdoor air supply rate (Chapter 6), due to its expected association with the prevalence and intensity of SBS symptoms.

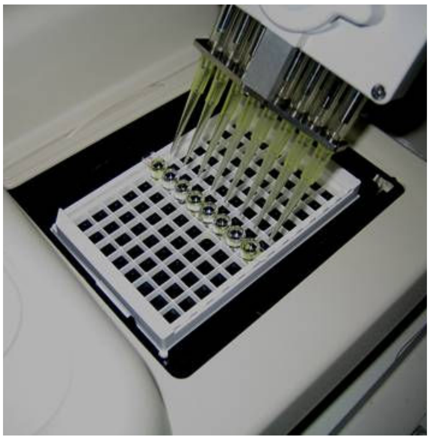

Figure 4.7 Standard microtiter plate

4.4.4. Performance measures

Measuring performance of an office worker is difficult and sometimes controversial due to the complexity and dynamisms of activities and tasks. It is not the purpose and scope of the laboratory experiments to settle any outsized questions, e.g. how thermal environment affects performance of complex office works and activities. Having obtained the knowledge of positive associations between air temperature and/ or outdoor air supply rate in the field studies reported in previous chapter, this laboratory experiment was intended to answer something easier to get at by looking at component skills and measures of performance at subliminal level, e.g. influence of air temperatures on the speed and accuracy of typing performance, search tasks, or thinking creatively – all of which must be understood if relationships between the indoor environmental parameters and work performance are to be established.

Subjects' performance was measured at two levels. Mental performance tests (also called psychological tests in other studies) measured performance at the subliminal level. These tests included logical reasoning, concentration endurance, arousal and creative thinking. More complex tasks simulating the office works were introduced as text typing, proof-reading and arithmetic tasks. The two basic criterion used in characterizing performance were speed and accuracy. The exact measures varied from one task to another as described in detail in the following sections. In addition to these objective measures of performance, self-evaluation of performance was also recorded using the visual analog scales.

4.4.4. A. Mental performance tests

The mental performance tests are described in the following:

1) Logical reasoning
   Two types of logical reasoning tests were used, namely the numerical and alphabetical reasoning. The numerical reasoning (code: RN) was basically the number sequencing tasks. Subjects were presented with rows of two-digit numbers between 11 and 99. Each row consisted of 10 numbers which were arranged in random orders. Subjects were then asked to rearrange them in ascending order in the blanks provided below each row. A total of 44 rows of numbers were available for solving within 8 minutes. In this test, subjects were required to utilize their numerical processing abilities in conjunction with concentration and short-term memory. The speed criterion was number of rows completed per minute, while accuracy was measured from the number of correctly rearranged row of numbers.

   The second type of logical reasoning test, alphabetical reasoning (code RA), was the exercise of transformational grammar (Baddeley, 1968). The test consisted of multiple statements, each of which described either true or false statement about the order of two alphabets in the alphabetical order, e.g. "M is *succeeded by* N in MN" or "R *comes before* Q in QR". Subjects were asked to indicate whether the given statement is "true" (correct statement) or "false" (wrong statement). The pairs of alphabet used in the test were selected in random from A-Z. A total of 192 statements were introduced within the 6 minutes test. The criterion used for speed and accuracy were the number of statements answered per minute and the total number of correct answers, respectively.

2) Concentration endurance (code: CN)
   The mental test was an alternative of search and cancel task inspired by and modified from Brickenkamp and Zillmer's (1998) test for concentration. Subjects were given an A3 size page consisting of 936 characters (26 rows of 36 characters). These characters were mainly three alphabets, i.e. "d", "b" and "p" and each alphabet was either accompanied or unaccompanied with dot(s) above and/or below them. The number of dots associated with the alphabets also varied between single dots to three dots. The subjects were required to identify and cancel (draw a diagonal line across the identified character) all characters of "d" alphabet accompanied by two dots. The rests of the characters included in the test were solely intended as distracters. Subjects scanned the test sheet from the left to the

right and marked on the test page the last character checked when the 6 minutes test duration elapsed. The total number of characters checked per minute was used to determine the speed, while number of missed out "d" alphabet with two dots was used as accuracy measure. Intuitively, the deficits of concentration can be associated with the slow down of processing speed and poor character identifications.

3) Arousal (code: AR)
   A modified Tsai-partington test was devised for testing arousal level of the subjects based on earlier versions introduced by Ammons (1955) and Wyon (1969). Originally known as Trial Making Test (TMT), it was devised for purposes including sequencing ability, mental flexibility, visual search and test of motor function. In this study, subjects were asked to connect/ link c.a. 55 numbers in descending order within 3 minutes. These circled numbers were given in the format of two digits (11 to 99) and arranged within one page such that crossing pathways between lines connecting two nearest numbers were minimized. The total number of links per minute as well as the number of incorrect links (in other words, a number was skipped) were employed as criterion measures for speed and accuracy, respectively. During high arousal level, subjects are expected to perform less than optimum by making more errors but may increase their speed of work. Mental tasks intertwined in office works are generally at the upper range of difficulty levels. In order to simulate the effect of indoor environmental parameters in such situation, the test difficulty level was therefore elevated by asking subjects to relate the numbers in descending manner.

4) Creative thinking (code: CN)
   Open-ended question about use and application of simple objects was devised as creative thinking test. A picture of the object and its description, e.g. an eraser, a ball, pieces of paper, etc, were shown on the top of a page. Subjects then wrote down or sometimes sketched as many as possible the logical use and applications of such object within a period of 12 minutes. Originality of answers benchmarked against all answers from the same group and experimental session were evaluated as the creativity measure of each subject. The probability of occurrence of an answer was calculated by dividing the number of subjects giving the same answer by the total number of subjects. The probability index was then transformed into C-score in bits based on the information theory (Shannon, 1948, Wyon, 1969) given in Equation 4.2.

$$\text{C-score} = \log_2 (1/P) = \log_2 (N/n) \qquad (4.2)$$

   where, C-score=creativity index based on probability of occurrence (bits), P=probability of occurrence, N=total number of subjects participating in session, n=total number of subjects giving the same answers.

4.4.4. B. Simulated office tasks

Three simple but common office-related tasks, namely text typing, proof-reading and numeric addition, were selected to represent the measures of office work performance. Although office works are complex, time dependent, and covering a wide range of intertwined skills and activities, typing, reading and arithmetic abilities are almost always present as part of the performance equation. Each of the tasks involves dual-paradigm performance measures, e.g. text-typing involves attention and manual dexterity (O'Donnell and Eggemeier, 1986). These simulated tasks are described as follows:

1) Text typing (code: TP)
   Subjects re-typed an exact version of the supplied text on a computer using standard Microsoft Office ™ Word 2003 for Windows XP™ in their own pace. All versions of supplied text were based on topics related to general knowledge and common interests obtained and standardized, as necessary, from magazines and internet resources. They were printed on A4 size paper with 12-point Times New Roman font and with double spacing. The length of all texts was designed such that none of the subjects could finish re-typing it within 48 minutes. Two-related measures of speed of typing were used, i.e. number of characters (with spaces) typed per minute and number of words typed per minute. The first provided a better measure of finger dexterity as it represented the number of finger strokes on the computer keyboard, while the later indicated a more complex measure of typing performance involving words recognition and processing, as well as short-term memory. The total number of errors, such as misspellings, inconsistencies to the original text, etc, was manually checked as the measure of accuracy.

2) Proofreading (code: RE)
   An article with intentional errors was read and checked by the subjects within duration of 14 minutes. The types of error were as follows: a) misspelling of words: a common and apparent text error, b) grammatical errors introduced in the context of phrases and sentences, and c) contextual errors: inconsistent or contradictive statements in the context of previous sentences or overall text content. The occurrences of these errors were randomly distributed throughout the text. Subjects were required to identify and underline these errors but not to give any corrections. As the indicator of proof-reading speed, the total number of underlines was used, while the number of unidentified errors in the text provided the measure of proofreading accuracy.

3) Numeric addition (code:AD)
   Double-digit numbers, excluding zeros, were arranged in pairs of single column (one below another). This is a simplified version of earlier version introduced by Wyon et al (1975), who used 5 two-digit number additions. In order to minimize confounding related to individual skill differences, simpler version was used. Subjects added as many as possible the pairs of numbers and wrote the answer directly beneath them during a period of 8 minutes. Two performance measures were used: speed, i.e. total numbers of completed units per minute, and accuracy, i.e. numbers of incorrect answers.

4.4.4. C. Self-evaluated performance

Subjects self-evaluated their productivity level and amount of effort needed from previously completed tasks on the VA scales. This evaluation was included as part of the questionnaire described in section 4.4.2, first introduced in the third survey within experimental session or after more than one hour of exposure and again in the final survey before the subjects completed their working session.

4.5. Procedures

4.5.1. Experimental set-up

The designed experiment for the effects of air temperature was conducted between third week of July and first week of August 2004, while the effects of outdoor air supply rate (with the presence carpet as additional pollution source) were studied between third week of August and first week of September. Before subjects were invited for their first experimental session, careful evaluation of air conditioning system performance was conducted for nearly one month and identified problems such as the inadequate response rate in the automated control, air infiltrations of the FEC, and room thermal stratifications were rectified.

The preparation for the experimental conditions in the morning sessions started from c.a. 8pm the previous evenings after the tracer gas measurement for afternoon sessions was completed. In order to achieve these conditions, the air temperature and relative humidity settings were modified through the control system, while outdoor air supply rates were achieved by manually adjusting the fresh air intake opening. The changes were carefully monitored until the conditions were achieved. At the same time, physical, physiological and performance measurements data were downloaded and performance folders were collected and sorted. The room was then prepared for the next group of subjects. In the morning at c.a. 07.00 am, the room conditions were again checked to ensure the stability from previous night and tracer gas measurement was conducted. After completion of morning sessions, the accumulated pollutants were immediately flushed away to achieve a similar initial level from the start of the next experimental (afternoon) sessions. Within the two-hour interval between the morning and afternoon sessions, the experimental conditions for afternoon sessions were achieved through the same protocols described above.

4.5.2. Preparation of subjects and schedules

Prior to the start of experiments, all participating subjects read and signed the "Patient information sheet and consent form" specified by the Institutional Review Board of the National University of Singapore, which described relevant details regarding their involvements such as duration of study, payment matters, possible discomfort and risk as well as other benefits, in addition to the information about the purpose of the study. The first three sessions attended by subjects were treated as the briefing and training sessions. No additional sessions were needed as preliminary evaluations on their subjective responses and performance indicated that the subjects understood the instructions well and were familiar with the tasks after two sessions. During these sessions, subjects were instructed to avoid using strong perfumes, drinking coffee and other kinds of revitalizing drink; and eating strong and spicy foods, all of which could affect their perceptions and others' who work around them, and also their work performance. They were also encouraged to maintain their normal sleep pattern and durations and to avoid activities that could over-exhaust their energy such as excessive exercise or long travel, prior to the experimental sessions.

The six groups of subjects were evenly divided according to "even" and "odd" numbers/ groups. The groups with odd numbers, i.e. groups 1, 3 and 5, attended morning sessions, whereas even numbered groups, i.e. groups 2, 4 and 6, agreed to attend all their sessions in the afternoon. Morning sessions started from 08.00 am to 12.05 pm and afternoon sessions took place between 02.00 pm and 06.05 pm. Each group came for the sessions twice a week with three days separating the first and second sessions of the week, i.e. Mondays and Thursdays, Tuesdays and Fridays; and Wednesdays and Saturdays. Subjects participated for the same days of week and the same time of day throughout the experiments to eliminate the confounding due to days of week and time of day.

Subjects arrived 10-15 minutes before each session and waited in another adjacent space, hereafter called the waiting area, outside the office. The waiting area was mechanically ventilated with air temperature kept at comfort range, c.a. 22-23°C, and had a presumably high air exchange rate due to direct access to the outdoors via opened windows and doors. While seated in the waiting area, the questionnaire on acceptability of air quality was distributed.

Subjects entered the room one person at a time and immediately assessed the acceptability of air quality, after which each subject settled down at a designated and permanent workstation and continued with the rest of the first questionnaire. For groups of subjects attending afternoon sessions, the first five minutes upon entering the chamber was used concurrently for collecting the saliva sample.

Each experimental session lasted for exactly 245 minutes (4 hours and 5 minutes) during which subjects stayed in the room and performed the performance test batteries in two halves with a ten-minute break in between. Subjects also completed a total of five surveys, i.e at 5th, 72nd, 118th, 168th, and 230th minute into session. A detail schedule is shown in Figure 4.6. The various tasks performed by subjects in the first half (before break) was repeated for a second time after the break with different order of presentation, except for reasoning test. The first reasoning test was number sequencing, whereas the second test was logical (alphabet) reasoning. The order of presentation of the tasks was randomized and care was taken to avoid repeated sequence of any two consecutive tasks between first and second halves.

Within each half of the session, a "walking and collecting pages" task was embedded. The main purpose of this task was to get the subjects to move around and thus, elevate their metabolic rate as is the case in the real office environments. In order to achieve this purpose as convenient and realistic as possible, subjects were asked to stand up and walk around the room while at the same time, they queued to find and collect "missing pages" from their next tasks. The whole process generally took about 3 minutes. The next task commenced after they were all seated and the collected pages were inserted into their task folder.

The subjects were encouraged to actively adjust their clothing attires so that at all times they felt thermally neutral. Carbon dioxide-free mineral water was supplied in the room while biscuits were distributed during the sessions' break. They were encouraged to stay inside the office throughout the experimental session.

It is important to highlight that assessments of acceptability of air quality between the 2nd and 4th surveys was conducted without refreshing their olfactory senses. In other words, their olfactory system may have adapted and therefore, less sensitive to the presence of any distinctive mixture of indoor pollutants. Thus, prior to completing 5th and last survey on acceptability of air quality, perceived odor and irritations, as well as inhaled air thermal sensation, subjects were asked to refresh their olfactory senses at the waiting area with opened windows and doors for c.a. 3 minutes. This was done in two cycles by dividing the group into 2 halves, which went out and refreshed one after the other. Upon reentering the room, subject immediately assessed the air quality and proceeded to the workstation for the final task. The rest of the final questionnaire was completed before subjects went out of the room for refreshing. After the completion of the final task, i.e. numeric addition, the groups of subjects attending afternoon sessions were again asked to donate their saliva into a new and labeled sampling tube.

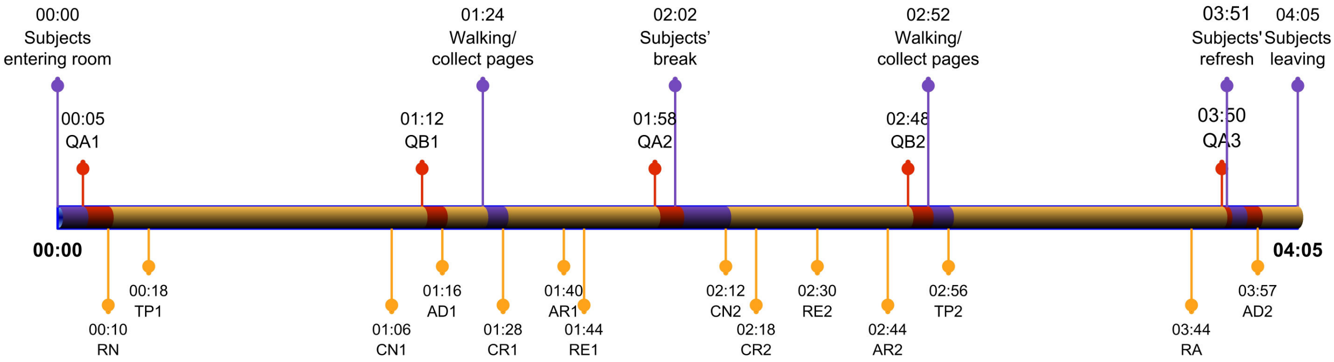

Figure 4.6 Schedule of tasks taking place during one experimental session based on elapsed time. (notes: QA=long questionnaire; QB=short questionnaire; RN=numerical reasoning; TP=text typing; CN=concentration endurance; AD=addition; CR=creative thinking; AR=arousal level; RE=proof-reading; RA=alphabetical reasoning)

4.6. Data analysis

4.6.1. Data structure

All the physical measurement data was sorted and sieved according to experimental sessions and time of day, and then, regrouped according to the experimental conditions. Descriptive statistical analysis was performed on data measured during each experimental session. For the carbon dioxide levels, data from steady-state condition was reported. At the lower outdoor air supply rate, carbon dioxide level at 80% of steady state condition and the extrapolated steady state concentration were reported. The amount of outdoor air provision measured using tracer gas decay-rate method was determined according to section 4.4.1.

Data from skin temperature and sweat rate measurements of each pair of male-female subjects from the six groups were sorted and sieved according to experimental sessions and time of day, and then, regrouped according to experimental conditions. As the records indicated gradual changes across time, averaging over the time of exposure would not provide meaningful interpretations to these time-dependent parameters. Thus, data for later analysis was based on five selected time range, which coincided with the exact time of surveys in the session. The approach ensured that the type of tasks, which may result in varying metabolic rates did not confound the effects of thermal environment on the cutaneous responses. In order to control for gender effects, another data template was prepared by separating male and female subjects.

Likewise, concentrations of salivary α-Amylase, Cortisol and sIgA were sorted according to experimental sessions, and then, regrouped following the experimental conditions. The sorted data was also separated according to sample taken before and after the 4-hour exposures. In order to control for gender effects, another data template was prepared by separating male and female subjects.

The survey data from questionnaires for both longer (1st, 3rd, and 5th surveys) and shorter (2nd and 4th surveys) versions were converted based on the coding specified as follows:

1) Acceptability of air quality scale: from “clearly acceptable”= (1) to “just acceptable/ just unacceptable”= (0) to “clearly unacceptable”= (-1).
2) Perception of odour scale: from “no odor”= (0) to “slight odour”= (1) to “moderate odour”= (2) to “strong odour”= (3) to “very strong odour”= (4) to “overpowering odour”= (5).
3) Irritation scales: from “no irritation”= (0) to “slight irritation”= (1) to “moderate irritation”= (2) to “strong irritation”= (3) to “very strong irritation”= (4) to “overpowering irritation”= (5).
4) Perception of thermal comfort scale: from “very comfortable”= (1) to “just comfortable/ just uncomfortable”= (0) to “very uncomfortable”= (-1).
5) Body thermal sensation scale: from “cold”= (-3) to “cool”= (-2) to “slightly cool”= (-1) to “neutral”= (0) to “slightly warm”= (+1) to “warm”= (+2) to “hot”= (+3).
6) Inhaled air thermal sensation scale: from “cold”= (-3) to “cool”= (-2) to “slightly cool”= (-1) to “neutral”= (0) to “slightly warm”= (+1) to “warm”= (+2) to “hot”= (+3).
7) Local body thermal sensations at:
    i. Forehead: from “warm”= (0) to “cold”= (100)
    ii. Neck (front side): from “warm”= (0) to “cold”= (100)
    iii. Neck (back side): from “warm”= (0) to “cold”= (100)
    iv. Chest: from “warm”= (0) to “cold”= (100)
    v. Back: from “warm”= (0) to “cold”= (100)
    vi. Upper arms: from “warm”= (0) to “cold”= (100)
    vii. Lower arms: from “warm”= (0) to “cold”= (100)

   - viii. Hands: from “warm”= (0) to “cold”= (100)
   - ix. Thighs: from “warm”= (0) to “cold”= (100)
   - x. Calves: from “warm”= (0) to “cold”= (100)
   - xi. Feet: from “warm”= (0) to “cold”= (100)

8) Clothing insulations were calculated by summing up the clo-values of all selected clothing attires. Clo-values were taken from ASHRAE (2001).
9) Visual analog (VA) scales:
   - i. Air humidness: from “too humid”= (0) to “too humid”= (100)
   - ii. Air stuffiness: from “air fresh”= (0) to “air stuffy”= (100)
   - iii. Air stillness: from “high air movement”= (0) to “air still”= (100)
   - iv. Room darkness: from “too bright”= (0) to “too dark”= (100)
   - v. Room noisiness: from “too quiet”= (0) to “too noisy”= (100)
   - vi. Room dustiness: from “office clean”= (0) to “office dusty”= (100)
   - vii. Nose dryness: from “nose running”= (0) to “nose dry”= (100)
   - viii. Intensity of blocked nose: from “nose clear”= (0) to “nose blocked”= (100)
   - ix. Intensity of flu-like symptom: from “no flu-like symptom”= (0) to “flu-like symptom”= (100)
   - x. Throat dryness: from “throat not dry”= (0) to “throat dry”= (100)
   - xi. Mouth dryness: from “mouth not dry”= (0) to “mouth dry”= (100)
   - xii. Lips dryness: from “lips not dry”= (0) to “lips dry”= (100)
   - xiii. Skin dryness: from “skin not dry”= (0) to “skin dry”= (100)
   - xiv. Eyes dryness: from “eyes not dry”= (0) to “eyes dry”= (100)
   - xv. Intensity of aching eyes: from “eyes not aching”= (0) to “eyes aching”= (100)
   - xvi. Intensity of watering eyes: from “eyes not watering”= (0) to “eyes watering”= (100)
   - xvii. Intensity of cold hand: from “hand not cold”= (0) to “cold hand”= (100)
   - xviii. Intensity of cold feet: from “feet not cold”= (0) to “cold feet”= (100)
   - xix. Chest tightness: from “breathing easily”= (0) to “chest tight”= (100)
   - xx. Intensity of headache: from “no headache”= (0) to “severe headache”= (100)
   - xxi. Ability to think clearly: from “head clear”= (0) to “difficult to think”= (100)
   - xxii. Dizziness: from “not dizzy”= (0) to “dizzy”= (100)
   - xxiii. Feeling/ mood: from “feeling good”= (0) to “feeling bad”= (100)
   - xxiv. Level of fatigue: from “rested”= (0) to “tired”= (100)
   - xxv. Ability to concentrate: from “easy to concentrate”= (0) to “difficult to concentrate”= (100)
   - xxvi. Level of depression: from “positive”= (0) to “depressed”= (100)
   - xxvii. Level of arousal: from “alert”= (0) to “sleepy”= (100)
   - xxviii. Level of tension: from “relaxed”= (0) to “tense”= (100)
   - xxix. Self-perceived effort: from “slight effort”= (0) to “strong effort”= (100)
   - xxx. Self-perceived productivity: from “not productive”= (0) to “productive”= (100)

Subjective response on acceptability of air quality was used to estimate the percentage of dissatisfied (Gunnarsen and Fanger, 1992). This index was subsequently used to determined perceived air quality (unit: decipol) and sensory pollution load (unit: olf) based on relationships established by Fanger (1988). As the indexes were more relevant and commonly used in studies involving air pollution loads, they were only used in the evaluation of the effects of outdoor air supply rate. Equations 4.3-4.5 used in the calculations are as follow:

$$PD = \{ e^{(-0.18 - (5.28 \times AQ))} \} / \{ 1 + [e^{(-0.18 - (5.28 \times AQ))}] \} \times 100 \qquad (4.3)$$

$$C = 112 \times \{ [\ln(PD) - 5.98]^{-4} \} \quad (4.4)$$

$$G = 0.1 \times Q \times \Delta C / A \quad (4.5)$$

where, PD = percentage dissatisfied (%), AQ = acceptability of air quality (based on survey results), C = perceived air quality (decipol), G = sensory pollution load (olf/m^2), Q = measured total outdoor air supply rate (L/s), ΔC = difference between perceived air quality indoor and outdoor, A= floor area of FEC (m^2).

Perceptual responses, including the estimated air quality indexes, and intensity of SBS symptoms were sorted according to experimental sessions and time of day, and then, regrouped following the experimental conditions. Principal component analysis further reduced the number of individual parameters to be considered in the subjective responses as it formed coherent groups of subjective parameters. These groups, representing various mechanisms, were called the subjective factors (SF) and for each SF, additional factor scores were derived for each subject, which were again sorted according to the experimental conditions.

Both mental performance tests and simulated office tasks were manually checked for the determined performance criterion. For each task, data was sorted according to experimental sessions, and then, regrouped following the experimental conditions. Differentiation was also made between the first-try and second-try on the same task, except for reasoning tests, so that time-related changes could be compared accordingly. Assuming that any directional changes in performance measures across experimental days indicated subjects' learning (positive direction) or experimental fatigue or boredom (negative direction), data categorized according to experimental sessions were also compared. The later analysis was required to confirm that external factors, such as learning and boredom, did not exist substantially and confound subsequent analysis, particularly when larger data sets were pooled from the various subsets of experiment to test the effects of combined exposures.

4.6.2. Data analysis procedures

Data from physical measurements were subjected to descriptive statistics. Variance and patterns of air temperature, relative humidity and carbon dioxide levels within each experiment were analyzed to ensure no major discrepancies between the actual and designed conditions.

Data from physiological measurements and performance tests as well as their residuals were subjected to Shapiro-Wilks' W test with normality rejection set at $P<0.05$. If discrepancies existed between data and residuals normality tests, further observations or in other words, the eyeball-test, were carried out on the Q-Q probability plot and the data frequency distribution histograms with normal distribution curve to determine which statistical procedures, namely parametric or non parametric, were more suitable or whether data required further transformations. In order to qualify for parametric analysis, homogeneity of variance for each data set was also tested using Levene's statistics on untransformed data with the rejection region at $P<0.05$. Data from subjective responses were analyzed using non-parametric procedures. The more conservative approach to the subjective data was opted since the continuous and VA scales did not, at least, represent interval measurements. In other words, a change of response within a scale did not necessarily inflict the same effect on the subject if the same change were to occur on another part of the same scale.

Except for data from subjective responses and the derived subjective factor scores, which adopted non-parametric procedures, other data with normal distribution and variance homogeneity was analyzed using the general linear model (GLM) ANOVA with repeated measures. Within this analysis, F ratio was adjusted using Greenhouse-Geisser criteria if data violated the sphericity assumption based of Mauchly's test with rejection region at $P<0.05$. Another robust analysis, which combines GLM and variance component procedures, i.e. the MIXED model was also applied in the analysis of performance data to control for systemic variance caused by order of presentation (learning/ boredom), time of day (morning vs afternoon session), time of exposure (first-try vs second-try on the same task), and gender (male vs female), if these effects were present. Paired-t test with Bonferroni adjustments was subsequently performed to test mean differences between any pair-wise combinations from different experimental conditions. Data of subjective responses and those violating the assumptions of normality and homogeneity of variance was analyzed through Friedman ANOVA for related samples, a non-parametric procedure equivalent to the GLM ANOVA. Likewise, paired comparisons were obtained from Wilcoxon matched-pairs signed-ranks test for two related samples. All statistics with the associated P-values were shown for two-tailed test. Data sorted according to time of occurrence within each session was subjected to time-course analysis, which followed the above procedures in testing the main effects of the selected indoor environmental parameter. This involved testing the null hypothesis that the means/ medians did not vary across time of exposure. Throughout the experimental sessions, occasional subjects' absence occurred. After pooling the data according to the experimental conditions, the maximum number of absentees who missed at least one or half of the experimental session (subjects attending half of the session due to other compulsory commitments as university student) was eight persons, thus, retaining the statistical power of the analysis based on the reasonably large number of subjects. Pair-wise and list-wise deletion methods were used in paired and main effect analysis. However, in the analysis using MIXED model, all data was included as the statistical procedures are robust in handling and modeling of data variance at inter- and intra- individual levels disregards of the presence of missing data (Krueger and Tian, 2004).

The next step upon establishing the effects of the experimental conditions on various human responses and performance variables was to explore the associations between these variables to postulate the possible pathways or mechanisms introduced earlier in Chapter 1. Structural equation modeling (SEM) using the Analysis of MOment Structure (AMOS^{TM}) program, which combines path analysis, causal modeling with latent variables and multiple regression models, were applied to fit identifiable and hypothesized models based on observed relationships in the previous analysis and logical theoretical constructs. In the human-indoor environment construct where interactions are often complex and multidimensional, SEM is the only analysis that allows for the complete and simultaneous evaluations of all postulated mechanisms. Details regarding SEM analysis were described in related sections in Chapters 5 and 6.

5

AIR TEMPERATURE EFFECTS ON HUMAN RESPONSES IN LABORATORY EXPERIMENTS

5.1. Introduction

The chapter focuses on the effects of thermal environment with air temperature as the independent variable. Here, the experimental approach is blind intervention study conducted in the laboratory set-up that simulates an office. This experiment explores the direct effects on perceptual responses, physiological measures, and the work output of the tropically acclimatized subjects.

Thermal equilibrium for comfort is generally achieved when a person is able to maintain body thermal neutrality through thermoregulatory controls (Fanger, 1970). This understanding has an enormous implication to the air conditioning practices for the tropics. The crucial questions are how much acclimatization to the warm and humid environment would affect the body physiological responses or thermoregulation and thus, thermal sensation and thermal comfort. The next important question is how these mechanisms in turn affect a person's abilities to perform his/ her work.

Figure 5.1 depicts the mechanisms explored in this chapter. These mechanisms are derived from the basic conceptual model introduced in Chapter 1 supported with the identified pathways in the field studies reported in Chapter 3. Although experimental protocols enable data collection of various intervening variables, it is beyond the scope of the present study to carefully control each preceding variable within the progressive links, i.e. the perceptual and physiological responses. The main independent variable controlled in this study is the room air temperature. Nevertheless, direct effects of air temperature on the intervening variables, i.e. thermal perceptions, SBS symptoms, stress biomarkers, and thermo-physiological responses, can be obtained and subsequently through the structural model analysis, the human-indoor environment interactions are investigated.

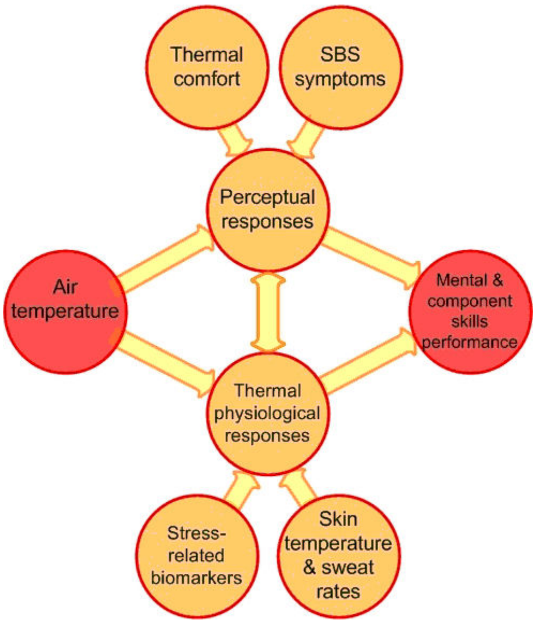

Figure 5.1 Postulated mechanisms by which air temperature affects human responses and work performance

5.2. Objectives and hypotheses

The objectives of this study are as follows:

a) To obtain the knowledge about thermal perceptions and physiological responses of tropically acclimatized subjects on selected thermal conditions.
b) To determine the impacts of selected thermal conditions on mental performance as well as simulated office tasks output of tropically acclimatized subjects.
c) To develop structural model of thermal environment - human performance relationships for tropically acclimatized subjects.

The following lists the main hypotheses tested in this study:

1) Lower room air temperature reduces thermal sensation vote below thermal neutrality and thus causes lower thermal comfort.
2) Lower room air temperature reduces cutaneous temperatures and sweat rate, elevates intensity of SBS symptoms and activates thermal-related (cold) stress indicated by physiological biomarkers.
3) Lower room air temperature improves mental performance and simulated office tasks but adversely affects task requiring manual dexterity, i.e. text-typing.

5.3. Experimental design

5.3.1. Experimental conditions

Three air temperatures were selected as the experimental conditions, ranging from moderate cool to moderate warm. These conditions were within the acceptable range of room air temperature, not uncommon to the actual office environment. The first condition was 20.0°C, representing the moderate cool stress situation commonly encountered in many offices in the tropics. The next condition was 26.0°C, selected to represent the lack of cooling in some offices that may cause moderate warm discomfort. And third condition, the mid-point of the selected range, 23.0°C, was selected to represent a condition that is considerably comfortable. During interventions to room air temperature, the level of relative humidity was kept at 60%Rh and outdoor air supply rate at c.a. 9.0L/s/p. All other indoor environmental parameters were also kept constant according the pre-existing design conditions.

The three air temperature conditions were introduced to the subjects following blind intervention approach. The experiment was fully balanced using the counter-balanced experimental plan to control for any confounding due to order of presentation of conditions and the learning effects (Table 5.1). The six groups of subjects attended their sessions in the same time of day and the same days of week to avoid confounding due to daily or weekly patterns. The experiment was conducted between July-August 2004. A more detailed description of the subjects' participation and tasks during exposure in the Field Environmental Chamber (FEC) could be found under section 4.5.2.

Table 5.1 Counter-balanced experimental design for three air temperatures in order to eliminate confounding due to order of presentation of conditions

Subjects group	Order of exposure		
	1st exposure	2nd exposure	3rd exposure
1	20.0°C	23.0°C	26.0°C
2	26.0°C	23.0°C	20.0°C
3	26.0°C	20.0°C	23.0°C
4	23.0°C	20.0°C	26.0°C
5	23.0°C	26.0°C	20.0°C
6	20.0°C	26.0°C	23.0°C

5.3.2. Other environmental parameters

During this experiment, the outdoor air supply rate was maintained constantly at c.a. 9.0L/s/p or equivalent to c.a. 1.6 ACH. The selected range was in compliance with the ASHRAE 62-1 (2004). No additional pollution sources were added to the pollution chamber during these series of experiment. The background pollution level was generated by subjects (bio-effluents), personal computers and photocopiers (volatile organic compounds) and the air conditioning system (outdoor air contaminants and oxidant). Observations of the carbon dioxide concentration indicated that bio-effluents level reached c.a. 90% of steady state condition after c.a. 200 minutes.

5.4. Results

5.4.1. Indoor environmental parameters

Measured physical parameters, which reflected the climatic set-ups in the office throughout the experimental sessions, are shown in Table 5.2. Average (± standard deviation) values were obtained from five points of continuous measurement in the simulated office. The measurements were conducted during each exposure of the six groups of subjects and each group was exposed once to the same experimental condition. Air velocity, background noise level, and lighting intensity were measured instantaneously, while outdoor air supply rate was measured once for each experimental session using tracer gas methods.

The measurement results indicated relatively small deviations from the designed conditions. The room air velocity also did not vary across the various settings. Likewise, the carbon monoxide and formaldehyde levels at steady state were almost consistent across the three air temperature settings. There was a slightly higher level of carbon dioxide under the moderate cold stress at 20.0°C, which may indicate an increased metabolic rate to maintain the body core temperature. Dust particulate levels gradually increased with higher air temperature. The air temperature, relative humidity and carbon dioxide concentrations outdoors were almost consistent throughout the experiments.

Daily profiles of air temperature are shown in Figure 5.2. The three-degree air temperature difference between experimental conditions was sufficiently maintained although some variations were attributable to the lower air temperature setting, i.e. at 20.0°C. Difficulty to achieve and maintain the air temperature setting at 20.0°C was particularly seen on day-7 afternoon with air temperature reaching c.a. 21.0°C. Another observation of the results showed that on day-6 morning, air temperature dropped below 26.0°C set-point by about 1.0°C and gradually increased to the set-point.

5.4.2. Perceptual responses to the thermal environment

The following sections report the results from perceptual responses of the tropically acclimatized subjects on their thermal environment based on the questionnaires distributed at the 5th, 72nd, 118th, 168th and 230th minute of the experimental sessions.

Table 5.2 Results of physical measurements in the office (FEC) at various experimental conditions. Values are means ±SD of data taken during experimental sessions

Measured parameters	Air temperature settings		
	20.0°C	23.0°C	26.0°C
Indoors			
Air temperature (°C)	**20.24±0.29**	**23.17±0.17**	**26.00±0.27**
Relative humidity (%)	63.9±2.6	64.9±0.3	64.6±0.2
Air velocity (m/s)	0.15±0.04	0.17±0.05	0.15±0.02
Carbon dioxide (ppm)	823±84	799±60	806±49
Carbon monoxide (ppm)	0.16±0.10	0.23±0.13	0.17±0.08
TVOC ref. Toluene (ppm)	2.25±0.21	2.36±0.27	2.24±0.16
Formaldehyde (ppm)	1.45±0.24	1.50±0.24	1.43±0.14
Dust particle PM10.0 (μg/m^3)	7.03±2.10	14.15±2.04	16.16±5.40
Dust particle >1.0μm (particle/l)	27.88±20.89	28.50±20.70	34.57±37.50
Outdoor air supply rate (L/s)	127±7		
Backgroud noise level (dBA)	30±2		
Lighting intensity (lux)	520±10		
Outdoors			
Air temperature (°C)	28.3±3.0	28.8±3.4	27.9±3.1
Relative humidity (%)	82.5±11.0	83.0±6.3	84.6±8.0
Carbon dioxide (ppm)	397±12	403±18	395±11

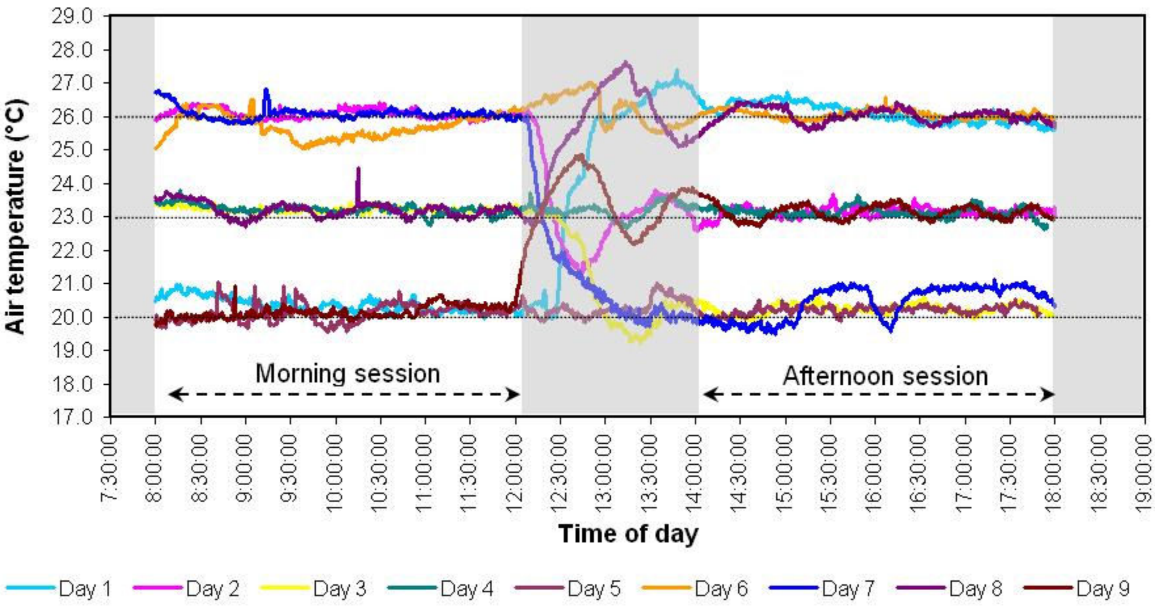

Figure 5.2 Daily air temperature profiles for all experimental sessions

5.4.2. A. Thermal sensation and thermal comfort

Figures 5.3-5.4 show the results of body thermal sensation votes and overall thermal comfort ratings. As anticipated, upon entering the room, 26.0°C was perceived as the least comfortable of the three settings ($P<0.0001$). The same air temperature also yielded a body thermal sensation vote close to "slightly warm", while at 20.0°C, body thermal sensation was between "neutral" and "slightly cool". The subjects were most comfortable at 23.0°C, a condition perceived as almost "neutral" on thermal sensation scale. The immediate effects of air temperature on thermal comfort and body thermal sensation were both significant at $P<0.0001$ with $X^2=28.16$ and $X^2=30.37$, respectively.

Results of the 4-hour exposure indicated that subjects felt least comfortable at 20.0°C or, to be exact, "just uncomfortable" ($P<0.0001$) at the end of exposure. This could be attributable to the thermal sensation vote which was perceived as "cool", which was also the lowest thermal sensation votes across the three air temperature settings ($P<0.0001$). This observation suggests that further departure from thermal neutrality might consequently reduce thermal comfort level of the tropically acclimatized subjects. On the contrary, the tropically acclimatized subjects seemed to be able to adapt and tolerate the moderate warm condition at 26.0°C air temperature after the prolonged exposure, resulting in thermal sensation closer to neutrality and thermal comfort level similar to that of exposure to 23.0°C.

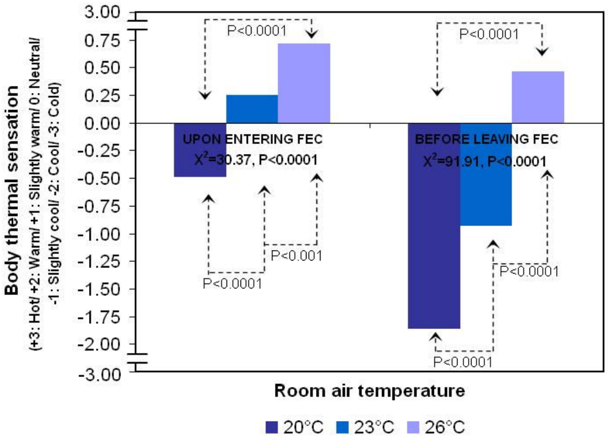

Figure 5.3 Subjects' body thermal sensation before and after the 4-hour exposure as the function of air temperature

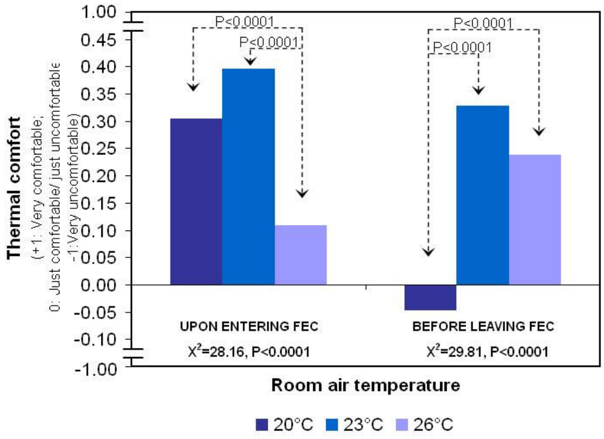

Figure 5.4 Subjects' thermal comfort before and after the 4-hour exposure as the function of air temperature

Figure 5.5 shows the subjective thermal comfort ratings as the function of time of exposure. As subjects entered the office, there was clear a delineation that 26.0°C was the least preferred condition, however as the exposure progressed, they felt gradually more comfortable and after c.a. 2 hours, the thermal comfort level was almost equivalent to that of exposure to 23.0°C, although towards the end of exposure (after 4 hours), there seemed to be a slight reduction of thermal comfort (X^2=38.42, P<0.0001). This slight difference of thermal comfort at the end of exposure between 23.0°C and 26.0°C, however, was not statistically significant (see Figure 5.4). On the other hand, a significant reduction of comfort levels after c.a. 60-minute was observed in the exposure to 20.0°C (P<0.0001). This decreasing trend continued as the exposure progressed (X^2=56.38, P<0.0001). At 23.0°C, subjects were able to maintain their thermal comfort level within the range of c.a. 0.3-0.4 or above "just comfortable". Despite this, the gradual changes over time were observed (X^2=10.37, P<0.035). In the first two-hour exposure, reduction of thermal comfort level was observed (P<0.04), while in the second half of the session or after the session break, subjects tended to be more comfortable (P<0.09).

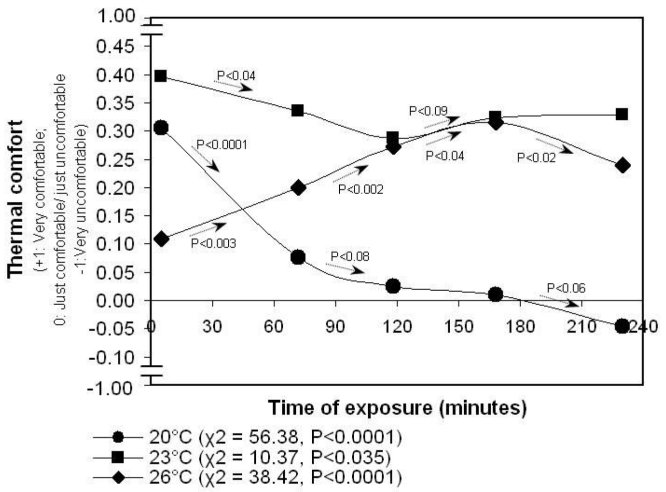

Figure 5.5 Subjects' thermal comfort as the function of time of exposure

A consistent trend of decreasing body thermal sensations across the three air temperatures is depicted in Figure 5.6 (P<0.0001). Most notable reduction in body thermal sensation occurred during the first hour of exposure and most profoundly observed at 20.0°C, which was likely related to the significant reduction of thermal comfort. This effect was a result of the subjects' inability to maintain their body thermal balance, which was evident from skin temperature and sweat rate measurements presented under section 5.4.3.A. While the body thermal sensations were maintained just above thermal neutrality on the warmer side at 26.0°C, the small but gradual change of body thermal sensation in the cooling direction correspondingly improved thermal comfort. Moreover, the reversion of thermal sensation, i.e. subjects felt warmer, during the last hour of exposure to 26.0°C could be responsible for the slight decrease of thermal comfort (see Figure 5.5). At 23.0°C, reductions of body thermal sensation were maintained within "neutral" to "slightly cool" region. The result could indicate that this region of thermal sensation response was generally preferred for comfort by the tropically acclimatized subjects.

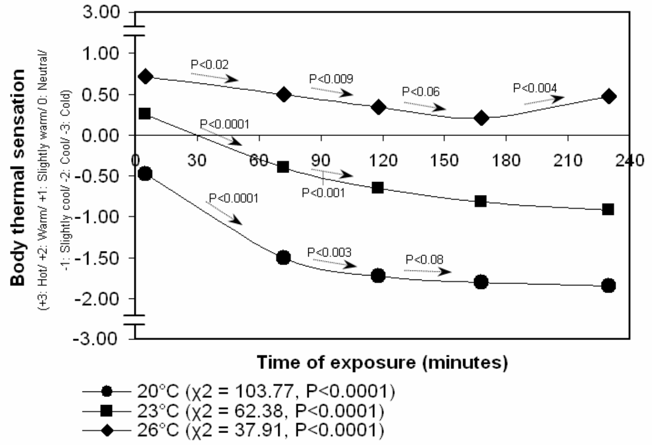

Figure 5.6 Subjects' body thermal sensation as the function of time of exposure

Throughout the experimental sessions, subjects were encouraged to actively adjust their clothing attires in order to maintain thermal neutrality according to their preferences. Figure 5.7 shows that subjects had been adjusting their clothing attires as expected. Throughout the four-hour exposure (Figure 5.7 (right)), the estimated clothing values at 26.0°C remained constant, while at the other settings, subjects gradually increased their clothing insulation. As seen from Figure 5.7 (left), clothing insulation was significantly higher at 20.0°C than the other settings ($P<0.0001$). Subjects' effort to counteract the cooling effects by increasing their clothing insulation became more profound as the exposure proceeded. This effort, however, failed to keep the subjects thermally neutral at 20.0°C and 23.0°C as already mentioned above.

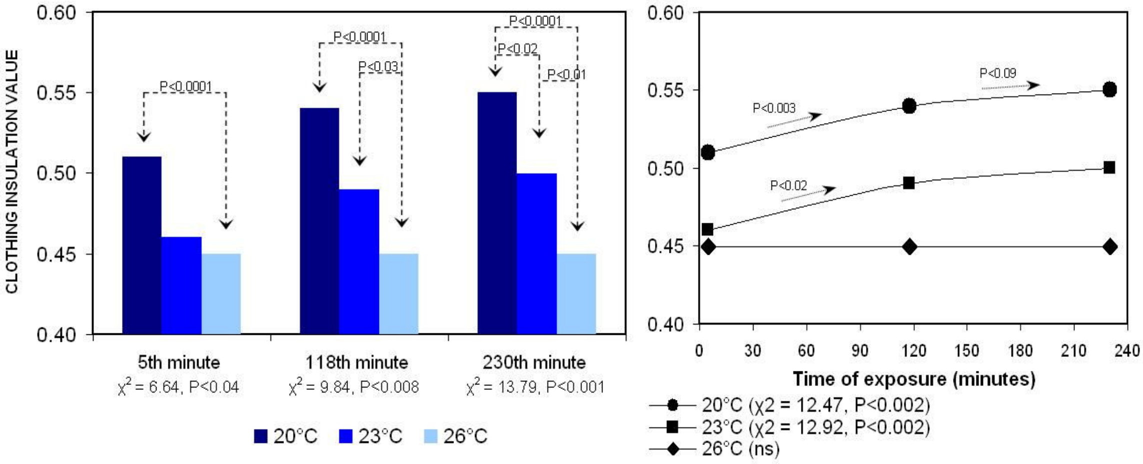

Figure 5.7 Clothing insulation values at different air temperature (left) and across time of exposure (right)

Table 5.3 shows that a three degrees Centigrade change of air temperature within 20.0-26.0°C not only significantly influenced overall thermal comfort and body thermal sensation, but also, was shown to profoundly affect local thermal sensations ($P<0.02$-$P<0.0001$). Marked changes of thermal sensations of the body extremities such as the lower arms, calves, hand and feet across air temperatures were exhibited, suggesting that as air temperature decreased, the body thermoregulatory control would initiate vasoconstriction to protect and stabilize the core temperature and thus, reduce the energy dissipated through extremities of the body. Continuous exposure to 20.0°C reduced thermal sensation in the cooling direction at all locations of the body, implying a substantial cold strain on the subjects. A similar trend but with lesser impact could be applied to subjects' thermal sensation responses at 23.0°C with exceptions for the chest and back of the body, suggesting that thermoregulation processes were able to maintain thermal sensation of the torso and abdomen areas. Continuous exposure in the moderate warm environment at 26.0°C did not impose any thermal strains on subjects as they felt indifferent across time of exposure at various locations of the body.

Based on the positive association between body thermal sensation and thermal comfort, an inverted-U relationship ($R^2=0.92$) could be derived as shown in Figure 5.8. The relationship suggested an optimum thermal comfort at 0.35 or above "just comfortable" on the perceived thermal comfort scale and that, this optimum level was achieved when the tropically acclimatized subjects experienced a thermal sensation of c.a. -0.40 on the ASHRAE thermal sensation rating scale. While it is obvious from previous results that subjects preferred the thermal environment at 23.0°C, the inverted-U shaped relationship between body thermal sensation and thermal comfort indicated that the tropically acclimatized subjects might prefer the moderate warm stress at 26.0°C more than the moderate cool stress at 20.0°C, particularly during long-term exposures.

Table 5.3 Effects of air temperature and exposure time on local cooling sensations

Local cooling sensations (0:Hot - 100: Cold)	Intensity score (effects of air temperature (°C))												Effects of time of exposure		
	1st survey (5')				3rd survey (118')				5th survey (230')						
	20	23	26	P	20	23	26	P	20	23	26	P	20	23	26
Forehead	**48**	**47**	**43**	**<0.02**	**52**	**49**	**45**	**<0.0001**	**53**	**50**	**45**	**<0.0001**	<0.0001	<0.02	ns
Neck (front side)	47	47	44	<0.10	**51**	**49**	**47**	**<0.0001**	**52**	**50**	**45**	**<0.0001**	<0.0001	<0.009	ns
Neck (back side)	**45**	**46**	**43**	**<0.004**	**50**	**47**	**45**	**<0.0001**	**52**	**49**	**45**	**<0.0001**	<0.0001	<0.02	ns
Chest	**48**	**48**	**44**	**<0.001**	**50**	**49**	**45**	**<0.003**	**53**	**50**	**45**	**<0.0001**	<0.0001	ns	ns
Back	**46**	**46**	**43**	**<0.02**	**50**	**47**	**42**	**<0.0001**	**52**	**48**	**42**	**<0.0001**	<0.0001	ns	ns
Upper arms	**51**	**49**	**45**	**<0.0001**	**60**	**51**	**46**	**<0.0001**	**65**	**53**	**47**	**<0.0001**	<0.0001	<0.02	ns
Lower arms	**56**	**52**	**47**	**<0.0001**	**65**	**57**	**48**	**<0.0001**	**73**	**60**	**50**	**<0.0001**	<0.0001	<0.003	ns
Hands	**61**	**55**	**49**	**<0.0001**	**84**	**67**	**51**	**<0.0001**	**87**	**74**	**50**	**<0.0001**	<0.0001	<0.0001	ns
Thighs	**49**	**50**	**45**	**<0.0001**	**59**	**52**	**46**	**<0.0001**	**64**	**54**	**43**	**<0.0001**	<0.0001	<0.0001	ns
Calves	**53**	**50**	**47**	**<0.0001**	**66**	**53**	**48**	**<0.0001**	**73**	**62**	**48**	**<0.0001**	<0.0001	<0.0001	ns
Feet	**57**	**51**	**48**	**<0.0001**	**79**	**62**	**47**	**<0.0001**	**83**	**74**	**48**	**<0.0001**	<0.0001	<0.0001	ns

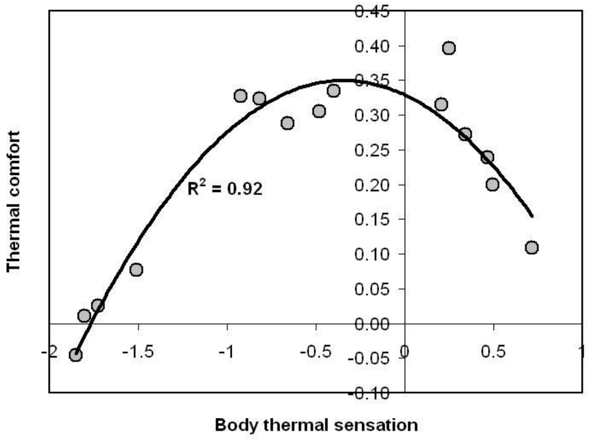

Figure 5.8 Relationship between body thermal sensation and subjects' thermal comfort

5.4.2. B. Respiratory cooling sensation, perceived odor and irritation, and perceived air quality

The effect of air temperature on subjects' acceptability of air quality is shown in Figure 5.9. The result was based on subjects' immediate perception about the room air quality: a) when they first entered the office (before the start of the session) and b) when they re-entered the office (after refreshing outside for the final survey). Effects of air temperature on acceptability vote in both surveys were significant (P<0.0001). A more detailed analysis revealed that subjects' acceptability of air quality did not differ significantly between 20.0 and 23.0°C and acceptability was significantly worst at 26.0°C.

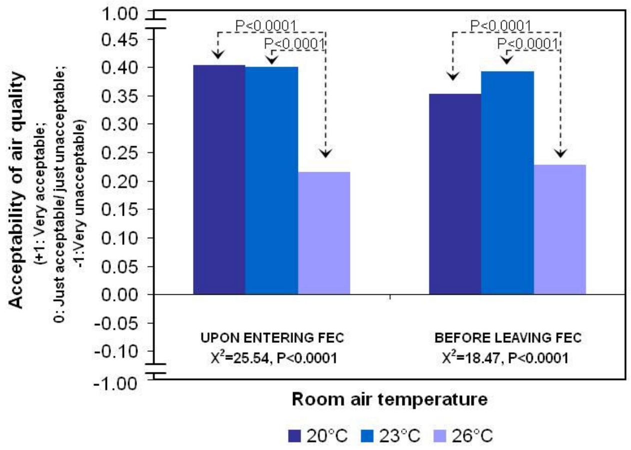

Figure 5.9 Acceptability of air quality at three air temperature upon entering and before leaving (subjects re-enter) the room

Figure 5.10 shows the acceptability of air quality at different air temperatures as the function of exposure duration. Generally, subjects perceived the room air quality to be the most acceptable at 23.0°C and the least at 26.0°C. The acceptability of air quality varied with time only at 26.0°C (P<0.0001). However, pair-wise comparisons indicated several significant and close to formal significance changes between surveys when subjects were exposed to air temperatures of 20.0 and 23.0°C. It should also be underlined that subjects voted the room air quality at 26.0°C to be more and more acceptable as the 4-hour exposure advanced, with a marked improvement in the first hour (P<0.0001). Both improvement of thermal comfort and olfactory adaptation might have contributed to the gradual changes at 26.0°C. After subjects refreshed and re-entered the office, acceptability fell to the level equivalent to their initial votes (P<0.0001), which demonstrated the profound influence of air temperature on the olfactory system.

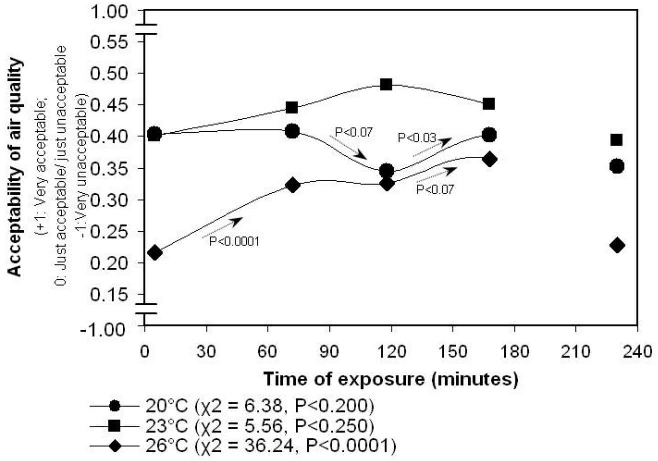

Figure 5.10 Acceptability of air quality as the function of time of exposure

In the previous studies, the air thermal properties such as enthalpy had been shown to affect the cooling of mucous membrane in the upper respiratory tract and subsequently influenced the perceived air quality. In this experiment, the cooling sensation was measured through the inhaled air thermal sensation scale and the results are summarized in Figures 5.11-5.12. The effects of air temperature on the cooling sensation of inspired air seemed to follow the trends observed from the body thermal sensation response. It is, however, important to note a difference that subjects rated the inhaled air thermal sensation after refreshing outside the office. This observation indicates that the effects of respiratory cooling sensation that occurred gradually throughout the experimental session persisted even after refreshing and as anticipated, the effects were obvious at 20.0 and 23.0°C. In other words, the initial perceptions of inhaled air thermal sensation were not repeated during the final survey. At 26.0°C, subjects reported a small but significant increase of thermal sensation of inspired air upon re-entering. These results provide the suggestive evidences that the tropically acclimatized subjects were more sensitive to air temperature closer to the surface temperature of nasal passages in the breathing system.

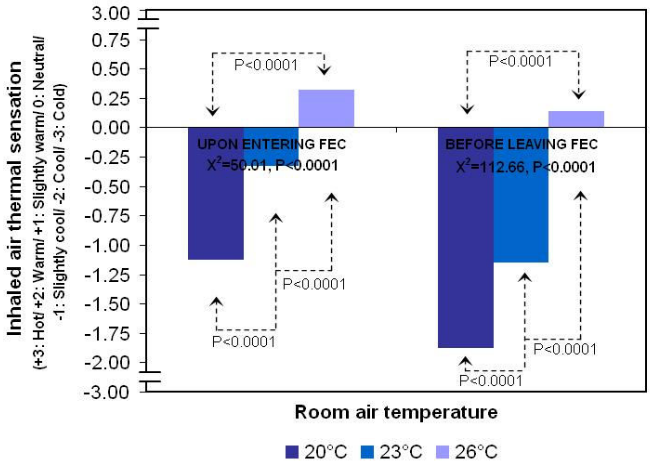

Figure 5.11 Perceived inhaled air thermal sensation as the function of air temperature voted immediately after entering and re-entering the chamber

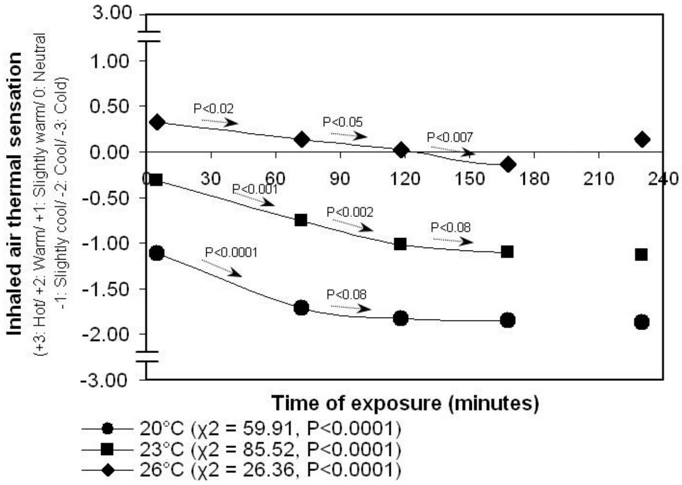

Figure 5.12 Inhaled air thermal sensation as the function of time of exposure

Figure 5.13 shows the effects of air temperature on perceived odor and irritation of the eyes, nose and throat. The perceived odor level and irritation of the eyes, nose and throat were considerably low. Perceived odor votes were kept below “slight odor” and correspondingly, irritation level was below “slight irritation”. Nevertheless, perceived odor was significantly higher during immediate assessments, i.e. when subjects entered the room at beginning and re-entered at the end of session, as compared with subjective votes after one-hour exposure ($P<0.0001$). After a prolonged exposure, the olfactory response was habituated. Analysis on the effects of air temperature on perceived odor during immediate assessments (1st and 5th surveys) ($X^2=10.00$, $P<0.007$) and habituation period (2nd-4th surveys) ($X^2=9.20$, $P<0.01$) showed that subjects perceived higher odor level at 26.0°C, which was plausibly related to higher materials emission and bio-effluents concentration at the higher air temperature.

The 4-hour long exposure tended to elevate intensity of eyes and nose irritation, while no effect was observed on the throat irritation. Intensity of eyes irritation and to a lesser extent the intensity of nose irritation were reduced after subjects refreshed outside the room before the final survey. Further analysis of effects of air temperature on pooled data from immediate exposures (1st and 5th surveys) demonstrated that subjects experienced higher irritation of the nose at 20.0 and 26.0°C ($X^2=6.20$, $P<0.05$) and of the throat at 26.0°C ($X^2=14.67$, $P<0.001$). During habituation (2nd-4th surveys), the irritation effect of the nose persisted at 20.0°C, while at 26.0°C subjects were relieved as they reported lower irritation levels of both the nose and throat ($X^2=10.60$, $P<0.005$). No significant effect of air temperature on the intensity of eyes irritation was observed.

A moderately strong relationship between acceptability of air quality and inhaled air thermal sensation is depicted in Figure 5.14. An inhaled air thermal sensation of -1.00 or “slightly cool” provided the optimum condition for acceptability of air quality. Further departure from this point to the warmer side of the thermal sensation scale gradually decreased the acceptability of the indoor air quality. While moderate warm environment was expected to have an adverse effect on acceptability of air quality, the moderate cool stress at 20.0°C was not. The finding suggests that inhaled air thermal sensation towards the “cool” region, which consequently increases cooling effects to the mucous membrane of the upper respiratory tract, may not always benefit subjective perception of the indoor air quality. The large water vapor and temperature gradients between the inspired air and the surface of the nasal passage at room air temperature of 20.0°C could lead to the overcooling of the mucous membrane and increase dryness that might be less favored by the tropically acclimatized subjects who were physiologically accustomed to hot and humid thermal environment. Despite the observed trends, the tropically acclimatized subjects generally perceived the air temperatures in the range of moderate warm at 26.0°C to moderate cool at 20.0°C within the acceptable region of the acceptability scale.

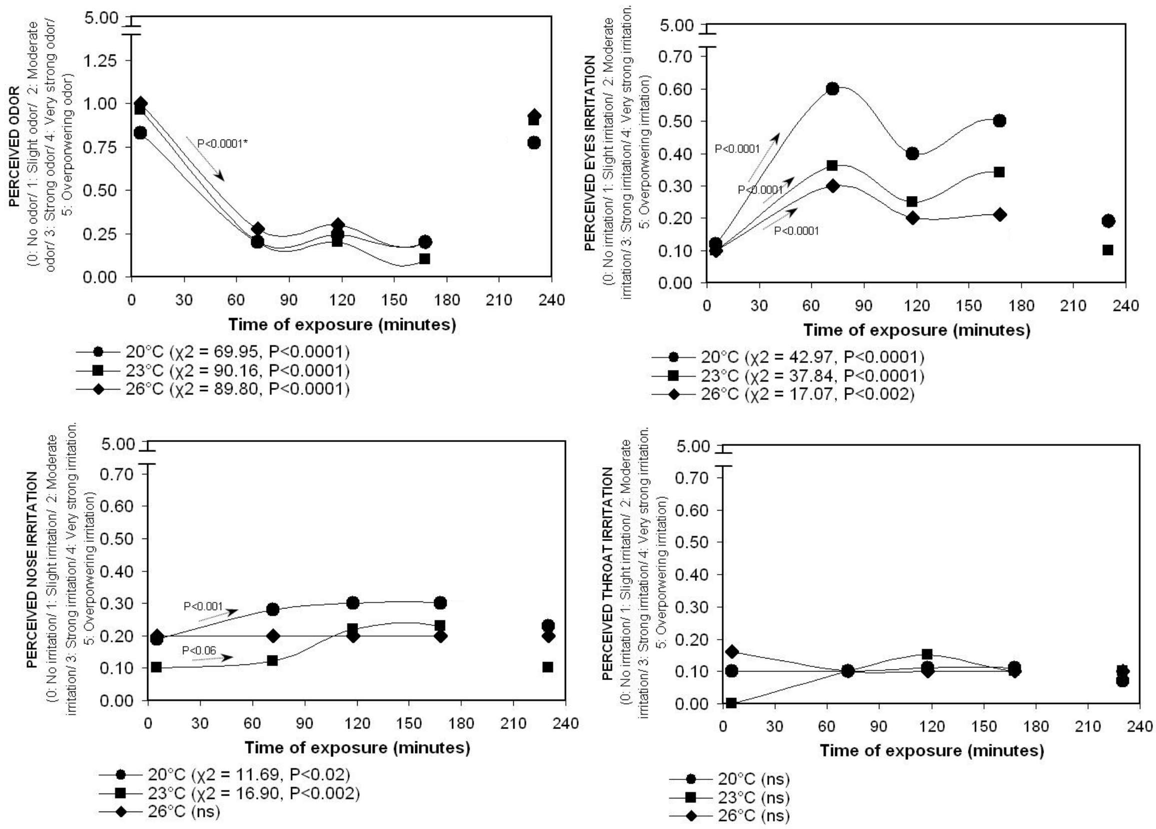

Figure 5.13 Perceived odor and irritation as the function of time of exposure

Note: * = statistics or P-value applicable to all air temperature settings.

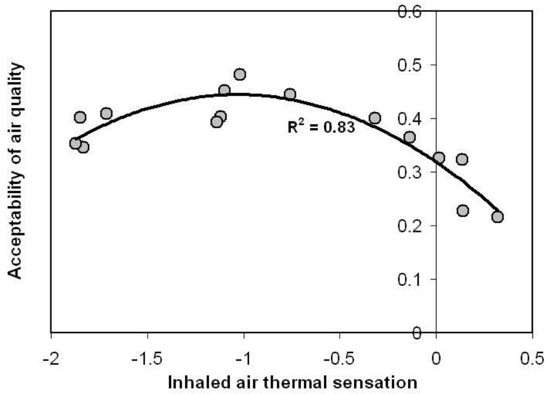

Figure 5.14 Relationship between inhaled air thermal sensation and the acceptability of air quality

5.4.2. C. Perception of indoor environmental conditions, intensity of SBS symptoms and the subjective factors

5.4.2. C.1. Effects of air temperature on perceived indoor environmental conditions

Table 5.4 shows that air temperature significantly affected subjects' perceptions of air stuffiness (P<0.0001) and air movement (P<0.0001) in all surveys throughout the occupation. Subjects perceived the indoor air to be stuffier as air temperature increased upon entering the room. After approximately 2 hours, subjects could not differentiate the air freshness between 20.0°C and 23.0°C, but persistently voted 26.0°C as the stuffiest condition. In parallel to the results of inhaled air thermal sensation response, perception of air stuffiness appeared to be dependent on the thermal environment as was the case for the acceptability of air quality.

Measured air velocity in the office at various air temperatures did not indicate any meaningful changes. The significant effect of air temperature on perceived air movement, particularly at higher air temperature, was therefore suggestive of the influence of subjective preference. It is not uncommon that people acclimatized to the tropical climate prefer a slightly drafty condition to compensate for the hot and humid air. Thus, under the moderate warm stress, subjects might prefer increased convective and evaporative cooling through higher air velocity. Subjects generally considered the office to be dustier at higher air temperature. The effect was significant when subjects first entered the office ($P<0.007$) and again when they re-entered the office at the end of session ($P<0.02$), while similar trend was observed in the middle of the session ($P<0.13$). This result corresponded with the objective measure of dust particulate concentration, which had been shown to increase with air temperature.

5.4.2. C.2. Effects of time of exposure on perceived indoor environmental conditions

Results of time-course analysis of the perceptions of indoor environmental conditions are presented in Table 5.4. Perception of air humidity decreased throughout the 4-hour session, with higher magnitude of change occurring at 20.0°C ($P<0.0001$). The perception of air humidity was related to the ability to evaporate and release moisture and heat energy from the skin surface to the air, which subsequently affected the skin “comfort” level. The result of this experiment also indicated that subjects experienced a decrease of moisture level on the skin over time. Continuous exposure to air temperature at 23.0°C, which resulted in the most optimum acceptability of air quality, significantly reduced perceived air stuffiness ($P<0.02$). Similar trend was not observed at the other settings, however, longer-term exposure at 20.0°C slightly increased perceived stuffiness, while the opposite was seen during exposure to 26.0°C.

Subjects reported the increase of perceived air movement at lower air temperatures, i.e. at 20.0 and 23.0°C, while at 26°C subjects perceived a slight increase of air movement in the middle of the session but a decrease of perceived air movement in the end of the session. There was a parallel trend between the overall thermal comfort vote and the perceived air movement, particularly in moderate warm condition. The changes in perceived air movement were not supported by the physical measurements of air velocity. Also, there was no reason to suspect that air velocity profile fluctuated over the course of the experiment since the air distribution system, particularly the supply air fan speed, was locked and regularly checked. Finally, subjects also perceived the room illuminance level to be higher upon entering the office, which could be related to the fact that the illuminance level within the waiting area was comparatively lower than that of the office, and thus, subjects experienced a brighter environment at first but throughout the working session, their eye receptors became gradually adapted to luminous environment.

Table 5.4 Effects of air temperature and exposure time on perceptions of the indoor environmental parameters

Perceptual responses	Intensity score (effects of air temperature (°C))												Effects of time of exposure (P)		
	1st survey (5')				3rd survey (118')				5th survey (230')						
	20	23	26	P	20	23	26	P	20	23	26	P	20	23	26
Air humidity (0: air too dry - 100: air too humid)	50	50	51	ns	48	47	49	ns	44	48	47	ns	<0.0001	<0.01	<0.04
Air stuffiness (0: air fresh - 100: air stuffy)	**44**	**49**	**62**	**<0.0001**	**49**	**50**	**60**	**<0.0001**	**46**	**43**	**62**	**<0.0001**	ns	<0.02	ns
Air stillness (0: air too drafty - 100: air too still)	**50**	**52**	**63**	**<0.0001**	**49**	**49**	**57**	**<0.0001**	**48**	**50**	**65**	**<0.0001**	ns	<0.002	<0.001
Room illuminance (0: too bright - 100: too dark)	48	47	48	ns	46	47	48	ns	46	46	47	ns	<0.0001	ns	<0.03
Room noisiness (0: too noisy - 100: too quiet)	48	49	47	ns	49	49	43	ns	49	47	46	ns	ns	ns	ns
Room dustiness (0: office clean - 100: office dusty)	**28**	**29**	**37**	**<0.007**	27	30	39	ns	**29**	**34**	**35**	**<0.02**	ns	ns	ns

5.4.2. C.3. Effects of air temperature on the intensity of SBS symptoms

Table 5.5 shows the effects of air temperature on the intensity of various SBS symptoms and the corresponding time-course effects. Intensity of nose running was higher at lower air temperature after c.a. 2-hour exposure (P<0.001) with a similar tendency at the end of the four-hour session. Other analysis of the 3rd survey, conducted during the middle of session, and 5th survey or the last survey, revealed that flu-like symptoms tended to increase as air temperature was lowered at P<0.09 and P<0.08, respectively. The effect on the runny nose symptom agreed well with the reported intensity of flu-like symptoms.

Statistically, air temperature was not identified as the parameter that altered the dryness of the mucous membranes, i.e. mouth, throat and eyes dryness symptoms. There existed, however, the tendency of lower intensity at 23.0°C, most consistently observed for the eyes dryness. Subjects also reported higher intensity of eyes dryness at 20.0°C. There was no apparent explanation to this effect, or thereof, the lack of it. The plausible reason was that subject’s perceptions on mucous membranes dryness were not affected within the range of experimental conditions and thus were overshadowed by the dominant effects of air temperature on thermal sensation responses. It is also pertinent to note that access to water was provided to the subjects, reducing the possibility of experiencing dryness to the mouth and throat. The effects of air temperature the lips and skin dryness were significantly higher at 20.0°C. These body surfaces were in direct contact with the surrounding air and were not protected against dryness effects by mucosal layers. The effects were observed when subjects first entered the room and again, in the end of the session.

Table 5.5 also shows that air temperature did not influence intensity of eyes aching (P<0.50) and watering eyes symptoms (P<0.30). The latter was reported by the subjects at a very low level, i.e. within 6-11 on the 0-100 intensity scale. It is worth noting that effects on eyes aching appeared to be bidirectional. During the first survey, subjects reported higher eyes aching intensity at lower air temperature. However, after 4-hour exposure, the higher intensity was associated with exposure to higher air temperature, which could plausibly be related to the presence of higher dust level at 26.0°C.

As anticipated, subjects experienced the steep increase of intensity of cold hand and feet symptoms as air temperature was lowered. During the first survey, a distinctly higher cold hand and cold feet symptoms was attributable to air temperature setting at 20.0°C in contrast to other air temperature settings. Analysis of surveys conducted in the middle and the end of the session showed that subjects suffered from varying degrees of cold hand (P<0.0001) and cold feet (P<0.0001) at different air temperature, the worst being at 20.0°C (Figures 5.15 (left) and 5.16 (left)). Discernable intensity of symptoms in the exposure to 23.0 and 26.0°C was clearly shown after longer-term exposure (P<0.0001). These results are in excellent agreement with the reported local thermal sensations of the hands and feet, signaling that subjects were under substantial cold strain at 20.0°C.

Further view of the results demonstrated the lack of influence of air temperature on the neurobehavioral-related symptoms. This was, presumably, because the length of exposure of the moderate thermal stressors was not long enough for these symptoms to develop. The intensity scores of these symptoms were considerably low, mostly below c.a. 50 on the scale of 0-100. Air temperature interventions only affected the depression and tension levels. Subjects felt slightly more depressed at 26.0°C upon entering the office (P<0.04) and after working in the office for c.a.2 hours (P<0.07). Elevated tension was observed after the longer exposure (P<0.08).

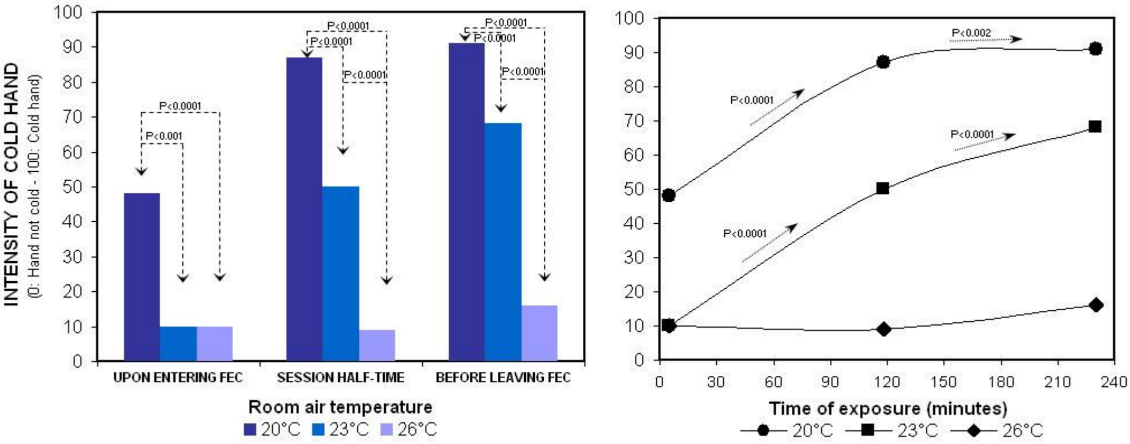

Figure 5.15 Intensity of cold hand symptom as the function of air temperature (left) and the corresponding time-course analysis (right)

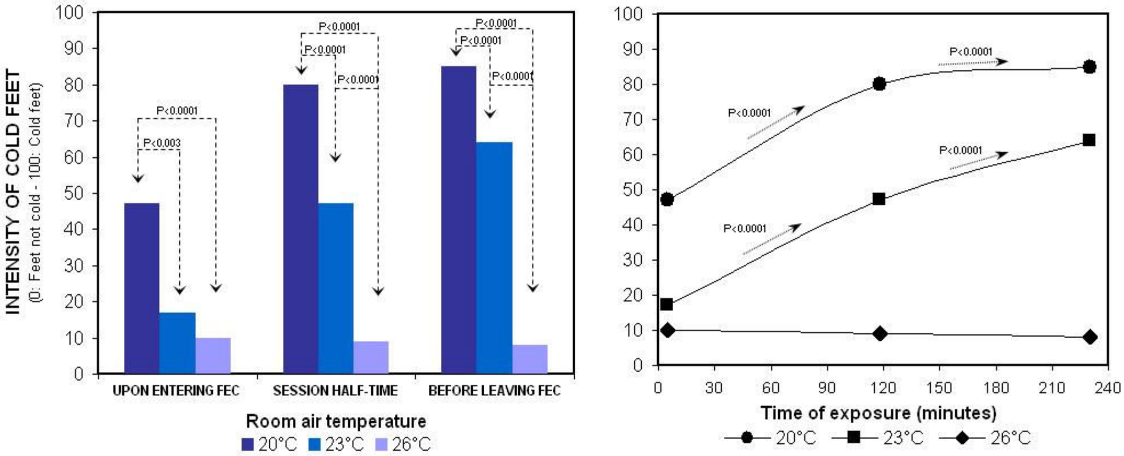

Figure 5.16 Intensity of cold feet symptom as the function of air temperature (left) and the corresponding time-course analysis (right)

5.4.2. C.4. Effects of time of exposure on the intensity of SBS symptoms

Results from time-course analysis of the intensity of SBS symptoms based on three surveys are summarized in Table 5.5. Continuous exposure under moderate cool temperature (20.0°C) significantly lifted the intensity of nose running ($P<0.02$) and flu-like ($P<0.05$) symptoms within the first two-hour of exposure. More prevalent effects of prolonged exposure were observed for the intensity of dryness symptoms. On the mucous membrane dryness symptoms, increases with time occurred at all air temperature settings, except for throat dryness, which approached formal significance only at 23.0°C ($P<0.07$). The significant increases were attributable to continuous exposures during the first half of the session. After the build-up, the magnitude of dryness intensity remained mostly unchanged at 20.0°C while at 23.0 and 26.0°C, subjects rated slightly lower dryness at the end of exposure. Apart from the change of eyes dryness across time, subjects also reported marked increase of eyes aching symptoms, and consistently, this occurred during the first half of the session.

Figures 5.15 (right) and 5.16 (right) show the marked increments of cold hand ($P<0.0001$) and cold feet ($P<0.0001$) symptoms during the first half of the session when subjects were exposed to 20.0 and 23.0°C. The increases continued during the second half, however, with smaller magnitude of changes. At 26.0°C, intensity of both symptoms remained very low and unchanged at c.a. 10 on the 0-100 scale throughout the session. These results are in excellent agreement with earlier findings from the time-course analysis of local cooling sensations of the hands and feet.

Intensity of headache and dizziness, the levels of fatigue, depression, sleepiness and tension, the state of mood/ feeling, as well as the difficulties to think clearly and concentrate strongly increased with time of exposure at all air temperatures ($P<0.06$-$P<0.0001$). These results may indicate that subjects experienced deteriorations of the mental and neurobehavioral-related abilities required for the optimum performance of their tasks. Figure 5.17 shows that subjects experienced very low intensity of headache and dizziness symptoms, which were slightly elevated as they continued to work. Difficulties to think and concentrate also increased with time and subjects seemed to have more difficulty in concentrating than thinking. Sleepiness, negative mood, depression and fatigue worsened with time during the first half of session, and while fatigue continued to increase for the rest of the session, sleepiness and negative mood did not; and depression was reduced during the second half of the session. A trend of decreasing symptoms intensity during the second half of the session under the exposure to 26.0°C was worth noting, although most effects were not statistically significant. Subjects may exert more effort at the start of their working session in dealing with the workloads and the warm environment. Their state of exhaustions could be ruminated in the neurobehavioral-related symptoms, as evident in the results obtained from the half-time survey. After the break and towards the end of their work, subjects might experience greater relieves and this was expressed through a lower depression and the generally indifferent state of feeling/ mood. This observation supports the notion that a better-sustained neurobehavioral state could be achieved when thermal strain was absent in the long-term.

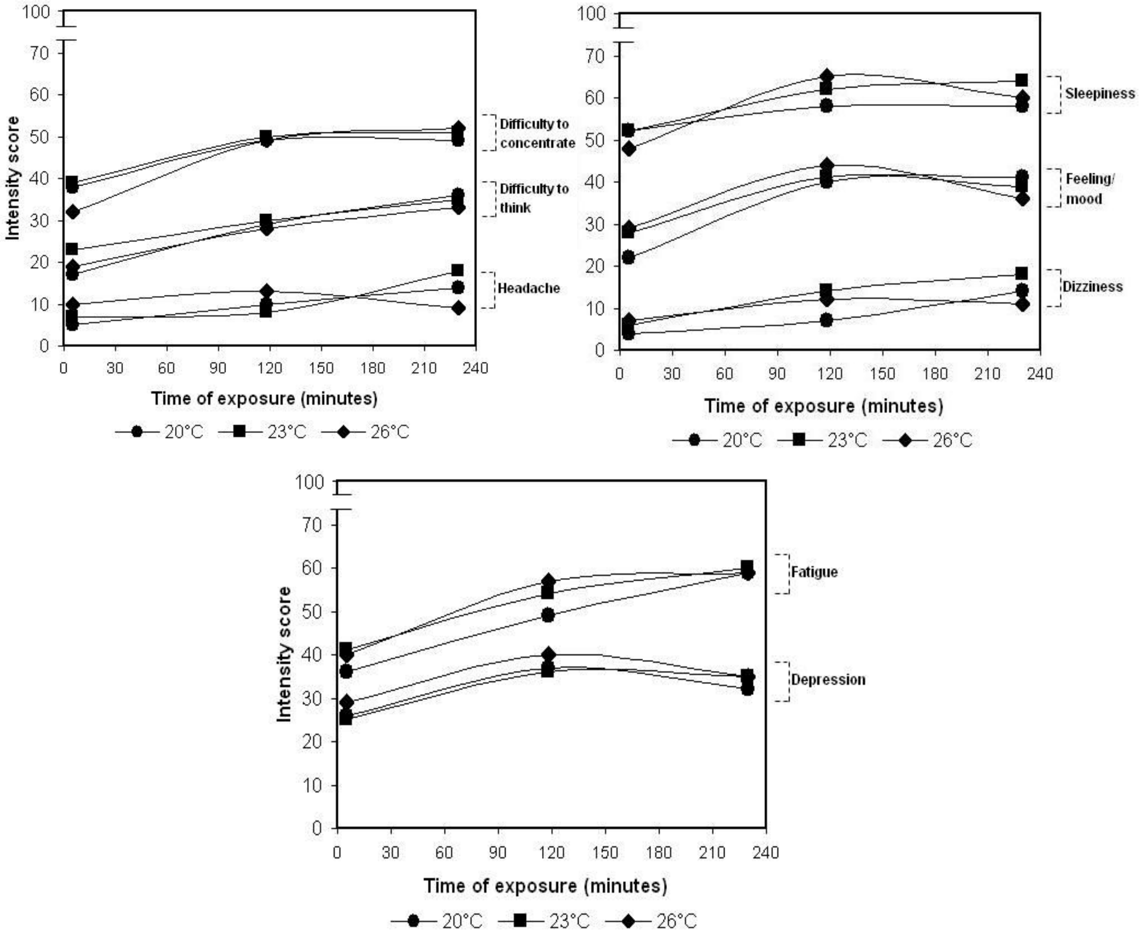

Figure 5.17 Intensity of neurobehavioral-related symptoms as the function of time of exposure, headache-difficulty to think-difficulty to concentrate (top left), dizziness-feeling/mood-sleepiness (top right), depression-fatigue (below)

Table 5.5. Effects of air temperature and exposure time on intensity of SBS symptoms

Intensity of SBS symptoms	Intensity score (effects of air temperature (°C))												Effects of time of exposure		
	1st survey (5')				3rd survey (118')				5th survey (230')						
	20	23	26	P	20	23	26	P	20	23	26	P	20	23	26
Nose dryness (0: nose running – 100: nose dry)	57	53	57	ns	**49**	**59**	**60**	**<0.001**	51	53	58	ns	<0.02	ns	ns
Nose blocked (0: nose clear – 100: nose blocked)	25	17	18	ns	18	22	19	ns	19	23	13	ns	ns	ns	ns
Flu-like symptoms (0: no flu-like symp– 100: flu-like symp)	6	6	8	ns	15	10	8	<0.09	13	7	5	<0.08	<0.05	ns	ns
Throat dryness (0: throat not dry – 100: throat dry)	48	31	35	ns	50	50	55	ns	49	47	51	ns	ns	<0.07	ns
Mouth dryness (0: mouth not dry – 100: mouth dry)	47	42	46	ns	53	56	57	ns	52	51	54	ns	<0.07	<0.002	<0.06
Lips dryness (0: lips not dry – 100: lips dry)	**61**	**50**	**52**	**<0.03**	63	66	66	ns	**70**	**62**	**62**	**<0.02**	<0.02	<0.0001	<0.002
Skin dryness (0: skin not dry – 100: skin dry)	**47**	**37**	**37**	**<0.04**	52	48	49	ns	**53**	**45**	**42**	**<0.001**	<0.009	<0.06	<0.02
Eyes dryness (0: eyes not dry – 100: eyes dry)	39	32	34	ns	55	51	53	ns	56	52	54	ns	<0.002	<0.004	<0.0001
Eyes aching (0: eyes not aching – 100: eyes aching)	23	21	14	ns	51	40	50	ns	37	43	49	ns	<0.0001	<0.005	<0.0001
Watering eyes (0: eyes not watering – 100: eyes watering)	7	6	8	ns	10	7	8	ns	11	8	6	ns	ns	ns	ns
Cold hand (0: hand not cold – 100: hand cold)	**48**	**10**	**10**	**<0.0001**	**87**	**50**	**9**	**<0.0001**	**91**	**68**	**16**	**<0.0001**	<0.0001	<0.0001	ns
Cold feet (0: feet not cold – 100: feet cold)	**47**	**17**	**10**	**<0.002**	**80**	**47**	**9**	**<0.0001**	**85**	**64**	**8**	**<0.0001**	<0.0001	<0.0001	ns
Chest tightness (0: breathing easily – 100: chest tight)	17	13	20	ns	20	22	15	ns	24	19	17	ns	ns	ns	ns
Headache (0: no headache – 100: severe headache)	5	7	10	ns	10	8	13	ns	14	18	9	ns	<0.002	<0.007	ns
Difficulty to think (0: head clear – 100: difficult to think)	17	23	19	ns	29	30	28	ns	36	35	33	ns	<0.0001	<0.02	<0.0001
Dizziness (0: not dizzy – 100: dizzy)	4	6	7	ns	7	14	12	ns	14	18	11	ns	<0.002	<0.03	<0.002
Feeling/ mood (0: feeling good – 100: feeling bad)	22	28	29	ns	40	41	44	ns	41	39	36	ns	<0.0001	<0.006	<0.0001
Fatigue (0: rested – 100: tired)	36	41	40	ns	49	54	57	ns	59	60	59	ns	<0.0001	<0.0001	<0.0001
Difficulty to concentrate (0: easy to concentrate – 100: difficult to concentrate)	38	39	32	ns	49	50	49	ns	49	51	52	ns	<0.0001	<0.0001	<0.0001
Depression (0: positive – 100: depressed)	**26**	**25**	**29**	**<0.04**	37	36	40	<0.07	32	35	35	ns	<0.001	<0.0001	<0.002
Sleepiness (0: alert – 100: sleepy)	52	52	48	ns	58	62	65	ns	58	64	60	ns	<0.0001	<0.001	<0.0001
Tension (0: relaxed – 100: tensed)	29	30	26	ns	33	33	35	<0.08	32	34	37	ns	<0.02	<0.06	<0.003

5.4.2. C.5. Subjective factors (principal component analysis)

The principal component analysis was performed on the survey data to better understand the perceptual constructs of the tropically acclimatized subject. Subjective responses recorded after c.a. 4-hour exposure was used in the analysis so that results may realistically reflect responses of long-term exposure encountered in the real offices. Table 5.6 shows the extracted components, hereafter termed as the Subjective Factors (SF). Accumulatively, the subjective factors accounted for 72% of data variance of the subjective responses. Each subjective factor was represented by a logical cluster of subjective responses which revealed specific mechanisms on how the subjects perceived the environmental parameters as well as their state of comfort and other health-related symptoms (the latent structure of perceptual constructs). The subjective factors are described and named as follows:

a) SF1: Local thermal sensations. The subjective factor comprised mainly of local cooling sensation responses at the neck areas, chest, forehead, back, upper arms, lower arms, and the thighs. Based on the factor loading distribution, it was obvious that thermal sensation ratings of locations closer to the body core substantially defined this subjective factor. Moreover, both hand and feet thermal sensations did not load to SF1 but to another factor (SF6). Thermal sensation of the calves was excluded as it did not contribute to SF1 and other SFs. The positive loadings of all variables indicate that a higher factor score corresponded to higher cooling sensation and vice versa.
b) SF2: Intensity of neurobehavioral-related symptoms (I). This was the first cluster of neurobehavioral-related symptoms extracted from the subjective data. Intensity of dizziness and headache, difficulty to think clearly and concentrate, level of tension and depression, chest tightness, and state of mood loaded positively to the subjective factor, which meant that higher factor score corresponded to increased intensity of the symptoms. The variables responsible for SF2 revealed that subjects associated symptoms related to the nervous system such as dizziness, headache and abilities to think and concentrate with those relevant to mental/ behavioural capacities such as tension, depression, and mood.
c) SF3: Perceived odor and irritation. The two human sensory mechanisms, i.e. olfaction and chemestesis, formed another cluster of subjective responses. The irritation to the eyes, nose, and throat seemed more superior to the perception of odor as indicated by the factor loadings. Higher factor score indicated higher intensity of odor and irritation as perceived by the subjects.
d) SF4: Intensity of dryness symptoms. Dryness of the throat, mouth, lips and skin positively loaded to this subjective factor. The mechanisms, which encompassed the subjective perception of mucous membrane dryness, appeared to overlap with those that affected the perception of dryness of the skin and lips (cutaneous responses). Eyes dryness was not substantially loaded to any SFs, and thus was excluded, while nose dryness together with other breathing-related symptoms formed another factor. Higher factor score of this SF suggested increased dryness intensity of the clustered symptoms.
e) SF5: Intensity of breathing-related symptoms. The symptoms in this cluster were related to each other in their adversarial influence to the breathing mechanisms (the

upper respiratory tract). Intensity of nose dryness loaded negatively to the factors, meaning that a higher factor score of SF5 was equivalent to a decrease of dry nose intensity and an increase of both blocked nose and flu-like symptoms.

f) SF6: Perceived thermal comfort and intensity of thermal-related symptoms. The cluster of symptoms apparently depicted and, in the light of previous results, confirmed the close correlations between thermal sensation of the hand and the intensity of cold hand symptoms, and as such, between thermal sensation of the feet and intensity of cold feet symptoms. The cutaneous responses also seemed to affect subjects' body thermal sensation and thermal comfort. The presence of inhaled air thermal sensation within the cluster suggested that this perceptual response was similarly affected by the interventions of air temperature. A higher factor score indicated lower intensity of cold hand and cold feet symptoms, reduced cooling sensation to the hands and feet as well as the body and inhaled air thermal sensations; and better thermal comfort.
g) SF7: Perceived illuminance and noise. The analysis singled out perception of lighting level and noise in the office as another factor. However, there was no apparent reason for any correlations between these environmental variables. Higher factor score of this SF would indicate lower perceived illuminance and increase noise level.
h) SF8: Perceptions of air quality, thermal comfort and indoor environmental parameters. The cluster, which was dominated by air quality parameters, such as perceived freshness and acceptability of air quality, suggested that subjects' acceptability of air quality and thermal comfort was inversely related to perceived air stuffiness and air movement. A higher factor score indicated that subjects perceived an increase of air movement or draft, lower air stuffiness, a more acceptable air quality and better thermal comfort.
i) SF9: Self-assessed productivity and effort. The factor loadings revealed that stronger effort in completion of tasks, indicated by higher factor score, could be attributed to the higher productivity according to subjects' self-evaluation.
j) SF10: Intensity of neurobehavioral-related symptoms (II). The last factor was a smaller cluster of neurobehavioral-related symptoms, which reflected fatigue and arousal mechanisms, and their impacts on ability to concentrate. Higher factor score suggested less fatigue, higher arousal and better concentration.

Analysis of factor scores derived for each subjects underscored the effects of air temperature on thermal-related responses, i.e. SF1, SF6, and SF8 (Table 5.7). Based on analysis of SF1 factor score, local cooling sensation was highest at 20.0°C and correspondingly, the lowest at 26.0°C ($P<0.0001$). This significant effect reiterated previous findings of the effects of air temperature on local thermal sensations. In the earlier results, lower air temperatures at 20.0 and 23.0°C were perceived as "cool" and "slightly cool", respectively. Exposure to 23.0°C was considered most optimal for thermal comfort. On the other hand, air temperature at 20.0 and 23.0°C also caused increments of cold hand and cold feet symptoms as thermal sensation dropped below neutral. The intricate and strong effects of air temperature on these subjective responses had been explained through the cluster of SF6, which unraveled the dominant effects of air temperature on thermal sensation responses and cold hand and cold feet symptoms ($P<0.0001$). Further observation showed that higher thermal sensation and lower intensity of both symptoms might lead to a better-perceived thermal comfort at 26.0°C as thermal comfort variable loaded positively on SF6. Highest factor score on SF8 at 23.0°C suggested an optimum air temperature for acceptability of air quality and thermal comfort. This was plausibly related to perceived lower air stuffiness and higher air movement (P<0.0001). Another analysis demonstrated that factor score of intensity of dryness symptoms tended to be higher at 20.0°C while there was no difference between 23.0 and 26.0°C (P<0.09).

Table 5.6 Extracted subjective factors and the corresponding factor loadings from principal component analysis on subjective responses recorded after 4-hour exposure in the office under three air temperature settings. Results shown for absolute factor loadings greater than 0.5.

Perceptual responses and intensity of SBS symptoms	SF1 21%	SF2 18%	SF3 7%	SF4 6%	SF5 4%	SF6 4%	SF7 3%	SF8 3%	SF9 3%	SF10 3%
Thermal sensation: Neck (back side)	0.94									
Thermal sensation: Neck (front side)	0.94									
Thermal sensation: Chest	0.93									
Thermal sensation: Forehead	0.89									
Thermal sensation: Back	0.88									
Thermal sensation: Upper arms	0.65									
Thermal sensation: Lower arms	0.58									
Thermal sensation: Thighs	0.53									
Intensity of dizziness		0.80								
Difficulty to think clearly		0.78								
Level of tension		0.76								
Level of depression		0.73								
Chest tightness		0.70								
Intensity of headache		0.69								
State of feeling/ mood		0.69								
Difficulty to concentrate		0.56								-0.55
Eyes irritation			0.83							
Throat irritation			0.81							
Nose irritation			0.81							
Odor level			0.57							
Intensity of mouth dryness				0.93						
Intensity of throat dryness				0.90						
Intensity of lips dryness				0.81						
Intensity of skin dryness				0.70						
Intensity of nose dryness					-0.76					
Intensity of blocked nose					0.66					
Intensity of flu-like symptoms					0.65					
Intensity of cold hand						-0.88				
Intensity of cold feet						-0.87				
Thermal sensation: Hands						-0.79				
Thermal sensation: Feet						-0.73				
Thermal sensation: Inhaled air						0.68				
Thermal sensation: Body						0.66				
Illimunance level (darkness)							0.77			
Noise level (noisiness)							0.69			
Air stillness level								-0.71		
Air stuffiness level								-0.71		
Acceptability of air quality								0.60		
Thermal comfort						0.50		0.54		
Self-perceived effort									0.75	
Self-perceived productivity									0.75	
Level of arousal (sleepiness)										-0.84
Level of fatigue (tiredness)										-0.61

Table 5.7 Effects of air temperature on factor score derived for each subjective factor (SF) extracted by the principal component analysis

Subjective factors (SF)	Factor scores			Statistics	Score description
	20.0°C	23.0°C	26.0°C		
SF 1: LOCAL THERMAL SENSATION	**0.16**	**0**	**-0.25**	**P<0.0001**	Higher score indicates cooler local thermal sensation
SF 2: INTENSITY OF NEUROBEHAVIORAL-RELATED SYMPTOMS (I)	0	0	0	ns	Higher score indicates higher intensity of the clustered symptoms (refer to Table 5.6)
SF 3: PERCEIVED ODOR & IRRITATION	-0.05	-0.18	-0.18	ns	Higher score indicates higher odor & perceived irritation
SF 4: INTENSITY OF DRYNESS SYMPTOMS	0.11	0	0	P<0.09	Higher score indicates higher perceived dryness
SF 5: INTENSITY OF BREATHING SYSTEM-RELATED SYMPTOMS	0.025	0	-0.1	ns	Higher score indicates higher intensity of nose blocked and flu-like symptoms but lower intensity of nose dryness
SF 6: PERCEIVED THERMAL COMFORT & INTENSITY OF THERMAL-RELATED SYMPTOMS	**-0.88**	**0**	**1**	**P<0.0001**	Higher score indicates lower intensity of cold hand and feet symptoms, warmer local thermal sensation of the hand and feet, warmer perceived body and inhaled air thermal sensation; and better thermal comfort
SF 7: PERCEIVED ILLUMINANCE & NOISE	0.01	0.01	0.225	ns	Higher score indicates darker and noisier environment
SF 8: PERCEPTIONS OF AIR QUALITY, THERMAL COMFORT & INDOOR ENVIRONMENTAL PARAMETERS	**0**	**0.24**	**-0.39**	**P<0.0001**	Higher score indicates lower perceived stuffiness, more air movement, more acceptable air quality and better thermal comfort
SF 9: SELF-ASSESSED PRODUCTIVITY & EFFORT	-0.02	0	-0.15	ns	Higher score indicates more effort and more productive completion of tasks
SF 10: INTENSITY OF NEUROBEHAVIORAL-RELATED SYMPTOMS (II)	0.12	0	0	ns	Higher score means better alertness, less fatigue and better ability to concentrate

5.4.3. Physiological (biomarker) responses

5.4.3. A. Skin temperatures and sweat rates

Figure 5.18 shows that mean skin temperature decreased with time in all three conditions (P<0.0001) with the least magnitude of change observed at 26.0°C. At the start of exposure, mean skin temperature at 20.0°C was approximately 0.95 times of the mean skin temperature at 26.0°C. By the end of exposure, skin temperature at 20.0°C became approximately 0.90 times of the mean skin temperature at 26.0°C. Here, the non-weighted mean skin temperature was used to show the relative effects of air temperature on skin temperature. Analysis of variance based on detail repeated measurements data suggested that lower air temperature significantly reduced the skin temperature (P<0.0001). Furthermore, the magnitude of effects of air temperature were dependent on locations of measurement on the body surface as expected (P<0.0001). The same analysis also revealed that effects of air temperature were not influenced by gender differences (P<0.10), although between-subjects analysis indicated that the skin temperature of male subjects (mean (CI): 33.4 (33.2-33.5)) were slightly lower than that of the female (mean (CI): 33.8 (33.6-33.9)).

The variations of skin temperature were largely attributable to the extremities, i.e. the skin temperature of the hand and foot. This was revealed by the recorded local skin temperatures at five locations of the body surface (Figure 5.19). Forehead skin temperature was consistently the highest of all measured locations. It also experienced the least fluctuations throughout the exposure to the three air temperatures. Under the presumption that body core temperature would not be substantially affected within the range of moderate thermal stress, the measured forehead skin temperature reflected the least deviation from the core temperature and indicated the ability of body thermoregulation system to protect the functioning of the brain. Similar pattern with small variations was also observed for measured skin temperature at the back (body torso). Despite the very small fluctuations of forehead and back skin temperatures, their corresponding (subjective) local thermal sensations appeared to decrease with time in the direction of cooling, which suggested the possibility of overlapping in the thermo-sensory feedback system. Analysis of measurement at the upper arm revealed that the body shell thickness (the outer layer of the body, which is affected by thermal environment relative to internal warm core area of the body) were reduced in the event of moderate cold exposures (20.0 and 23.0°C). The skin surface temperature at this location was slightly reduced during the first half of the session before the body eventually reached the equilibrium level.

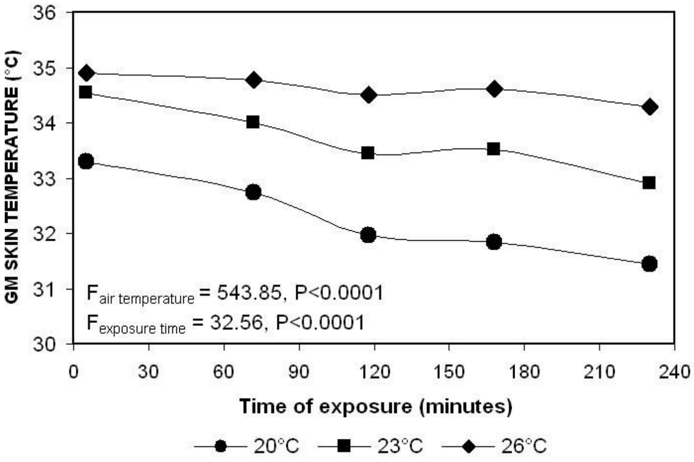

Figure 5.18 Geometric means of skin temperature during exposure to three air temperatures as the function of exposure time.

Hand skin temperature at 26.0°C was reasonably maintained, while at 20.0 and 23.0°C, it dropped at an almost consistent rate across the time of exposure. During the first half of the session, the hand skin temperature was reduced by c.a. 3.0°C at 20.0 and 23.0°C. It is also pertinent to note that hand skin temperature was already lower even after a relatively short period in the office at 20.0°C. After about 3 hours of exposure in the moderate cool stress, hand skin temperature reached an almost equilibrium condition at c.a. 27.5°C. The observations of hand skin temperature were generally applicable to the foot skin temperature, except that of exposure to 26.0°C. At this temperature, the skin temperature decreased with time at a marginally smaller rate. Seemingly, the body thermoregulatory system attempted to maintain the foot skin temperature after one hour. This was unsuccessful as it continued to decrease for the rest of the occupation period without indications of reaching equilibrium after the four-hour long exposure. These results closely mirrored the previous findings from the local thermal sensations of the hands and feet as well as the intensity of cold hand and cold feet symptoms, signifying the onset of cold strain when the tropically acclimatized subjects were exposed to lower air temperatures.

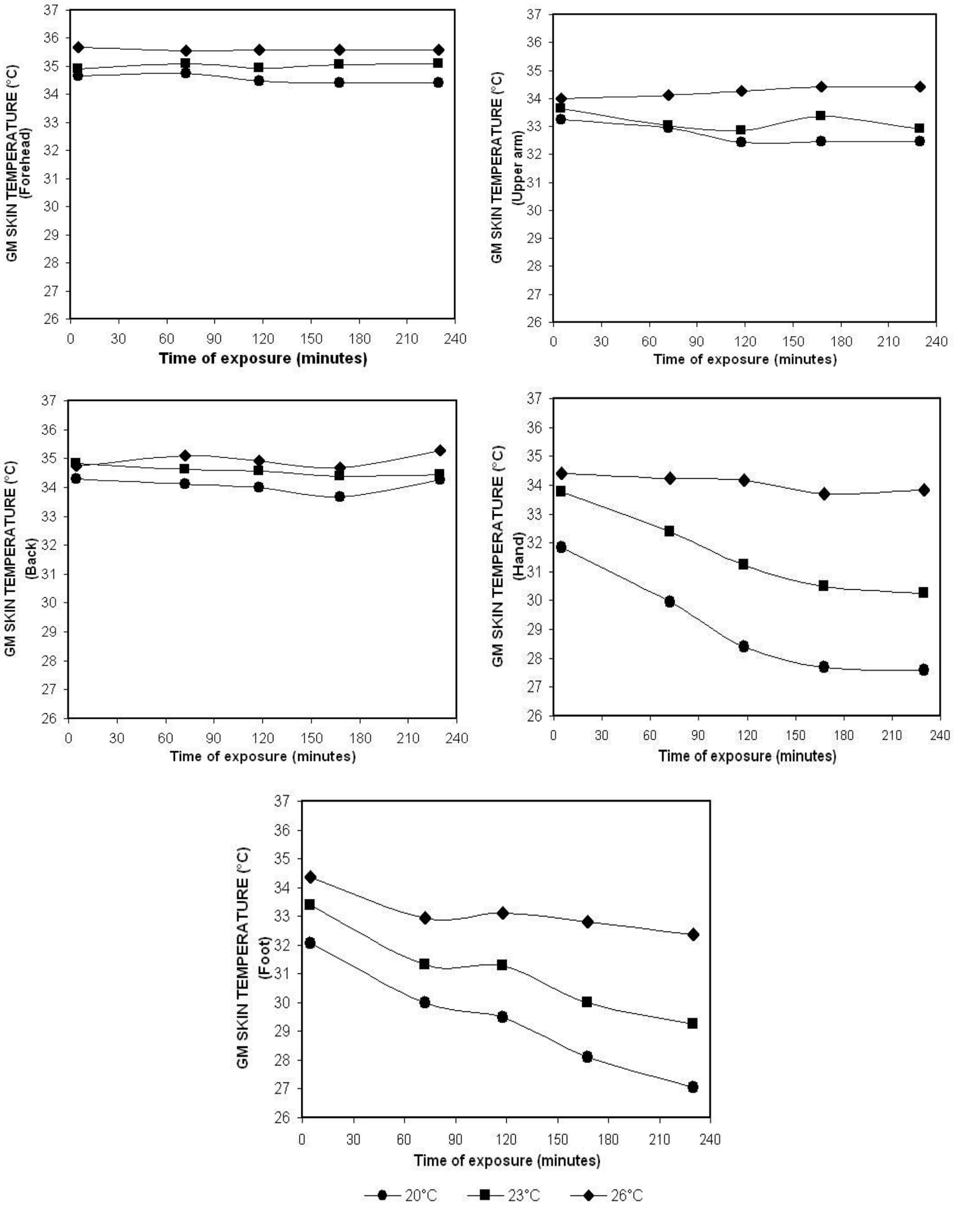

Figure 5.19 Geometric means of skin temperature during exposure to three air temperatures measured at the forehead (above left), upper arm (above right), back (middle left), hand (middle right), and foot (below) as the function of exposure time.

Within the range of moderate air temperatures, mean skin temperature appeared to be a strong predictor of body thermal sensation following a linear correlation (R^2=0.95) (Figure 5.20 (left)). A mean skin temperature above 34.0°C was rated slightly above neutral or on the warmer region of the AHSRAE thermal sensation scale, while skin temperatures below 34.0°C were perceived below neutral or on the colder side of the scale. The skin temperature below 32.0°C corresponded to perceived "cool" thermal sensation. Expanding this model by looking at the impacts of the skin temperatures at various locations on the local thermal sensations yielded a quadratic curvilinear relationship (R^2=0.92) (Figure 5.20 (right)). In tandem with the earlier model, it is shown that skin temperatures within c.a. 33.0-36.0°C (mostly from measurements at the forehead and back) were perceived about neutral (40-50) within the 0-100 point VA scale. As the skin temperature continued to decrease from c.a. 33.0°C to 27.0°C (from measurements at the upper arm, hand, and feet), subjects reported the increase of cooling sensation from 50 to 90 within the same VA scale.

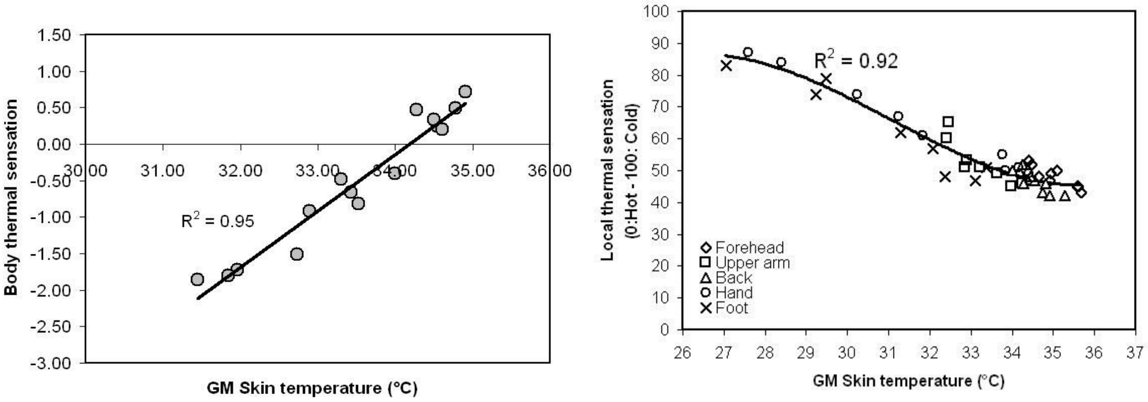

Figure 5.20 Observed linear and quadratic relationships: between overall thermal sensation of the body and mean skin temperature (left); and local thermal sensations at five locations of the body to their respective measured skin temperatures (right).

Sweat rate of subjects' performing sedentary office works were expectedly low (Figure 5.21). The recorded values were generally below 100 nanoliter per minute (nl/min) with the steady-state level reaching 20 nl/min. This result was obtained from measurement performed at one location of the body, i.e. the inner side of upper arm. Similar to measured skin temperature profiles, there was the effects of time of exposure on the sweat generation rate ($P<0.0001$). At air temperatures 20.0 and 23.0°C, the first-hour of exposure caused the highest decline of sweat rate, while at 26.0°C there was a gradual decrease over time. Despite the low values, the effects of air temperature on sweat rate was significant ($P<0.0001$). The differences across air temperature were, however, dependent on time of exposure. In other words, the magnitude of impacts of air temperature on sweat rate became smaller as time progressed. Looking at the profiles of the 4-hour session, the equilibrium sweat rates under sedentary activities (background levels) were achieved after approximate exposure duration of 4 hours at 26.0°C, 3 hours at 23.0°C, and one hour at 20.0°C. Based on average sweating over 4 hours, the total sweat volume generated at 26.0 and 23.0°C was c.a. 1.60 and 1.25 times higher than that generated at 20.0°C, respectively.

Evaporative heat loss through the skin by means of sweating during sedentary activities did not strongly affect thermal sensation, contrary to the case of skin temperature, which receptors provide strong feedbacks to body thermoregulatory system for conserving or releasing the body heat. Plot of local thermal sensations at the inner upper arm and the corresponding sweat rates shows only marginal reduction of cooling sensation as sweat rate increased (R^2=0.36) (Figure 5.22).

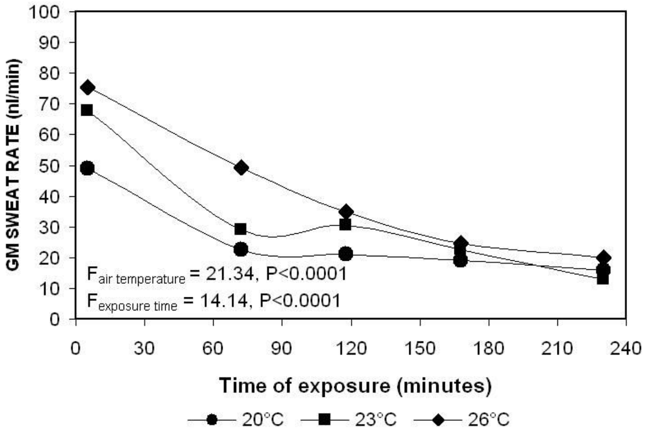

Figure 5.21 Geometric means of sweat rates at three air temperatures as the function of time of exposure.

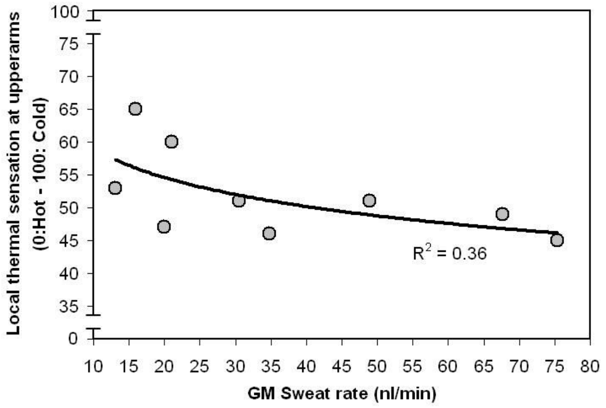

Figure 5.22 Local thermal sensation at the upper arm as the function of sweat rates measured at the same location.

5.4.3. B. Salivary Cortisol and α-Amylase

It is shown in Figure 5.23 that concentrations of salivary Cortisol collected upon entering the office (before exposure) did not vary between air temperatures (c.a. 6 nmol/l), citing a similar basal HPA activity level during immediate exposure or at the start of the simulated work session. Subsequently, results after the 4-hour exposure indicated significant reductions of salivary Cortisol (P<0.0001). Exposures to moderate cool (20.0°C) and warm stress (26.0°C) led to a reduced Cortisol level by approximately 2.52 and 1.67 times, respectively, while a 1.60 times reduction was attributed to a continuous exposure to 23.0°C. The consistent reductions of Cortisol level highlights that subjects' HPA axis experienced substantially higher activation level at the start of their sessions and gradually deactivated towards the end of sessions, which indicated lower psychological stress following the workload relieve. Analysis of variance and pair-wise comparisons on data taken from after-exposure showed that there was the significant effects of air temperature on the Cortisol level in saliva (F=10.36, P<0.0001) and that the Cortisol levels after exposure to 23.0 and 26.0°C were 1.61 (P<0.05) and 1.59 times (P<0.001) higher than that of 20.0°C, respectively. Although the differences were identified at relatively low concentrations (subjects under allostasis load), these effects could positively elicit lower basal HPA activity level, which was indicative of better stress relieve when subjects were exposed to lower air temperature (20.0°C). Within subjects analysis also revealed that the effects of air temperature on secretion of Cortisol enzyme did not differ between male and female donators (P<0.50).

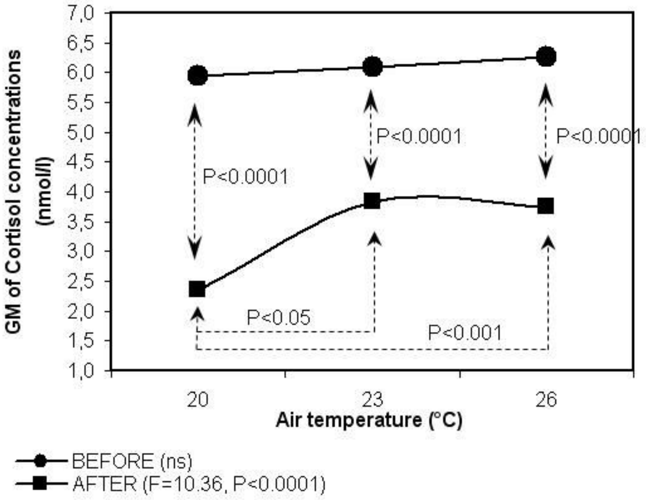

Figure 5.23 Geometric means of salivary Cortisol concentrations as the functions of air temperature (before and after 4-hour exposure in the FEC)

Analysis of another physiological trait, i.e. the SAM axis, showed that salivary α-Amylase did not vary significantly between air temperatures during immediate (before) exposure (c.a. 55 u/ml). This result implied a similar basal activation level of the sympathetic nervous system at the beginning of the session. Figure 5.24 further highlights the consistently greater increments of salivary α-Amylase concentrations across the three air temperature settings, suggesting activation of sympathetic nervous system throughout the four-hour session. A relatively small increased of c.a. 1.16 times were seen during exposure to air temperature of 26.0°C., whilst much higher increments were attributable to lower air temperature, c.a. 1.76 and 1.88 times during exposures to 23.0 and 20.0°C, respectively (the interaction of effects of air temperature and time of saliva collection was significant at P<0.02). This observation led to an important observation that following the increase of moderate cool stress by reduction of air temperature, there was a significant increased of catecholamines secretion after the 4-hour long exposure. Salivary α-Amylase concentrations at 23.0 and 20.0°C were 1.47 and 1.92 time higher than that at 26.0°C (F=12.38, P<0.0001). As the correlate of norepinephrine (catecholamines) level in plasma secreted by activation of the sympathetic nerves, this result supported the notion of increased adrenergic state or mental activation at the lower air temperature settings. The effects of air temperature on the level of salivary α-Amylase were not influenced by subjects' gender, i.e. no significant interaction effect was observed (P<0.30).

Analysis of saliva flow data did not detect the effects of exposure to various air temperatures and likewise across the gender groups. There was, however, a significantly higher saliva flow rate in the after-exposure samples (P<0.02) with the means ± S.E as follows: 1.99 ± 0.16 ml (before) and 2.44 ± 0.16 ml (after). Nevertheless, there was no interaction with the air temperature effect, indicating that the differences of the salivary biomarkers concentration under exposure to the three air temperatures were not affected by the saliva flow.

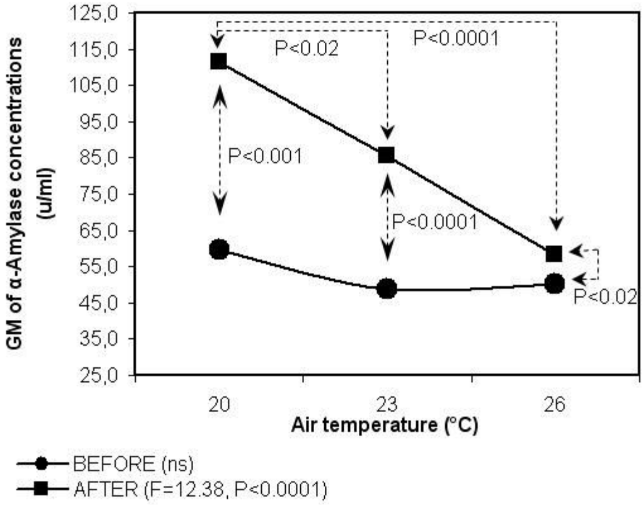

Figure 5.24 Geometric means of salivary α-Amylase concentrations as the functions of air temperature (before and after 4-hour exposure in the FEC)

5.4.4. Performance measures

The following section presents the results of mental performance tests, simulated office tasks and the self-evaluated performance measures. The main analysis of the first two measures was performed using the MIXED model approach. Apart from treating air temperature as the fixed effects (predictor) of performance measures, the model also accounted for other time-course parameters such as time/sequence of exposure for the effects of learning/ fatigue or carry-over, time of day of experiment for the diurnal pattern (between-subjects factor) and time within exposure for any within session related changes. It is pertinent to reiterate that the time-related effects, when present, had been minimized using the counter-balanced experimental design described in Chapter 4. The random component was included to control for the individual variability among subjects in the model. For most cases, multilevel analysis was performed for each performance tests criteria for speed and accuracy until best model solution was attained. At the initial phase, all fixed effects and random parameters were included in the model. Non-significant effects were considered as non potential predictors or confounders, and were subsequently excluded from the final model. The time-course parameters were also treated as covariate if linear model adjustments were reasonable based on the slopes estimates. Since most tasks were presented twice to the subjects (first-try and second-try), separate analysis was also conducted on each test to identify probable inconsistencies. To satisfy further comparisons with other measure conducted only during the afternoon sessions, i.e. the salivary biomarkers data, more analysis was carried out by separating morning and afternoon groups of participant. The latter could also serve as comparative study on subject's performance during morning and afternoon hours. Finally, the self-evaluated performance measures on level of effort and productivity were analyzed according to the technique used for analyzing the VA scale.

5.4.4. A. Mental performance tests

Tables 5.8 shows the estimated marginal means of mental performance tests at various air temperature exposures. Two mental performance tests were significantly affected by the air temperature settings, i.e. the concentration endurance and arousal level for both the speed and accuracy measures. Results of other performance tests seemed to indicate better performance at 23.0°C with slightly higher average speed of work and lower error rate for alphabetical reasoning, while the C-score for creativity also improved. These results, however, were not significant at P<0.05.

Table 5.8 Speed and accuracy of mental performance tests at three air temperatures. Results obtained from mixed model estimated marginal means.

Mental performance	**Speed***					**Accuracy***				
	20.0°C	23.0°C	26.0°C	P**	unit	20.0°C	23.0°C	26.0°C	P**	unit
Numerical reasoning	2.4	2.5	2.4	ns	rows/min	21.6	22.9	22.1	ns	% error
Alphabetical reasoning	18.9	19.6	19.1	ns	units/min	2.3	1.6	1.9	ns	% error
Concentration	148.8	152.5	149.7	<0.03	characters/min	2.0	2.4	2.4	<0.07	% error
Arousal	14.0	14.0	15.0	<0.0001	links/min	3.3	2.9	1.9	<0.0001	% error
Creativity$^{\#}$	7.3	7.6	7.2	ns	bits					

Notes: *: values are geometric means, **: based on mixed model fixed (main) effects statistics, $^{\#}$: data shown for C-score

Figure 5.25 shows that subjects performed concentration task at a lower speed under exposure to 20.0 and 26.0°C. The paired comparison revealed that this was attributable to the difference between exposure to 20.0 and 23.0°C (P<0.03). Subjects also made fewer errors at 20.0°C, while at higher air temperatures subjects' performance worsened by c.a. 0.4% based on the difference in absolute values. The overall results of speed and accuracy analysis suggested worst concentration endurance in the moderate warm stress. A trade-off mechanism was observed at the lower air temperature range, i.e. between 20.0 and 23.0°C. Subjects performed slower with better accuracy at 20.0°C; while on the contrary, they worked faster with the tendency of making more errors (failing to identify more characters) at 23.0°C. Tasks requiring concentration abilities often emphasize on accuracy of the work than the overall speed, which means exposure to 20.0°C is perhaps more preferable for concentration-related tasks. Across the sequence of exposures (experimental sessions 1-3), subjects performed the task faster (P<0.001) while the percentage errors remained constant. Speed of work also improved between the first-try and second-try of the sessions (P<0.007). Between-subjects analysis on time of day effect, i.e. performance between morning and afternoon, revealed that subjects attending afternoon sessions performed less accurately than those attending morning sessions (P<0.05). Overall, subjects had better concentration endurance in the morning and more so during the second-try of the session.

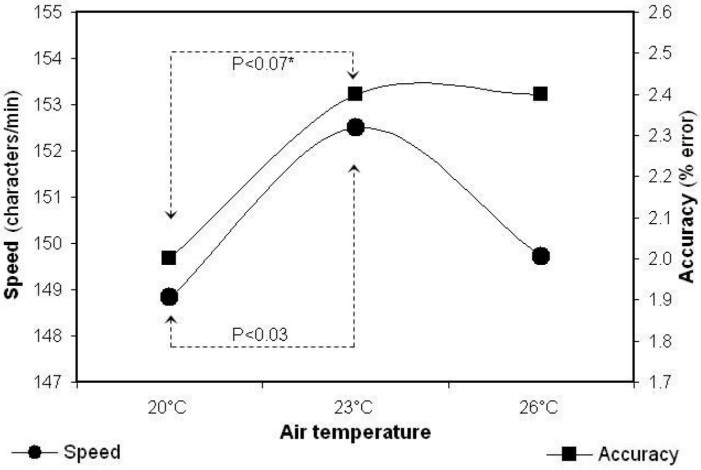

Figure 5.25 Geometric means of speed and accuracy measures on concentration endurance test as the function of air temperature (: one-tailed statistics)*

Table 5.9 summarizes the analysis on tests conducted during the first and second half of the session. Results from separate analysis on morning and afternoon participants are presented. Counteractive effects of air temperature on speed of performance between first-try and second-try were noted. In the first-try, lower air temperature (20.0°C) substantially reduced speed, i.e. the total characters searched per minute, by c.a. 5% ($P<0.001$), while during second-try, subjects performed gradually faster ($P<0.001$) and more accurate ($P<0.04$) with lower air temperature. The trends yielded an optimum condition for concentration (speed) at 23.0°C as seen in Figure 5.25. The first-try on the concentration task was carried out after c.a. one hour exposure. During this period, major acclimation process occurred as subjects' thermal sensations dropped while the corresponding SBS symptoms such as cold hand increased profoundly. In parallel to the fact that the first-try was completed after the exhaustive typing task that required certain level of sustained attention and finger dexterity, the moderate cool stress at 20.0°C was likely to have negative effect on the "d-with-two-dots" character search task.

After an extended exposure of more than 2 hours and right after their half-time break, subjects appeared to have lower concentration endurance signified by lower speed and higher error rate at 26.0°C, a condition related to lower activation level or arousal (results of arousal test are presented in the following discussion). While first-try seemed to be affected by fatigue and worsened by thermal stress, the effects on the second-try could be explained by activation theory. After a certain period of acclimation and with lower workload, sustaining concentration ability would require higher activation. In the present experiment, this was achieved by elevating cold stress with lower air temperature. Another result from separate analysis of morning and afternoon sessions suggested that air temperature did not affect concentration endurance level during the morning hours, while in the afternoon, subjects performed faster at higher air temperatures ($P<0.02$), i.e. at 23.0 and 26.0°C, but in the expense of accuracy level ($P<0.04$). Subjects attending morning sessions seemed to be able to consistently maintain their concentration level disregards of the thermal conditions.

Table 5.9 Speed and accuracy of concentration endurance tests a) during first and second half of session b) between morning and afternoon sessions. Results obtained from mixed model estimated marginal means.

Mental performance	**Speed** (characters/min)				**Accuracy** (% error)			
	20.0°C	23.0°C	26.0°C	P	20.0°C	23.0°C	26.0°C	P
a) Concentration (1st-try)	143.4	152.9	150.6	<0.0001	2.3	2.4	24	ns
Concentration (2nd-try)	154.5	152.2	148.9	<0.001	1.9	2.5	2.3	<0.04
b) Concentration (morning)	152.2	152.6	149.5	ns	2.6	2.7	3.0	ns
Concentration (afternoon)	145.8	152.3	149.7	<0.02	1.6	2.2	1.9	<0.04

Figure 5.26 shows that subjects linked more numbers per minute at 26.0°C. They performed the test approximately 7.1% faster with this exposure, indicating a broader attention span over the task (P<0.0001). While performing the task at faster speed, subjects also made fewer errors as air temperature increased, with a more profound effect as air temperature was elevated from 23.0 to 26.0°C (P<0.0001). As the Tsai-partington test measures the arousal level, the present findings indicated a lower activation during moderate warm stress at 26.0°C with subjects performing better on speed and accuracy, while at 20.0°C, subjects made more errors even at lower speed, suggesting higher arousal. Analysis also revealed that subjects' speed of work was affected by the sequence of exposure (P<0.001). Subjects seemed to perform their work faster throughout the three experimental sessions, which might indicate the learning effect. However, they also made more errors in this analysis (P<0.001), which counteracted the earlier effect on overall performance. The statistical model accounted for the effects of time of exposure, i.e. between first-try and second-try within the session. Subjects performed faster (P<0.01) and made fewer errors (P<0.001) during the first-try, indicating lower activation during the first half of the session. In other words, prolonged exposures may increase subjects' activation level. The findings of increased arousal level at lower air temperature within the moderate thermal stressors based on Tsai-partington test were in excellent consistency to the increased SAM activation level measured by the concentration of α-Amylase in the saliva. As such, salivary α-Amylase, as the objective indicator of physiological activation through the sympathetic nerves, could serve as potential predictor of arousal level, which is commonly attributed to work performance.

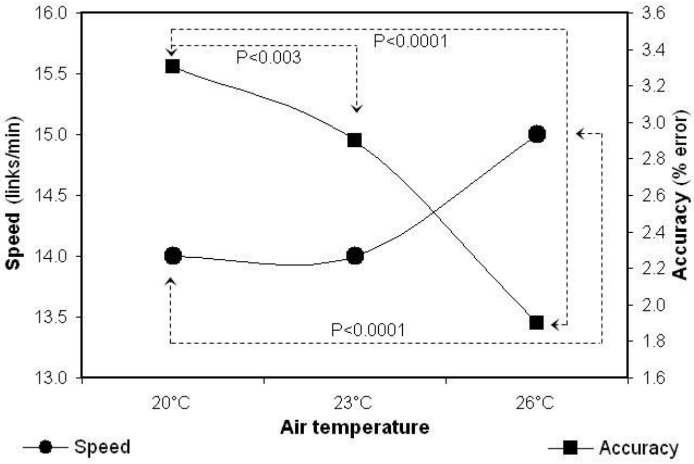

Figure 5.26 Geometric means of speed and accuracy measures on Tsai-partington test as the function of air temperature

Subsequent analysis of the first Tsai-partington test within each session shows that subjects completed lower number of links per minute at 26.0°C (P<0.001). However, the absolute change suggested that this effect was marginally too small to have any practical significance; moreover, the effect was not accompanied by significant impacts on accuracy level. After a prolonged exposure of more than two and a half hours, subjects' performed significantly faster at 26.0°C with an average of 15.4 links per minute, or two links per minute more than other exposure conditions (P<0.0001). There was a gradual decrease of accuracy when air temperature setting was reduced (P<0.0001). A broader attention span and lower error rate at higher air temperature suggested lower arousal while more error and narrow attention span during moderate cool condition indicated higher arousal or activation level. These effects of air temperature were seen in the morning and afternoon groups when analyzed separately, i.e. higher arousal was associated with the lower air temperature.

Table 5.10 Speed and accuracy of arousal (Tsai-partington) tests
a) during first and second half of session b) between morning and afternoon sessions.
Results obtained from mixed model estimated marginal means.

Mental performance	**Speed** (links/min)				**Accuracy** (% error)			
	20.0°C	23.0°C	26.0°C	P	20.0°C	23.0°C	26.0°C	P
a) Arousal (1st-try)	14.4	14.4	14.1	<0.001	2.2	2.1	2.0	ns
Arousal (2nd-try)	13.5	13.4	15.4	<0.0001	4.7	3.7	1.8	<0.0001
b) Arousal (morning)	13.9	13.9	14.4	<0.0001	3.5	2.8	2.1	<0.02
Arousal (afternoon)	13.9	13.8	15.1	<0.0001	3.1	2.8	1.6	<0.0001

5.4.4. B. Simulated office tasks

Two simulated office tasks involving word-processing skills, namely the proofreading and text-typing were significantly affected by air temperature interventions, while numeric addition performance did not vary with air temperature (Table 5.11). The present analysis showed that of the two performance measures, only speed of work was significantly affected.

Table 5.11 Speed and accuracy of simulated office tasks at three air temperatures.
Results obtained from mixed model estimated marginal means.

Mental performance	**Speed***					**Accuracy***				
	20.0°C	23.0°C	26.0°C	P**	unit	20.0°C	23.0°C	26.0°C	P**	unit
Numeric addition	27.1	26.8	27.0	ns	units/min	1.3	1.4	1.3	ns	% error
Proof reading	21.7	18.8	21.1	<0.0001	lines/min	48	50	50	ns	% error
Text-typing (words)	31.9	30.7	30.9	<0.008	words/min	0.7	0.8	0.8	ns	% error
Text-typing (characters)	195.5	188.2	189.4	<0.003	characters/min					

Notes: *: values are geometric means, **: based on mixed model fixed (main) effects statistics

Figure 5.27 shows the speed and accuracy criterion of the proofreading task. Subjects read more number of lines in each minute at 20.0 and 26.0°C (P<0.0001), with a slightly better accuracy of identifying inserted text-errors at 20.0°C. Time-course analysis also revealed that subjects read gradually less accurate (by missing more inserted errors) across the sequence of exposures (P<0.001) and between the first and second reading tasks within a session (P<0.001). The latter were further explored. The results are summarized in Table 5.12, which also includes the results of separate analysis of morning and afternoon groups. Subjects consistently read more number of lines per minute under exposure to the moderate cool stress environment and the least (slowest) at 23.0°C in the first- and second-try of the proofreading tasks (P<0.002). During the first-try subjects also skipped more embedded text-errors at higher air temperature (P<0.05). Combining these results warrants that proofreading performance was better at 20.0°C than other temperatures, while at 23.0°C, proofreading performance was considerably the worst. Better activation (higher arousal) and concentration endurance (as indicated by lower percentage error) were the potential factors affecting the proofreading performance at 20.0°C. While this mechanism maybe applied on proofreading performance at 23.0°C (lower arousal and concentration accuracy), the same explanation failed in rationalizing the improved reading speed at 26.0°C. The moderate warm stressor appeared to cause subjects to change their cognitive responses or strategies. As higher air temperature was generally ill-perceived, elevated psychological stress and lowered arousal and concentration, it is possible that subjects counteracted these stressors by reading or scrolling through more text without sufficiently focusing on identifying the embedded errors, thus resulting in more number of lines completed while compromising on the accuracy of the task. Results from separate analysis on morning and afternoon groups were in parallel with the overall findings, except that accuracy level was significantly affected by air temperature interventions only for the proofreading performance of afternoon groups.

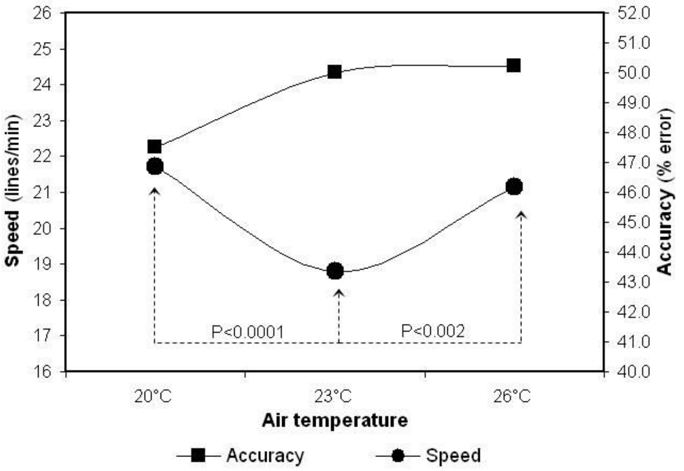

Figure 5.27 Geometric means of speed and accuracy measures on proofreading task as the function of air temperature

Table 5.12 Speed and accuracy of proof reading tasks
a) during first and second half of session b) between morning and afternoon sessions. Results obtained from mixed model estimated marginal means.

Mental performance	**Speed** (lines/min)				**Accuracy** (% error)			
	20.0°C	23.0°C	26.0°C	P	20.0°C	23.0°C	26.0°C	P
a) Proofreading (1st-try)	20.3	17.3	19.9	<0.002	42	45	46	<0.05
Proofreading (2nd-try)	23.2	20.4	22.5	<0.002	54	56	55	ns
b) Proofreading (morning)	21.5	18.5	21.5	<0.006	49	49	49	ns
Proofreading (afternoon)	21.9	19.1	20.8	<0.01	46	51	52	<0.02

It is apparent from Figure 5.28 that typing speed (number of characters typed per minute) was significantly higher at 20.0°C, relatively 3.8% and 3.2% faster than the typing speed at 23.0°C ($P<0.005$) and 26.0°C ($P<0.02$), respectively. Likewise, as shown in Table 5.11, the number of words typed per minute was affected by air temperature in the similar trend and magnitude. There was no effect of air temperature on typing accuracy, which was generally less than 1% of error in all cases. The mixed model analysis revealed that there was no systematic improvement or decrement in both typing speed and accuracy across the sequence of exposure. However, subjects retyped the text faster during the second-try of text-typing task ($P<0.0001$).

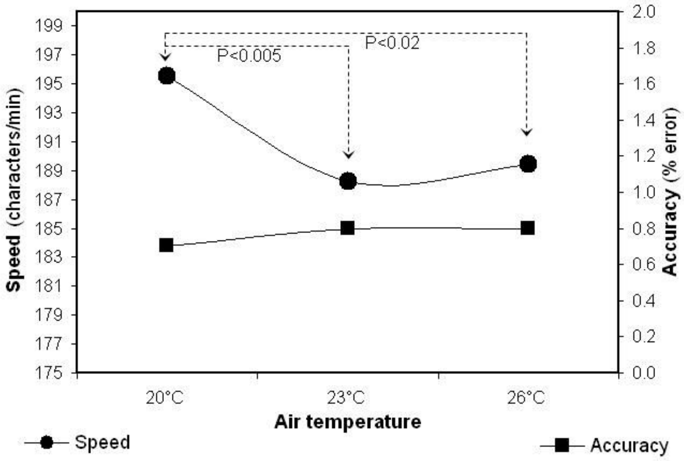

Figure 5.28 Geometric means of speed and accuracy measures on text-typing task as the function of air temperature

Table 5.13 highlights the difference between first and second text-typing performance, particularly in the measure of speed of work. Speed of retyping the text was c.a. 8.0% faster in the second half of session (second-try). Of the three air temperatures, typing performance was superior at 20.0°C. The effects were only significant during the typing task within the first-half of session. A similar effect of air temperature was consistently observed in the afternoon groups. Two plausible mechanisms may be offered. These mechanisms may synergistically improve performance of typing at the lower air temperature. Typing work generally involved multitask paradigm such as reading, memorizing, re-typing, and error checking, which could be performed in sequence and simultaneously. The complexity involved in the typing task would require optimum level of arousal or activation level. In the present study, the optimum level was associated with air temperature at 20.0°C, which also increased arousal level. Another explanation to the positive effect at lower air temperature was related to the state of thermal comfort. The fact that subjects typed faster after longer exposure suggested greater effort to elevate their activity rate and counteract the adverse effect on cold hand. At this point, it is important to highlight that the extent of cold hand symptom reported earlier did not negatively affect subjects' speed of work on typing performance. Subjects could even strategically reverse the anticipated negative effect, as the arousal mechanism was able to overcome other thermo-physiological effects.

Table 5.13 Speed and accuracy of text-typing task
a) during first and second half of session b) between morning and afternoon sessions.
Results obtained from mixed model estimated marginal means.

	Speed								**Accuracy** (% error)			
	(words/min)				(characters/min)							
Mental performance	20.0°C	23.0°C	26.0°C	P	20.0°C	23.0°C	26.0°C	P	20.0°C	23.0°C	26.0°C	P
a) Text-typing (1st-try)	30.8	29.2	29.8	<0.02	189.2	179.7	182.4	<0.02	0.8	0.8	0.7	ns
Text-typing (2nd-try)	33.0	32.3	32.1	ns	202.1	198.0	197.0	ns	0.7	0.8	0.8	ns
b) Text-typing (morning)	32.5	31.3	32.0	ns	200.0	192.5	196.5	ns	0.9	0.8	0.8	ns
Text-typing (afternoon)	31.3	30.1	29.9	<0.003	191.4	183.8	183.1	<0.002	0.7	0.7	0.7	ns

5.4.4. C. Self-evaluation of performance

Two VA scales on self-performance evaluation, namely effort and productivity, were introduced, first after they completed the first half of the experimental session (before half-time break) and again at the end of the session (before subjects started working on the final task). Figure 5.29 indicates that air temperature settings did not affect self-perceived effort and productivity in either survey. Nevertheless, subjects reported a better productivity towards the end of experimental session consistently across the air temperature settings. The magnitude of improvement across time suggested that increase of self-perceived productivity was greater during exposure to 20.0°C (10.8%) than 23.0°C (9.0%) or 26.0°C (7.3%).

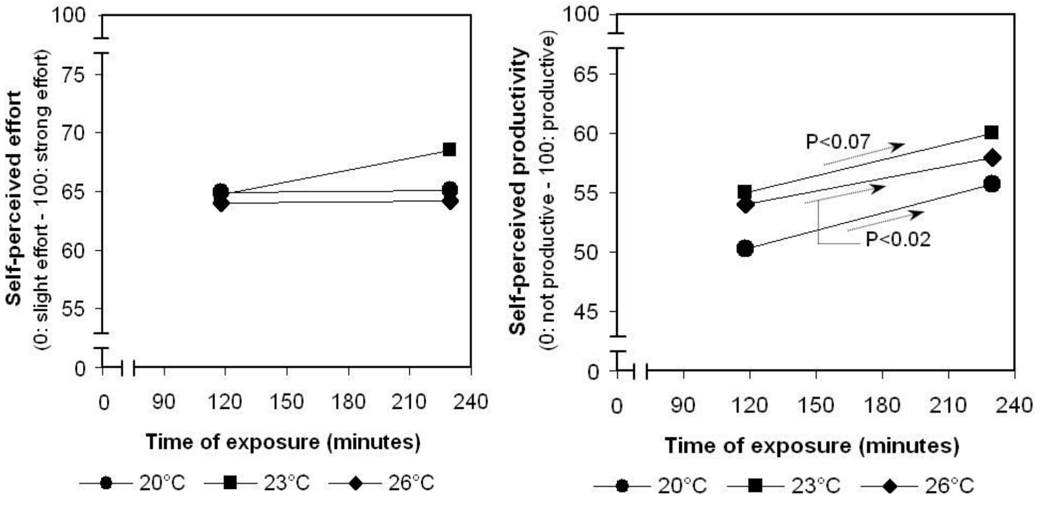

Figure 5.29 Self-perceived effort (left) and productivity (right) as the function of time of exposure

5.5. Structural equation model

The existence of coherence findings in the occupants-indoor environment interactions, or more exactly between the thermal environment, perceptual/ physiological responses, and work performance was articulated in various parametric measurements reported above. The posited mechanisms formed larger structure of related hypotheses that were explored and fitted through the structural equation modeling (SEM). It is imperative to highlight that these models were not intended as the causative models of occupants-indoor environment relationships (although SEM procedures have been commonly used for developing causal relationships), but more of predictive and confirmative tools of the observed and hypothesized mechanisms in the present study. It would be fallacious to reduce the complexity surrounding occupants' responses to the indoor environment within the measures of the present study and to assume causative relationships. Each main component in the basic model depicted in Figure 5.1 was expanded into factors that contributed to the effects of air temperature on work performance. The model was initially assessed through two main mechanisms by means of treating perceptual responses and physiological measures as the intermediary factors separately. After evaluating relationships (and restrictions) among the variables in each mechanism, the final model that combines both mechanisms was derived. The full model is hereafter termed as the Man-Performance-Indoor Environment-Structural Model or abbreviated as MPIESM.

Earlier results clearly showed the strong influence of air temperature on subjects' perceptions on thermal environment, thermal sensations, and the intensity of cold hand and cold feet symptoms. The effects were probably best illustrated through the clusters of subjective variables. These subjective factors of interest, namely SF1 (local thermal sensation), SF6 (perceived thermal comfort and intensity of thermal-related symptoms) and SF8 (perceptions of air quality, thermal comfort and indoor environmental parameters) were employed in the structural model to represent the perceptual construct of subjects responses. Suggestions of relationship between perceptual responses and performance had been shown for concentration endurance test and proofreading task, particularly in relation to prolonged-exposure to the cold and its acclimation process, and the negative perception associated with the moderate warm environment.

The process of modeling the relationships started from smaller subsets of relationships to ensure that the postulation of larger model structure did not erroneously included irrelevant parameters and that the final model yielded sufficient fit to the data. These smaller subsets of data are illustrated in Figure 4.35 and will be briefly described in the following section, while results on the detail parameter estimates would be focused on the final model.

A simple model (Figure 5.30 (above left)) with 9 variables (4 observed and 5 unobserved) showing the effects of air temperature on a latent variable termed as "perception" with three indicators, SF1, SF6 and SF8 yielded a sufficiently good fit to the data with statistics: X^2 = 2.30 (df=2, N=288, P<0.32) (a non-significant probability level indicates that the postulated model did not deviate significantly from the data). Other common goodness-of-fit criteria such the comparative fit index (CFI)=0.95 (a value greater than 0.95 often indicative of good-fitting models (Hu and Bentler, 1999)) and the root mean square error of approximation (RMSEA)=0.02 (a value larger than 0.10 indicates a poor-fitting model relative to the model degrees of freedom (Browne and Cudeck, 1993)) also supported the model postulation. Air temperature was a significant predictor of perception variable in the model (standardized coefficient=-0.60, P<0.001). Apart from the latent and observed variables, four error terms variables were added to the endogenous variables. The numeric one (1) next to the one-headed arrow was needed to fix the unit of measurement of the variables and did not affect the model standardized parameter estimates and statistics.

Another model on physiological measures with 3 observed and 4 unobserved variables yielded a saturated model, i.e. sample moments equals parameters to be estimated. In such case, parameters of the model could still be estimated, while the overall probability level is not computable (Figure 5.30 (above right)). The problem of lack of degrees of freedom was resolved when the sub-model was combined with other sub-models to achieve identifiability. Air temperature appeared as good predictors for the latent variable "physiology", which has two indicators, i.e. skin temperature and Amylase level (standardized coefficient=1.00, P<0.001). Another physiological parameter, i.e. the salivary Cortisol level, was not included in the model due to its poor prediction of the latent variable and thus compromising the model fit. This was probably related to the small magnitude of changes relative to the other parameters and this observation does not mean that salivary Cortisol was unaffected by the room air temperature. The biomarker indeed served as good correlate for the HPA axis activation as discussed in later section 5.6.6.

The effects of air temperature on work performance appeared to be more complex as the measures involved both performances at subliminal level as well as the more complex but simulated actual office task. The structural model on work performance shown in Figure 5.30 (below) assumes that mental performances (represented by a latent variable) preceded the effects on more actual office tasks such as proofreading and text-typing. The model yielded a very good fit to the data with $X^2 = 0.97$ (df=2, N=288, P<0.62), CFI=1.00 and RMSEA=0.0001. This was achieved after two additional constraints/ paths were added based on modification indices, the Lagrange multiplier test and theoretical relevance of possible covariance between the factors affecting the performance measures. Another latent variable representing simulated office works was also deleted from the model as it did not load on any of the performance measures and subsequently replaced by the direct effects.

The full model was illustrated in Figure 5.31. The structural part of this model (the latent components indicated by circular boundary) reflected the latent variables postulated in Figure 5.1. It also consisted of the sub-models of Figure 4.35 with several paths added based on the observed relationships presented in previous sections and the Lagrange multiplier tests, which improved the model robustness and the model fit. The direct path between air temperature and performance in the structural model was excluded as a redundant path when relationships between perception-performance and physiology-performance were considered. In summary, the full model hypothesized that air temperature affects subjects' performance and is mediated by subjects' perceptual and physiological constructs.

Correlated error terms were modeled in the full SEM. Direct effects between SF6 and typing performance as well as between skin temperature and typing performance were added as covariance, i.e. ESF6 – ETP, EST – ETP. The postulated effect of poor perceptions of the air quality at higher air temperature which may cause the change in cognitive strategies was represented by the covariance between SF8 and proofreading as well as between SF8 and text-typing. Other modification indices suggested that there were correlated error terms between ESF1 and EST as well as between ESF6 and EST. These paths were added to the final model as there was reasonable evidence of the direct associations between skin temperature and SF1 (local thermal sensation) as well as between skin temperature and SF6 (perceived thermal comfort and intensity of thermal-related symptoms). Likewise, there also existed a high score of modification indices between EAM and EAR, which confirms the earlier result on the positive relationship between the concentration of salivary α-Amylase and the arousal/ activation level. Finally, the correlated error between EPR and ETP was deleted from the model as it was not a significant contributor to the model estimation.

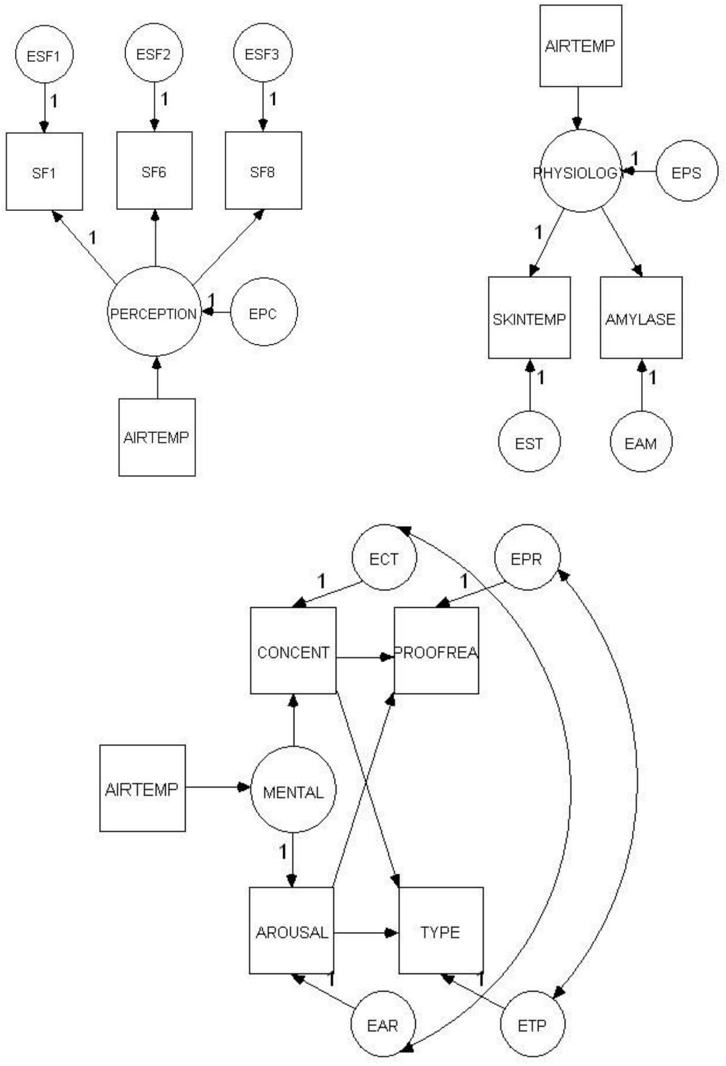

Figure 5.30 Postulated sub-models of the man-performance-indoor environment structural model (MPIESM) for effects of air temperature on perceptual responses (above left), physiological measures (above right) and performance measures (below). Figures taken from AMOS^{TM} 5.0 SEM program.

The final model as shown in Figure 5.31 comprises of 22 variables with 10 observed and 12 unobserved variables. The solution of this model was based on 55 distinct sample moments and 29 parameters to be estimated, thus, resulting in 26 (=55-29) degrees of freedom. Test on the assumption of normality did not show significant skewness deviations in the data. However, from the test on data linearity, two cases were detected as outliers and therefore excluded based on the Malahanobis distance and the largest contribution to the Mardia's coefficient ($P<0.001$). The maximum likelihood estimation method achieved the minimum criteria for convergence after 18 iterations with $X^2 = 22.63$ (df=25, N=286, $P<0.60$), suggesting a reasonable model fit of the data. Other goodness-of-fit criterions used in the evaluation of the model were also in good agreement: CFI=0.99 and RMSEA=0.001. The final model along with the significant standardized coefficients is given in Figure 5.31.

On the structural model level (latent variables), air temperature was shown to be a good predictor of latent variable "physiology" (standardized coefficient/ SC=1.00) and elevated "physiology" tended to decrease "mental" performance (SC=-0.32). Both skin temperature (SC=0.64) and α-Amylase concentration (SC=-0.33) served as the indicators of "physiology". These findings confirm that increased air temperature could decrease mental performance through the physiological mechanisms. Increased air temperature led to lower "perception" (SC=-1.00). Decrease "perception" subsequently lowered the "mental" performance of subjects (SC=0.68). SF1 and SF6 were two predictors of "perception", although they did not exhibit high standardized coefficients. In summary, both mechanisms reflected earlier results of better mental performance at lower air temperature. Increased arousal level led to higher mental performance (SC=0.35) and as expected, there was a significant covariance between arousal level and α-Amylase concentration (correlation estimate = 0.12).

The direct effects of concentration and arousal on simulated office tasks performance, i.e. proofreading and text-typing, was not clearly demonstrated. Other result indicated that lower concentration may elevate proof reading (SC=-0.16). The mechanism leading to the adverse effect had been postulated earlier through the change in reading behavior (subjects read faster without paying attention to error identification) due to inability to concentrate and the lower arousal. This explanation was supported by the significant correlation between ESF8 and EPR at -0.20 ($P<0.002$), suggesting that perception of poor air quality and thermal discomfort may increase reading speed. Although arousal measure based on Tsai-partington test did not significantly predict the simulated office tasks, the additional path representing covariance between α-Amylase concentration and typing performance (EAM-ETP), which was included earlier based on the modification indices, suggested a positive correlation at 0.12 ($P<0.06$). Therefore, as the objective measure of activation (arousal) level, the salivary α-Amylase could probably be a more sensitive indicator to changes in performance.

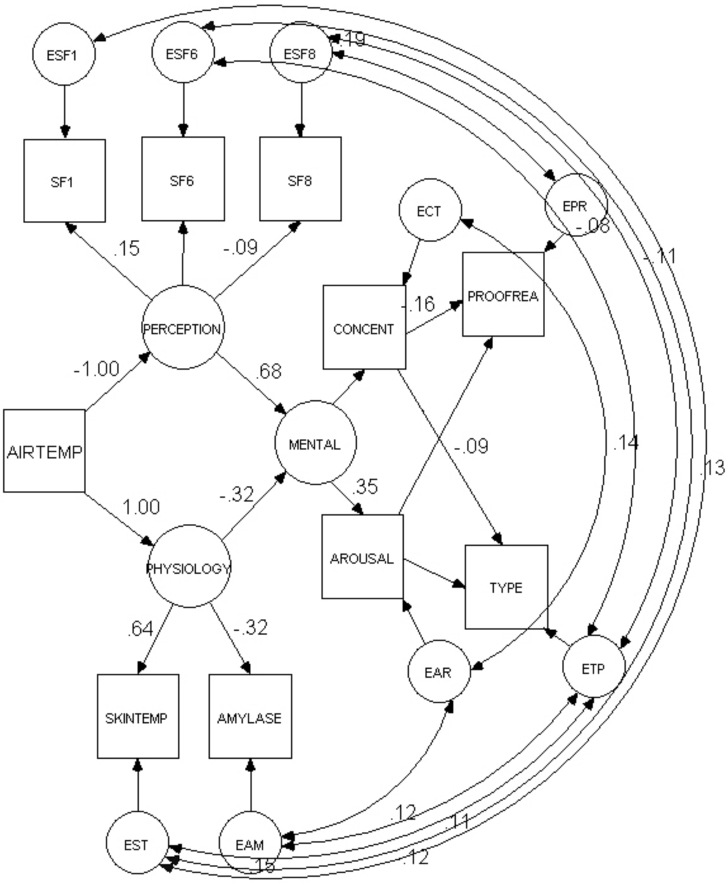

Figure 5.31 Man-performance-indoor environment structural model (MPIESM) for effects of air temperature. Figure taken from AMOS^{TM} 5.0 SEM program.

5.6. Discussions

The experiment described in this chapter was aimed to explore the effects of room air temperature on work performance of the tropically acclimatized subjects and the plausible mechanisms relating the indoor environmental parameter and the performance indicators. The measured intervening parameters covered a myriad of basic physiological indicators and perceptual responses, including possibly, the first time applications of salivary biomarkers in the evaluation of the effects of moderate thermal stress in the office settings for tropically acclimatized office workers. The results have provided the evidence that optimum air temperature for performance within the acceptable range or tolerance limits for sedentary office activities can be defined and that this must be applied according to the occupants' needs and the types of occupation activities, or otherwise, loss in work performance and overall productivity are likely to follow.

The main hypothesis that as the results of lower room air temperature, thermal sensation and thus thermal comfort would be reduced, intensity of SBS symptoms would be elevated while skin temperature and sweat rate are lowered and stress biomarkers are activated; and mental performance would be improved whereas task requiring manual dexterity would be impaired, was accepted and supported by the present findings, except that text-typing task improved at the lower air temperature contrary to the original hypothesis. In this experiment, three air temperatures were introduced in counter-balanced order of presentation with each session lasting for slightly more than four hours. Based on a total of 96 tropically acclimatized subjects, the experimental results showed that air temperature at 23.0°C was consistently perceived as most comfortable with thermal sensation ranging between neutral and slightly cool, while prolonged exposure at 20.0°C led to sharp decrease of thermal comfort in contrast to prolonged exposure at 26.0°C which gradually improved thermal comfort. Consequently, subjects experienced marked increase of the cold hands and cold feet symptoms. These effects closely mirrored the results of local thermal sensations of the hands and the feet. Measured unweighted-skin-temperature strongly supported the trend of increased cooling sensation with lowered air temperature across time of exposure. The initial measured sweat rate was lower and diminished to the basal level at faster rate under exposure to 20.0°C. Higher room air temperature significantly elevated the HPA activity indicating higher psychological stress after 4-hour exposure in the moderate warm as measured by the salivary Cortisol concentrations despite subjects feeling generally more comfortable at the end of exposure, while exposure to the moderate cold stress increased the activation of sympathetic nerves (mental activation) as measured by the level of salivary α-Amylase. These human biomarkers served as good correlates for the changes in mental performance and could objectively support or explain the effects of air temperature on perceptual responses as well as the work performance indicators. Finally, exposure to lower air temperature improved concentration endurance and increased arousal level. The same exposure also increased the speed of proofreading and text-typing. The following sections discuss and combine the results of the present experiment in the light of related studies in the literature. Results of the call center studies, whenever applicable, are also discussed.

5.6.1. Associations between thermal sensation and thermal comfort

One of the main hypotheses of the present study could be expanded as follows: that for tropically acclimatized subjects, lowering room air temperature within 20.0-26.0°C would shift body and local thermal sensations from warmer to colder region and thus thermal comfort from comfortable to less comfortable. This hypothesis was correct in the light of present experimental results. The largest variation of thermal sensation across time was observed at 20.0°C within the first hour of exposure, while at 23.0°C and, to a lesser extent, at 26.0°C, thermal sensation reduced gradually across the duration of exposure. The changes occurred despite subjects' attempts to maintain neutrality of body thermal balance by means of adjusting their clothing attires throughout the exposures to 20.0 and 23.0°C.

As anticipated, the reduction of thermal sensation in the moderate cold was followed with significant and marked decrease of thermal comfort, while thermal acclimation coupled with the lowering of metabolic rate during the sedentary (seated) office tasks, slightly reduced thermal sensation and thus, led to improved thermal comfort in the moderate warm. Subjects were more sensitive when exposed to the low air temperature as indicated by decreased thermal comfort at 20.0°C from 0.30 to 0.08 ($\Delta_{\text{thermal comfort}}$ = -0.22) within the first hour, while exposure to the moderate warm condition improved thermal comfort from 0.10 to 0.32 ($\Delta_{\text{thermal comfort}}$ = 0.22) after 3-hour exposure. In the present experiment, the exposure conditions imposed greater cooling effects to the subjects rather than heating. Under the cooling exposures, the cold nerve endings would respond with transient burst of activation, while the warm nerve endings would respond with slow activation (Hensel, 1981), which may explain the faster response of thermal sensation and the shift of thermal comfort at the lower air temperature. The same mechanism could also explain the dissociations between thermal sensation and thermal comfort during the prolonged exposure. Thermal sensation under exposure to 20.0°C tended to level-off after three hours while thermal comfort did not. In the moderate warm (26.0°C), thermal sensation improved towards thermal neutrality in slow transient changes while subjects performed sedentary activities in the office. In such case, the warm receptors of the skin might have a greater role in contrast to the domination of cold receptors in the moderate cold. The physiological traits had been previously demonstrated by Hardy et al (1971). In their experiment, a two-hour exposure under cold exposure yielded an almost steady-state thermal sensation, while thermal discomfort continued to increase. Candas and Dufour (2005) highlighted that thermal comfort was not strictly associated with thermal sensation and argued that multi-sensory interactions of various environmental factors could influence subjects' overall thermal comfort.

In the present study, subjects felt most comfortable throughout the 4-hour occupation at 23.0°C although thermal sensation slowly decreased over time and reached the steady state level after c.a. 3 hours. The relationship derived from the subjective votes on thermal comfort and thermal sensation indicated that subjects felt most comfortable when thermal sensation was around the mid-point between "neutral" and "slightly cool" (thermal sensation = -0.40), which corresponded with room air temperature of c.a. 24.2°C. The room air temperature for comfort based on the subjective votes of tropically acclimatized subjects can also be calculated from the ASHRAE thermal comfort model (Fanger, 1970, ISO 7730, 1994). Assuming the steady state conditions of the measured physical parameters, the predicted air temperature for comfort is 23.7°C or about 0.5°C lower than the air temperature derived from the relationship shown in Figure 5.8. This observation indicates that thermal comfort model slightly underestimates the air temperature level for comfort or, in other words, over predicts the thermal sensation for optimum thermal comfort of the tropically acclimatized subjects.

Fanger and Toftum (2002) introduced an expectation index to improve the prediction of thermal sensation resulting from thermal parameters in the non-air-conditioned buildings in the warm climatic regions underscoring that the more people are acclimatized or acquainted to the warm, the higher the tolerance level. Although PMV estimation (unadjusted for expectation) is believed to be applicable to most air-conditioned environment disregards of the outdoor climatic conditions, the present findings in the tropics suggest otherwise. Perhaps the reason that studies have shown the good agreement in most air-conditioned environment is that subjects in temperate climate prefer "neutral" sensation for comfort while, in the tropics, subjects show the preference for thermal sensation "between neutral and slightly cool". Nevertheless, despite the difference in thermal preference, the range of temperature for comfort still arrives at a similar range, c.a. 24.0-25.0°C. This is because the does-response relationship between the air temperature and thermal sensation of the tropically acclimatized subjects is shifted towards the lower air temperature range as shown in the present study.

A possible outcome to this observation is that the thermal expectation theory (Fanger and Toftum, 2002) may be applicable to the narrow range of indoor thermal conditions in the tropical context. Furthermore, the shift in thermal sensation not only highlights the difference of the perceptual responses but also suggests that other physiological attributes such as early vasoconstriction process in respond to cold exposure initiated by more sensitive (non acclimatized) cold receptors, insufficient increase of metabolic rate or clothing insulation to compensate for the cooling effects particularly in the longer exposure, and other adaptive controls as pointed out by Nicols (2004), need to be controlled or accounted for. Thermal sensations of occupants in the call centers reported in Chapter 3 after adjusting for clothing insulation and metabolic rate were comparable to that of the present experiment in the field laboratory study with the estimated air temperature for comfort within the range of 24.0-24.8°C, indicating the consistent impacts of room air temperature on the perceptions of tropically acclimatized subjects.

5.6.2. Respiratory cooling sensation and perceptions of air quality

The conditioning of the mucous membrane in the upper respiratory tract induced by the temperature and water vapor difference between the inspired air and the surface of the nasal passage potentially alleviate the perceptions of poor air quality (Berglund and Cain, 1989, Fang et al, 1998b, and Toftum et al, 1998b). This concept is confirmed in the present study. Subjective vote on acceptability of air quality and perceived air freshness was significantly altered in the moderate warm condition, while at 20.0 and 23.0°C, acceptability of air quality did not vary significantly and perceived air freshness were marginally better at 20.0°C. There was also the tendency of lower acceptability during reassessment of the air quality at 20.0°C as seen in Figure 5.32. As the difference was not observed in other conditions, increased bio-effluents in the office was not likely the negative contributor. Instead, this effect could be associated with the prolonged exposure in the moderate cold that resulted in the "overcooling" of the upper respiratory tract. This was confirmed by the low inhaled air thermal sensation at 20.0°C, i.e. in the range of -1.00 (1st survey/ upon entering) and -1.75 (5th survey/ after refreshed). This trend was followed by subjective response of Call center C, which showed decreased acceptability of air quality when air temperature was reduced. That short refreshing period outside the room did not elevate the perceptions to the original sensations during reassessment signified the profound effects of respiratory cooling after the prolonged exposure. A comparative analysis demonstrated that effects of respiratory cooling on acceptability were stronger in people from temperate climate (based on Toftum et al, 1998) than those in the tropics and that the discrepancy became more profound as air temperature increased. Figure 5.32 shows that subjects in temperate climate would vote the air quality at 26.0°C as "just unacceptable", while in the tropics this would still be considered within the acceptable range, confirming that tropically acclimatized subjects are more tolerant to moderate warm exposure.

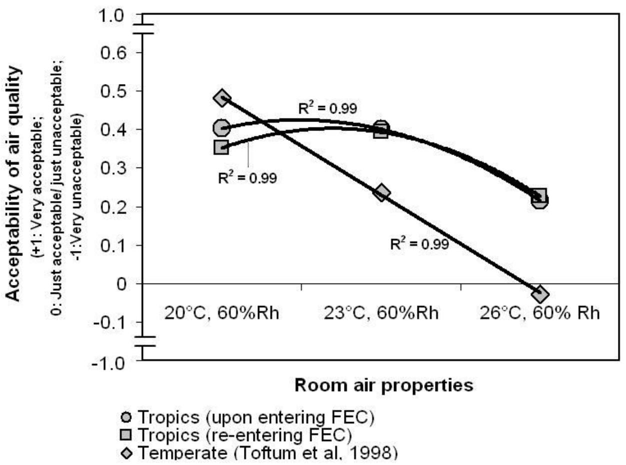

Figure 5.32 Acceptability of air quality as the function of air temperature (enthalpy) based on results of the present study (tropics) and the predicted acceptability model associated with respiratory cooling effects in the temperate climate (Toftum et al, 1998b)

5.6.3. Local thermal sensation, cutaneous responses and thermal-related symptoms

The effects of room air temperature on thermal sensation were reflected in the responses of local cooling sensations at various locations of the body with the most changes of thermal sensation occurring at the extremities of the body. In accord with this result were the changes of intensity of cold hand and cold feet symptoms. Based on subjective votes, the increments of both symptoms with time of exposure were most profound at 20.0 and 23.0°C between 0-120th minute. There was no change of both symptoms at 26.0°C. A further look at the range of changes ($\Delta_{symptom}$= ~50 on the 0-100 VA scale) indicated that vasoconstriction processes were initiated almost immediately during the moderate cool stress. In a review by Heus et al (1995) on the functioning of the hands in the cold, it was concluded that hand skin temperature was correlated with finger temperature and was physiologically related to cold exposure due to lower blood flow rate. The hand skin temperature at 20.0°C or below could therefore affect manual dexterity performance, while overall mean skin temperature generally did not affect manual work or motor tasks. The present experiment has shown that hand skin temperature was reduced to c.a. 27.5°C under the 4-hour exposure to the cold. This value is reasonably higher than the reported hand skin temperature for impaired performance, and thus, the negative expressions of increased intensity of cold hand (and cold feet symptoms) in the moderate cold by the subjects may not necessarily pose detrimental effects on tasks requiring manual dexterity such as text-typing.

The cutaneous responses, i.e. the changes in skin temperature, excited and caused the changes of thermal sensation. Subjects experienced a reduction of skin temperature of the hand and feet by c.a. 2.2°C during the first hour in the moderate cold at 20.0°C. The reduction of skin temperature gradually leveled off towards the end of experiment for the hand and continued to drop for the feet. Within the range studied, the mean skin temperature could be used to predicted body thermal sensation following a linear function (see Figure 5.20), while the sweat rate did not strongly correlate with the subjective thermal responses. The strong correlations between skin temperatures and thermal sensations at the respective locations of the body has been reported by Tamura and An (1993), while the association between sweating rate and local thermal sensation is perhaps best shown at high ambient water vapor pressure (Berglund and Gonzalez, 1977) but less profound during moderate thermal stress at a constant relative humidity.

The selected air temperatures in the present study was kept reasonably in the neutral zone of human body thermoregulation, within which, according to Savage and Brengelmann (1996) and Huizenga et al (2004), a reduction in skin temperature related to local cooling effects is correlated with higher body core temperature as the result of skin blood flow control. Furthermore, in the study about sweating responses during moderate conditioning, Shvartz et al (1979) arrived at the conclusion that exposure to 24.0°C reduced sweating intensity throughout the time of day in which subjects performed minor exercise and that at the onset of sweating, body core temperature decreased slightly. Wright et al (2002) reported that a slight increase in body temperature improved self-perceived alertness, reduced lapses in attention and neurobehavioral function was better independent of internal biological time (circadian phase). In the light of these reports, the results of the present experiment are in accord with the postulated mechanism of improved mental performance during cooling sensation in the moderate cold environment.

5.6.4. Room air temperature and the intensity of SBS symptoms

Jaakkola et al (1989) showed that SBS symptom score increased monotonously with the increase of room air temperature from 21.0 to 26.0°C in a study of prevalence of SBS symptoms in 2150 office workers in eight buildings, while Mendell et al (2002) reported the decrease of symptoms' prevalence by 12.0 to 24.0% with lowering of air temperature within 22.2-25.6°C. Reduction of SBS symptoms was also related to a 1.5°C lower air temperature (Wyon, 1992). However, in the present study, apart from the strong effects of room air temperature on cold hand and cold feet intensity, other general symptoms pertaining to dryness, eyes-related symptoms, breathing-related symptoms as well as the neurobehavioral-related symptoms intensity at the three room air temperatures were less distinguishable. Nevertheless, the tendency for the increased intensity of symptom at the end of the 4-hour exposure suggests that given a longer exposure under various thermal conditions, subjects may start to develop and experience higher intensity of SBS symptoms.

Intensity of nose dryness was significantly elevated while flu-like symptoms tended to be lower in the moderate warm condition during the middle and end of exposure. Given that relative humidity was controlled and that effects of irritation were not a major concern, the result was seemingly influenced by satisfaction factor associated with thermal environment related to other perceptions of air quality such as perceived freshness, odor intensity and the inhaled air thermal sensation, all of which were related to olfactory bulb and respiratory cooling sensation of the sensory system. This postulated mechanism is consistent with the higher prevalence of dryness sensation in Jaakkola et al (1989), which, as suggested by the authors, could be improved by introducing individual control to the subjects. The strong influence of thermo-sensory system was not observed in the other dryness-related symptoms. Lips and skin dryness were significantly higher at the lower air temperature (20.0°C) only at the beginning and end of exposure, which is perhaps best if associated with cutaneous responses in the moderate cold.

In an experimental study, Fang et al (2004) reported higher intensity of difficulty to think clearly, headache and fatigue when subjects were exposed to higher enthalpy, combining higher air temperature and relative humidity, i.e. 26.0°C/ 60%Rh. While the same result could be anticipated due to common believe of adverse effects of warm environment, it is worth reiterating that tropically-acclimatized subjects did not perceived thermal environment at 26.0°C/ 60%Rh as thermally discomforting. Better still, thermal comfort at 26.0°C improved after the prolonged exposure. On the other hand, exposure to 20.0°C/ 60%Rh evidently caused thermal discomfort after 4 hours. In a study conducted in the hot and humid Australian climate, Erlandson et al (2003) concluded that raising office temperature might be possible in hot environments and that this could lead to greater acceptance by the occupants.

The influence of thermal perceptions and the associated psycho-physiological mechanisms seemingly affected the intensity of neurobehavioral-related symptoms, which is perhaps the reason for the lack of consistent effects of room air temperature on these symptoms. Of the statistically significant results, subjects reported slightly more depressed and tended to be more tensed at higher air temperature. Further observation of the intensity scores revealed that subjects experienced higher intensity of headache, difficulty to think, dizziness and feeling bad in the moderate warm at the onset of occupation, while the opposite was true at the end of occupation with subjects reporting higher intensity of headache, difficulty to think, dizziness and feeling bad in the moderate cold.

5.6.5. Perceptual constructs of subjective responses to the thermal environment

The subjective factors derived from principal component analysis revealed that subject's responses of various parameters were induced by similar mechanisms. These subsets of subjective responses have been demonstrated to cluster along several principal axes (see section 5.4.2.C.5). The most dominant perceptual construct in the present experiment was that of local thermal sensations, which demonstrated the superiority of local cooling responses over other subjective responses during the air temperature interventions. This result is expected considering the high sensibility of the local afferent skin receptors to surrounding air temperature. Analysis of the Anderson-Rubin (AR) factor scores for each subjective factor clearly elicited the significant effects on air temperature on thermal sensations (SF1), thermal comfort and thermal-related symptoms (SF6), and perceptions of air quality (SF8). The last-named could be associated with the effects on respiratory cooling sensation discussed in section 5.7.2. The application of the visual-analog and continuous scales as a feasible tool to detect any changes in the subjective responses (Kildesø et al, 1999) when combined with the principal component analysis would provide the information on the subjects' perceptual constructs defined relative to the interventions. This would extend the observed relationships among the variables beyond the correlation analysis and allow for simultaneous comparisons of variables. The new latent (factor) scores, which are the estimates of the intensity scores that each subject would have voted for, had the latent variables (subjective factors) been measured directly, may affirm and explain the results from previous analysis on individual responses.

5.6.6. Salivary biomarkers as the indicator of cutaneous responses, psychological stress and mental activation

The exposure to different room air temperatures induced the changes of salivary Cortisol and α-Amylase concentration in the samples taken after the 4-hour exposure. However, they were affected in different directions of change since both measures were driven by varying neuro-physiological and -behavioral mechanisms.

Continuous 4-hour exposure reduced the level of salivary Cortisol consistently in all temperature exposures, implying deactivation of the HPA axis (result has been published in Tham et al, 2005). This result suggests a lower psychologically-induced stress towards the end of the work session, which is consistent with findings by Hyyppä et al (1983). In their study, 31 male subjects were subjected to 1-hour computer-based mental tasks consisting of ten 5-minute choice reaction task with one minute break in between. They found no significant increase of plasma epinephrine and norepinephrine, while plasma Cortisol and prolactin levels decreased. They further attributed the reduction with the low task demand that was insufficient to elicit psychoneuroendocrine responses. Also in the same study, the postulated explanation was supported by the fact that subjects reported only slight increase of (work) strain. Likewise, in the present study, there have been significant but marginal increases of the individual neurobehavioral-related symptoms across the time of exposure. However, the increases did not impose any strains to the psychoneuroendrocrine system as shown by lowering of salivary Cortisol concentrations. The normal circadian hormonal rhythm of Cortisol secretion was also partially responsible for the reduction of salivary Cortisol levels. Although the increase of Cortisol secretion is most profound in the morning, after awakening, the pulse amplitude of detected Cortisol level during the afternoon and evening hours are gradually smaller (Kirschbaum and Hellhammer, 1989, Clow, 2004). By contrast, Bohnen et al (1991) reported increased salivary Cortisol level of 24 female subjects performing 4-hour continuous mental tasks, such as memory comparison, geometrical recognition, divided attention, concentration, arithmetic with noise, sham video recording of subjects speaking about their personality, and reaction tasks. The continuous mental load on subjects caused by these tasks and their repetitions are consistent with the elevation of psychological stress that could lead to the activation of HPA axis in response to the stress level. Both noise stress and speech task have been shown to elevate the stress and negative affect associated with higher Cortisol level. In the present study, despite several short mental tasks requiring attention, for most part of the experimental session, subjects worked on the self-paced simulated office tasks such as proofreading and text-typing. The mental performance tasks were also randomly distributed between the simulated office works and subjects were given a short break in the mid time of session. Furthermore, subjects were acquainted with the experimental procedures and tasks before commencement of the experiment. Hence, instead of elevating stress level, the prolonged-exposure may counteract the negative affect or anticipation at the onset of experiment.

The integration of neural pathways responsible for thermoregulation processes is controlled within the central nervous system and the human brain region that responds to the change in skin temperature and codes for the direction of temperature variation is identified in the hypothalamus (Nagashima et al, 2000). Thermal sensation responses (cooling or warming) as the interoceptive experience of thermoregulatory behaviour also serve as suggestive evidence to the integrations of cutaneous thermal afferent signals and internal thermoreceptors within the hypothalamus. Egan et al (2005) reported in a study involving 12 healthy subjects (10 male and 2 female) that skin cooling from c.a. 34.0 (control) to 30.5°C (cooling) induced significant deactivation of the right ventral hypothalamus while skin warming activated the same region of hypothalamus based on positron-emission tomography (PET) imaging to monitor activity of discrete brain areas. The results were consistent with another study on hyperthermia effects which showed increased cerebral metabolic rate in the hypothalamus during heating (Nunneley et al, 2002). Combining their findings with the measured activation of the HPA axis in the present study strongly suggests the following mechanism: under exposure to moderate cold (20.0°C), subjects experienced a substantially lower skin temperature, and thus led to deactivation in hypothalamus of the brain as evident in the lower salivary Cortisol level. The magnitude of effects was reduced as the subjects were exposed to higher air temperature. The same mechanism may also contribute to the trend of reduced Cortisol after the four-hour exposure, which corresponded well to the significantly lower skin temperature.

Watanuki and Kim (2005) underlined that sensory input from various human senses converged at the amygdala of the brain. Kanosue et al (2002) demonstrated that whole-body cooling exposure causing thermal discomfort led to the activation of amygdala region of the brain as shown by the functional magnetic resonance imaging (fMRI). The study was administered on eight male subjects who were exposed to reduction of air temperature from 28.0 to 12.0°C. Subjects reported feeling of discomfort close to the "very uncomfortable" vote during the 22-minute exposure. There was no report of pain sensation but most subjects experienced shivering. They further argued that the activation of amygdala is specific to thermal comfort/discomfort response, following the emotional stress induced by sensory cutaneous responses. In the present study, exposure to the moderate cold (20.0°C) reduced subjects' thermal comfort from the comfortable to the uncomfortable region, while at 23.0°C thermal comfort level was also slightly lowered within the comfort response, and by contrast, under exposure to 26.0°C, subjects reported feeling more comfortable, after four-hour exposure. Prolonged exposure to moderate cold and the reduction of skin temperature, resulting in thermal discomfort or a lower comfort level is therefore believed to have the potential of activating the amygdala to some extent, depending on the eventual negative affect. This postulation is in compliance with the significantly higher level of salivary α-Amylase recorded after 4-hour exposure to the lower air temperature. In the present study, a reduction of c.a. 6.0°C almost doubled the concentrations of salivary α-Amylase (Tham et al, 2005). The rapid increase of salivary α-Amylase of ten male subjects moving from room air temperature at 22.0°C to cold room at 4.0°C in a 40 minutes exposure was also reported by Chatterton et al (1996), suggesting the biomarker as a good correlate for thermal responses, particularly in the cold.

Higher α-Amylase secretion predicts the increase of norepinephrine (NE) in plasma. As one of the excitatory neurotransmitters of the sympathetic nervous system that causes blood vessels to contract and heart rate to increase, higher NE indicates the activation of SAM axis in the autonomic nervous system controlled by the hypothalamus (Rolls, 1999, Kandel et al, 2000). The activation of amygdala of the brain due to thermal discomfort, presumably caused by cutaneous responses, would be projected to the sub-cortical structure, i.e. the hypothalamus, and thus the activation of the sympathetic nervous system, as the mechanism to counteract the negative affect. The activation of sympathetic nervous system further stimulates the various autonomic body functions and adrenergic activity such as increased heart rate, dilation of pupils and muscles' blood vessels, activation of sweat gland, etc, which under normal stressors, would eventually increase mental alertness (arousal). In the light of the results from the Tsai-partington arousal tests, which indicated consistently higher arousal at lower air temperature particularly at 20.0°C, it is obvious that salivary α-Amylase should be considered as an objective measures to the mental arousal.

It is also worth mentioning here that the slight increase of salivary α-Amylase after the four-hour exposure could be influenced by the circadian rhythm of secretion of α-Amylase which falls sharply after awakening but gradually increase towards the afternoon and evening (Rohleder et al, 2004). However, the pronouncedly higher salivary α-Amylase as the air temperature was lowered could not be attributable to the diurnal pattern.

5.6.7. Effects of room air temperature on work performance and the mechanisms

The mechanisms by which mental performance and simulated office work may be affected by the exposures to moderate thermal stress, i.e. between 20.0 and 26.0°C, are evidently influenced by thermo-sensory responses and the psycho-physiological traits. The state of thermal neutrality of subjects throughout the exposure period thus plays an important role. Fang et al (2004) in their study involving 30 female subjects, who were exposed in random to the various levels of combined indoor air temperature and relative humidity argued that the ability to remain thermally neutral obliterated the anticipated effects of thermal stress on work performance as suggested in a review by Wyon (1993). In the present study, despite adjusting their clothing, subjects could not achieve and maintain the thermal neutrality in the moderate cold at 20.0 and 23.0°C. This is in accord with the field studies result in which most occupants in the call centers reported thermal sensation below neutral at both air temperature settings in spite of having the opportunity to put on additional clothing.

The structural portion of the MPIESM for effects of room air temperature depicts two main mechanisms explored in the present study, in which the main hypotheses were also tested. Along with observation of correlated predictor variables between the two mechanisms, the model suggests direct associations between the perceptual and physiological mechanisms as already implied in the previous discussions on cutaneous responses, human biomarkers and thermo-sensory responses. The following discussions would be based on the direct effects on work performance and relevant explanations based on the two mechanisms and their associations would be highlighted accordingly.

The thermal conditions tested in the study were kept within the range of moderate thermal stress. These conditions were not uncommon to the real office environment. Several studies suggested that changes in work performance within thermal comfort range may be negligible. In addition to the study reported by Fang et al (2004), Witterseh et al (2002) did not observe any effects of alternating room air temperature between 22.0, 26.0 and 30.0°C on simulated office works of 30 subjects in the laboratory settings. In a subsequent analysis of their data, they found that subjects who perceived "warm" sensation exhibit an increase error of 56% in numerical addition task (Witterseh et al, 2004). Another study by Langkilde et al (1973) showed that the mental performance of 12 subjects attained from addition, word memory and cue-utilization tests was not significantly different between exposures to 18.6, 22.6 and 26.5°C during a one-time 2 and a half hours exposure in the chamber set-ups. However, this study was not performed using balanced experimental design and thus, possible decrease of mental performance at higher air temperature may be confounded by learning effects. Subjects may also be over-motivated due to the payment scheme which was based on the work output. In the field study, Federspiel et al (2002) demonstrated using multivariate analysis that room air temperature between the range 21.0-25.4°C did not pose any negative effects of call handling performance of the call center workers. The results of present study conducted using the tropically acclimatized subjects did not comply with the postulation above. Already in the call center studies, changing air temperature by a mere 2.0°C between 22.5 and 24.5°C affected call handling performance of the CSOs following the changes in thermal sensation. Expanding the range of air temperature in the present study in the simulated office environment with significant results on mental tasks and simulated office works provided compelling evidence that room air temperature has considerable effects on work performance and that this is measurable within the range of thermal comfort. One of the possible explanations for the discrepancies, apart from the thermal acclimatization and personal factor differences between subjects from the different regions, is that the present study employed 96 subjects who were exposed to the experimental conditions in the counter-balanced experimental design and that random effects in the data have been accounted for, all of which may improve the sensitivity of the analysis for detecting significant changes in performance.

Two measures of mental performance, i.e. concentration endurance and arousal, were significantly affected by the air temperature. Concentration endurance was generally better (speed: $P<0.03$ and accuracy: $P<0.07$) and arousal level was increased (speed and accuracy: $P<0.0001$) during exposure to the moderate cold. In concentration endurance task, subjects sustained high concentration throughout a character search task involving various distracters, while arousal measure using Tsai-Partingtons test involved sustained attention span. Easterbrook (1959) described the latter task as cue-utilization measure, in which higher arousal would reduce the span of attention and subsequently impaired performance on speed and accuracy. Wyon (1969) demonstrated that performance on various versions of Tsai-Partington test were better under the moderate warm exposure (27.0°C) than that under moderate cold (20.0°C), which suggest higher arousal in the moderate cold and thus may elevate the performance on task requiring attention. The findings attained from the present study provide more evidence that exposure to moderate warm is under-arousing and that exposure to moderate cold elevated arousal as suggested by Ellis (1982). Teichner et al (1958) proposed that performance is negatively affected when attention is distracted away by distracting environmental stimuli. This hypothesis is not supported by the results of concentration tests in the present experiment conducted within the moderate thermal stress with simulated office tasks. Subjects benefited from the slightly higher thermal stress level in the moderate cold, while under exposure to moderate warm, in which subjects felt gradually more comfortable, concentration level was lower. This result agrees well with the postulation made by Wyon and Wargocki (2005) that "thermal comfort providing optimum comfort may not give rise to maximum efficiency". Moreover, it was found that both mental tasks were affected consistently for the speed and accuracy in the second-try of the tasks after longer exposure. It is likely that the gradually increasing cold strain indicated by higher thermal-related symptoms and measured cutaneous responses would have greater influence during the second half of the occupation. The improved mental alertness as room air temperature was reduced has been confirmed by the measures of activation of the brain and peripheral nervous system as presented and discussed in sections 5.4.3 and 5.6.6.

In the call centers, simultaneous tasks handling such information searching, processing inputs from and responding to customer could be impaired without sustained attention and/or deactivation of mental alertness. However, it is imperative to highlight that application of the mechanisms for mental performance may result in different range of air temperature in the real office settings owing to various reasons. These are, but not limited to, the longer working hours (exposures), the higher complexities even in the case of the well-defined activity of a call center operator, and the varying strategies employed for achieving thermal neutrality. Taking an example of call center A, in which the clothing insulation value was slightly higher than that of subjects in the present study during the moderate cold exposure, it was found that 22.5°C room air temperature corresponding to thermal sensation of c.a. -0.2 on the ASHRAE thermal sensation scale was preferred for performance. In the light of mental performance tests in the present study, it seemed that a slightly lower air temperature between 20.0 and 22.5°C may further improve mental state and thus, increase the service level of the CSOs in the call center, whereas in the other call centers, in which subjects' wore substantially lighter clothing, lowering air temperature further would cause over-arousal, increased plasma norepinephrine level and impaired manual dexterity, and thus, adversely affect work performance. Taking these observations together, it can be surmised that optimum concentration and arousal level may be achieved following a dynamic function of thermal parameters, such as room air temperature, clothing value, and time of exposure, and that the resultant thermal sensation and the corresponding mental activation are potential tools for predicting performance in the actual office settings.

While moderate thermal stress clearly affected proofreading performance in the present study, this has never been observed before in the past research. Witterseh et al (2004) employed proofreading test in the study on the combined effects of noise and temperature. However, no thermal effects on proofreading tasks on either speed or accuracy criterion was demonstrated. In the present study, subjects were able to read faster and tended to have less unidentified error in the text at the lower air temperature. On the contrary, they read slower and had the tendency to have more unidentified error at 23.0°C. It also seemed that subjects improved their reading speed in the moderate warm but tended to miss more errors. As the present proofreading task was introduced as self-paced reading tasks, higher arousal and better attention are the pre-requisite for performance in the identification of embedded errors. The results fit well with the previous results of mental performance. Under moderate cold, subjects proofread the supplied text faster with less error, in congruence with the better mental state (better concentration and higher alertness) and better perceptions of the air quality (SF8) as predicted based on the MPIESM. At 23.0°C, subjects read slower concurrent with less identified errors, suggesting that as concentration and arousal were lowered, subjects may attempt to read slower in the bid to maintain performance, however, to no avail. Further increase of air temperature led subjects to change their cognitive strategies. In this condition, subjects were unable to maintain concentration and became less alert, however, as their performance was evaluated, the subjects then attempted to read more text or to complete the supplied text within the given duration but tended to leave out the text-inserted errors.

In the office settings, computerized text-typing task is often one of the basic, crucial and highly utilized skills. In the last few decades, typing has been made much easier with the advancement of computer programs and ergonomically improved typing pad (keyboard) for the hands and fingers dexterity. In the present study, the effects of moderate thermal stress on typing speed were unexpected in the view of thermal physiology. Based on the increased of cold hand and cold feet symptoms accompanied with reduced hand skin temperature, there seemed to be more suggestive evidence in the direction of the lowering speed at 20.0°C. However, the results indicated otherwise with subject typing c.a. 4% faster than the other conditions. Although subjects did not indicate they had exerted more effort, they might have unconsciously done so under the moderate cold to compensate for the lower thermal sensation. Morton and Provins (1960) and Meese et al (1982) arrived at the same conclusion that manual dexterity was affected only when finger skin temperature reached 20.0°C and below. Such skin temperature would require subjects to be exposed to a much colder room air temperature, which is unrealistic to the normal office environment. The results of skin temperature measurements showed that the steady-state hand skin temperature was kept above c.a. 27.5°C or way above the threshold limit suggested in the past studies. The improved typing pad, in which finger strength is less of a requirement when using the “soft keyboard”, may also reduce the requirement of finger and/or hand dexterity in text-typing.

The above arguments provide persuasive suggestions that text-typing performance within acceptable range of thermal environment is more dependent on mental state (as demonstrated in the predictive association of salivary biomarker level on typing performance in the MPIESM, see Figure 5.31) than the hand and/or finger dexterity. The mental performance plays the important role in coordinating the subsets of activities involved in text-typing, i.e. reading, mental and language processing, typing and proofreading, all of which are conducted almost simultaneously within short time spans. The present results are consistent with the study by Wyon (1973). In his study, young female and male typists were subjected to room air temperature of 20.0 and 24.0°C in several experiments. His results showed that subjects tended to work considerably less and in most cases statistically significantly less at 24.0°C than 20.0°C. The consistency of these evidences and their relevance to modern office activities suggest the applicability of the results to the real offices settings.

6

OUTDOOR AIR SUPPLY RATE EFFECTS ON HUMAN RESPONSES IN LABORATORY EXPERIMENTS

6.1. Introduction

It has been demonstrated that work performance of the call center operators in three offices was consistently affected by the outdoor air provision. The present experiment is designed to reestablish the impacts of outdoor air supply rate on simulated work performance in the laboratory settings with a better control to the indoor environmental parameters and to explore the detailed underlying mechanisms that may explain the effects on the office worker's performance.

Wargocki et al (2000) successfully demonstrated the effects of outdoor air supply rate on work performance in a randomized experiment involving 30 female subjects acclimatized to the temperate climate. Increasing outdoor air supply rate between 3, 10, and 30 L/s/p led to improve simulated work performance, i.e. text-typing, proofreading, and addition. The present study would attempt to extend these relationships, if applicable, to the tropically acclimatized subjects.

Changing outdoor air supply rate had been shown to affect the prevalence and intensity of SBS symptoms (Sundell et al, 1994, Mendell et al, 1996, Seppanen et al, 1999), perceived air quality (Fanger, 1988, Wargocki et al, 2000), and sickness/ absenteeism (Milton et al, 2000). This showed that indoor air quality affected the health-related indicators, which could be one of the mechanisms through which occupants' performance might be affected. The present study therefore postulates the mediating effects of perceptual responses and health-related mechanisms on work performance of tropically acclimatized subjects.

Occupants' perceptual responses can be directly measured using surveys/ questionnaires. On the contrary, the measures of health-related mechanisms associated with the changes of outdoor air supply rate are often challenged with the lack of identifiable physiological indicator, measurement sensitivity, and complexity surrounding human psycho-physiological responses. Most studies have relied on subjective feedbacks through the evaluations of intensity or prevalence of the SBS symptoms. There is the compelling need to identify and adopt precise, sensitive, and established measures of physiological responses to the indoor air quality. The present study introduces the application of a non-invasive technique, i.e. the salivary biomarkers, to detect any changes or activities in the central nervous system invoked by the alterations of outdoor air supply rate that would eventually imposed measurable effects on work performance.

Figure 6.1 shows the mechanisms for the study of outdoor air supply rates in this experiment, which is a parallel to the model used in the study of air temperature effects (Figure 5.1). In this model, perception of air quality replaces thermal comfort as one of the main determinants of subjects' perceptual construct. The intensity of SBS symptoms is the other determinant of the perceptual component in the model. The stress-related biomarkers and the bio-indicator of immune system represent the physiological measures in the model.

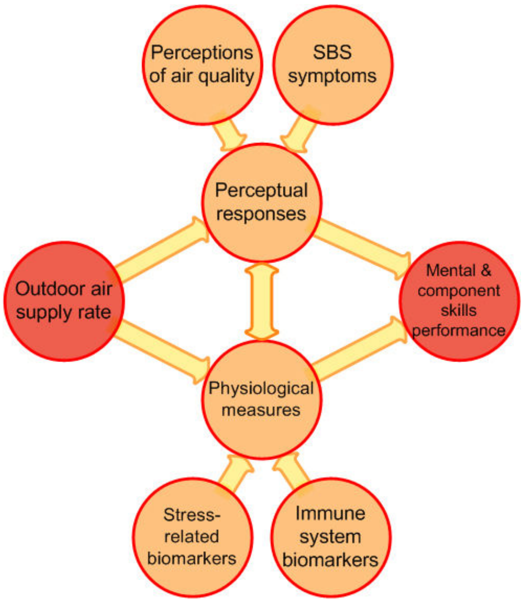

Figure 6.1 Postulated mechanisms by which outdoor air supply rate affects human responses and work performance

6.2. Objectives and hypotheses

The objectives of this study are as follows:

a) To obtain the knowledge about perceptions of indoor air quality, intensity of SBS symptoms and physiological responses of tropically acclimatized subjects at three levels of outdoor air supply rate.
b) To determine the impacts of outdoor air supply rate on mental performance as well as simulated office tasks output of tropically acclimatized subjects.
c) To develop structural model based on observed occupants' performance – outdoor air supply rate relationships for tropically acclimatized subjects.

The following lists the main hypotheses tested in this study:

1) Higher outdoor air supply rate improves acceptability and perceptions of air quality and reduces perceived odor and irritation.
2) Higher outdoor air supply rate lowers intensity of SBS symptoms and relieves the level of stress and the body immunological system.
3) Higher outdoor air supply rate improves mental performance and simulated office tasks.

6.3. Experimental designs

Three outdoor air supply rates within the range recognized from the field studies were selected for the experiment conducted between August and September 2004. The counter-balanced experimental design is shown in Table 6.1. At the lower setting, 3.0 L/s/p represented the low fresh air provision or higher recirculation. At 9.0 L/s/p, the fresh air provision was kept reasonably near the recommended minimum value of 10.0 L/s/p to avoid higher prevalence of SBS symptoms (Mendell, 1993, Sundell et al, 1994, Menzies and Borbeau, 1997). This setting complied with the recommended ventilation previously suggested in the ASHRAE 62-1 standards for ventilation (2001). The higher setting of outdoor air provision, although may not be common for office premises in the tropics, was intended to derive the projected outcomes, if any, on the work performance as well as other mediating effects. The selected conditions were within the capacity of the air distribution system of the Field Environmental Chamber (FEC).

In this experiment, used carpet (c.a. 10 years) with surface area equivalent to 80% of the net floor area of the chamber was added to simulate the normal office pollution load in offices. The presence of the carpet was kept blind to the subjects by hanging them back to back on the racking. They were subsequently placed inside an allocated area in the FEC (see Figure 4.1). This area was separated from the occupied space by opaque curtain blinds. Two wall-mounted fans gentle mixed and pushed the air polluted with emission from the used carpet into the occupied office space. The air conditioning system filter was not maintained prior to the experiment in order to keep a similar filter's pollution loading throughout all the series of experiment conducted in the FEC. This filter has been under operation for c.a. 5 months prior to the start of the present experiment. Air temperature and relative humidity were maintained at the settings for comfort, i.e. 23.0°C and 60.0%Rh, respectively, while the rest of indoor environmental parameters were kept constant.

Table 6.1 Counter-balanced experimental designs for three outdoor air supply rates in order to eliminate confounding due to the order of presentation of conditions
Note: the lower setting was achieved at 4.5L/s/p instead of the 3.0L/s/p designed condition

Subjects group	Order of exposure		
	1st exposure	2nd exposure	3rd exposure
1	3.0 L/s/p	9.0 L/s/p	18.0 L/s/p
2	18.0 L/s/p	9.0 L/s/p	3.0 L/s/p
3	18.0 L/s/p	3.0 L/s/p	9.0 L/s/p
4	9.0 L/s/p	3.0 L/s/p	18.0 L/s/p
5	9.0 L/s/p	18.0 L/s/p	3.0 L/s/p
6	3.0 L/s/p	18.0 L/s/p	9.0 L/s/p

6.4. Results

6.4.1. Indoor environmental parameters and experimental settings

Table 6.2 summarizes the measured indoor environmental parameters in the field environmental chamber. Results from tracer gas measurements indicated that outdoor air supply rates at 9.0 and 18.0 L/s/p had been reasonably achieved. However, the lower setting at 3.0 L/s/p was not achieved due to air infiltrations to the air distribution system. Thus, the lower outdoor air supply rate could only be reduced to 4.5 L/s/p. The highest level of outdoor air supply rate at 18.0 L/s/p was associated with lower concentrations of Formaldehyde and total volatile organic compounds and with a higher level of respirable dust particulate. While increasing outdoor air supply rate elevated dilution of the gaseous chemical pollutants, this also appeared to increase desorption from the used ventilation filter.

The carbon dioxide profiles indicated that equilibrium levels were not reached when the outdoor air supply rate setting were kept at 4.5 and 9.0 L/s/p (Figure 6.2). The values reported in Table 6.2 were averaged over the carbon dioxide concentrations recorded in the last half an hour of the session. At 4.5 L/s/p, the levels reached slightly above 1000 ppm (c.a. 90% of the projected steady state level). The measured carbon dioxide concentrations (and the estimated steady state concentrations) predicted slightly higher outdoor air supply rates than those calculated from the tracer gas method. After adjusting for the generation rate by the tropical subjects, the measured carbon dioxide concentrations corresponded to outdoor air supply rates of c.a. 5.0, 9.5 and 19.0 L/s/p.

Table 6.2 Results of physical measurements in the office (FEC) at various experimental conditions. Values are means±SD of data taken during experimental sessions

Measured parameters	Outdoor air supply rate settings		
	3.0 L/s/p	9.0 L/s/p	18.0 L/s/p
Indoors			
Outdoor air supply rate (L/s)	**75.7**	**144.6**	**294.0**
Air temperature (°C)	23.25±1.10	23.18±1.08	22.99±1.22
Relative humidity (%)	62.7±2.6	63.9±2.6	64.6±0.3
Air velocity (m/s)	0.10±0.03	0.19±0.02	0.18±0.03
Carbon dioxide (ppm)	1021±63 (1180*)	758±50 (810*)	557±27
Carbon monoxide (ppm)	0.23±0.07	0.30±0.19	0.22±0.08
TVOC ref. Toluene (ppm)	1.90±0.33	1.69±0.26	1.62±0.15
Formaldehyde (ppm)	1.39±0.34	1.02±0.30	1.03±0.17
Dust particle PM10.0 (μg/m^3)	3.57±0.58	2.36±1.97	9.92±1.53
Dust particle >1.0μm (particle/l)	35.20±15.85	37.00±29.72	68.22±24.30
Background noise level (dBA)	31±4		
Lighting intensity (lux)	490±20		
Outdoors			
Air temperature (°C)	29.2±2.4	30.1±3.1	29.7±2.7
Relative humidity (%)	80.0±5.3	82.0±6.7	83.9±5.0
Carbon dioxide (ppm)	403±10	410±12	399±10

Notes: (*) indicates projected concentration at steady state based on extrapolation of built-up curve, outdoor air supply rate was calculated based on the tracer gas decay rate measured for three times

6.4.2. Perceptual responses at three outdoor air supply rates

6.4.2. A. Perceptions of air quality

Various facets of subjective responses were used to assess perceptions of air quality. Median subjective vote on acceptability of air quality was used to predict the percentage dissatisfied and perceived air quality (decipol) (Gunnarsen and Fanger (1992)). Sensory pollution loads at three outdoor air supply rates were estimated from the calculations derived by Fanger (1988). At this point, it is pertinent to note that the main intention for using this evaluation was to demonstrate the perceptual sensory differences among the outdoor air supply rates and that the absolute levels may not be directly applicable to the tropical context since these predictive tools were derived from subjects' accustomed to the temperate climate.

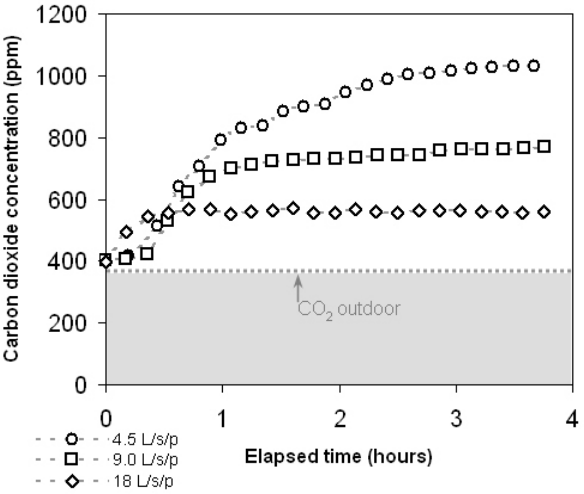

Figure 6.2 Typical carbon dioxide concentrations built-up curve at three outdoor air supply rate settings

Figure 6.3 shows that subjects voted the air quality at 18.0 L/s/p to be most acceptable, followed by 9.0 L/s/p and the least acceptable at 4.5 L/s/p upon entering the office ($P<0.001$). Pair-wise analysis between the 1st and 2nd surveys indicated significant adaptation to the indoor air quality the first hour of exposure. It was obvious that the olfactory adaptation to the indoor air caused the indiscernible air quality between the experimental conditions in the subsequent surveys (2nd-4th surveys). Furthermore, there was the trend of increasing acceptability to air quality as the exposure advanced. The acceptability rating after subjects refreshed outside the office, returned to a range closer to the initial vote given by the subjects during their first entry. The higher amount of bio-effluent accumulated over the 4-hour session as indicated by the increase level of carbon dioxide did not seem to affect the acceptability of air quality.

Two explanations may be offered to explain this result. First, the air quality outside the office (the refreshing area) may not constitute total fresh air although the area was connected to the outdoors. The premise was partly served by centralized air distributions system with recirculation. It was therefore likely that the reference condition was already polluted to some extent by the re-circulated air. In other words, subjects' olfactory sense was already influenced by some levels of pollution and became less sensitive. Thus, they did not perceive the office air quality as markedly worse than the reference condition during the re-entering assessment. Another possible explanation is related to the respiratory cooling factor, which may positively influence subjective perception of the air quality. The result of inhaled air thermal sensation vote is discussed in a later section.

The results of immediate evaluations of the office air quality, i.e. upon entering and re-entering, were subsequently combined for further analysis. An almost linear relationship between acceptability of air quality and fresh air provisions could be seen in Figure 6.4 (left). Increasing outdoor air supply rate by four-fold resulted in improved acceptability of air quality by approximately 100% ($P<0.0001$). The predicted percentage dissatisfied and perceived air quality (Figure 6.4 (right)) suggested that as acceptability of air quality increased with outdoor air supply rate, the percentage dissatisfied and perceived air quality decreased monotonically. The sensory pollution loads across three outdoor air supply rates were calculated as 0.16, 0.22 and 0.23 olf/m^2 floor area at 4.5, 9.0 and 18.0 L/s/p, correspondingly. Despite the improvements of the perceived air quality, increasing outdoor air supply rate led to higher sensory pollution load. Based on the equation (4.5), this result was likely caused by the difference between the perceived air quality in the office at various outdoor air supply rates and the perceived air quality of outdoor air (median acceptability vote: 0.47). Even at the lower end of outdoor air supply rate, i.e. 4.5 L/s/p, subjects still rated the air quality within the acceptable range (slightly better than "just acceptable" or equivalent to 27% dissatisfied). Taking the subjective votes on acceptability of air quality at the face value, the results indicated that tropically acclimatized subjects have a high tolerance for indoor air quality.

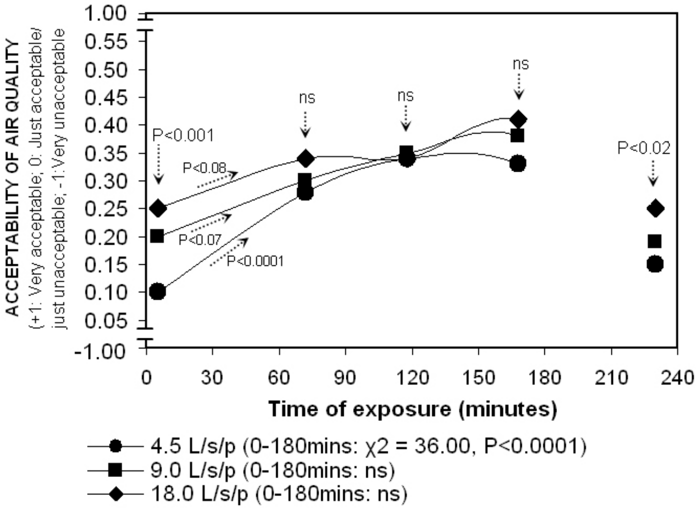

Figure 6.3 Acceptability of air quality as the function of time of exposure at three outdoor air supply rates

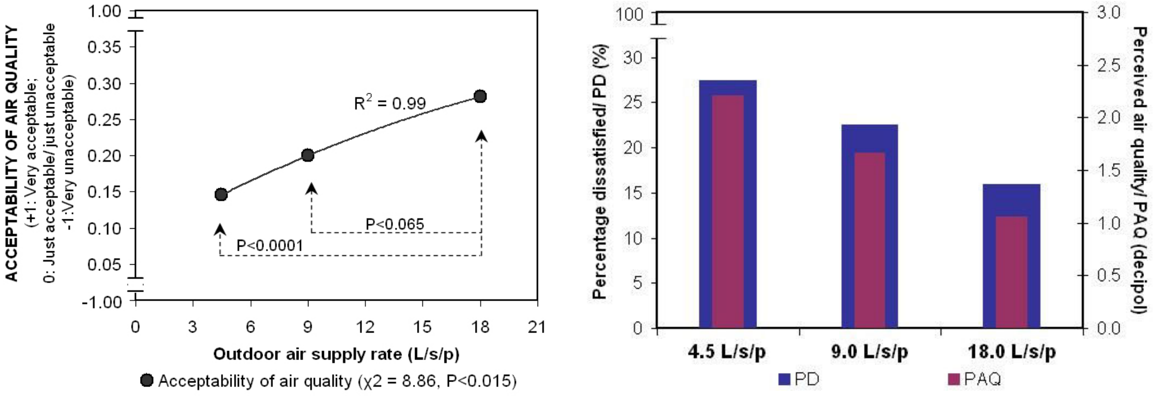

Figure 6.4 Acceptability of air quality based on subjects' evaluation upon entering and re-entering the office as the function of outdoor air supply rates (left) and the corresponding percentage dissatisfied and perceived air quality (right)

Figure 6.5 shows that subjects' olfactory senses adapted almost immediately after entering the office. Perceived odor was reduced by c.a. 50% between the first and second surveys (P<0.0001) and remained almost constant for the rest of the experimental session. During the first evaluation, subjects' perceived the odor level for the three outdoor air supply rates in similar order to the acceptability vote. Odor was highest at 4.5 L/s/p and least perceived at 18.0 L/s/p. During the final evaluation, a significantly lower perceived odor was observed at 18.0 L/s/p. A direct comparison of perceived odor between the first and the final evaluations showed the tendency of higher odor level after the four-hour session. This, however, did not reach the formal significance. The results of perceived air quality and odor tended to downplay the effects of bio-effluents. Further analysis of the perceived odor from immediate assessments indicated that increasing outdoor air supply rate by c.a. 4 folds from 4.5 to 18.0 L/s/p could reduce perceived odor by c.a. 15% (P<0.0001) (Figure 6.6).

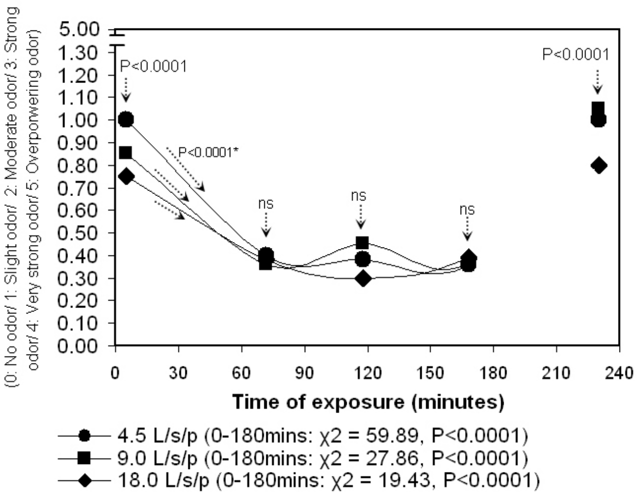

Figure 6.5 Perceived odor as the function of time of exposure at three outdoor air supply rates

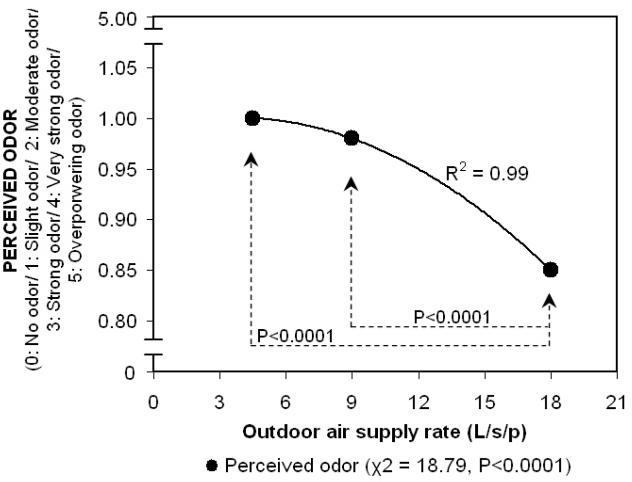

Figure 6.6 Perceived odor based on subjects' evaluation upon entering and re-entering the office as the function of outdoor air supply rates

Figures 6.7-6.9 show that only eyes irritation changes across time of exposure, while nose and throat irritation remained unaffected. In contrast to the adaptive patterns seen in the acceptability of air quality and perceived odor, eyes irritation was significantly higher after c.a. one hour exposure in the office, possibly related to the active use of VDU during the text-typing task. There were no significant effects of outdoor air supply rates on perceived eyes irritation in any of the surveys. Nevertheless, Figure 6.7 shows the tendency of higher eyes irritation at higher outdoor air supply rate during the habituation period (60th -180th minute). Upon re-entering the office, eyes irritation at the three outdoor air supply rates was reduced to the similar level as initially perceived. There was also the tendency of lower eyes irritation before the half-time break, suggesting relieved eyes strain from the preceding proofreading tasks.

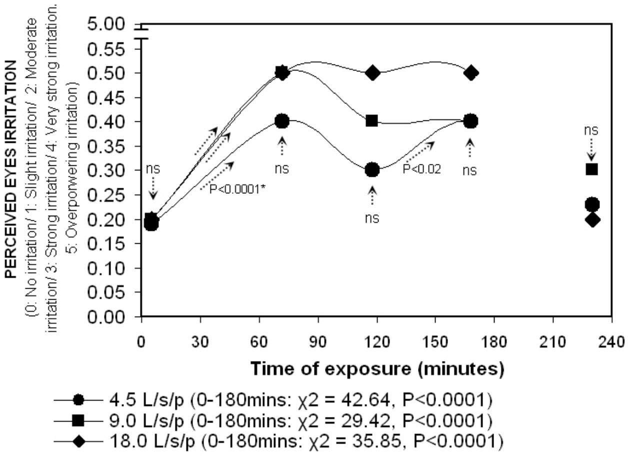

Figure 6.7 Perceived eyes irritation as the function of time of exposure at three outdoor air supply rates

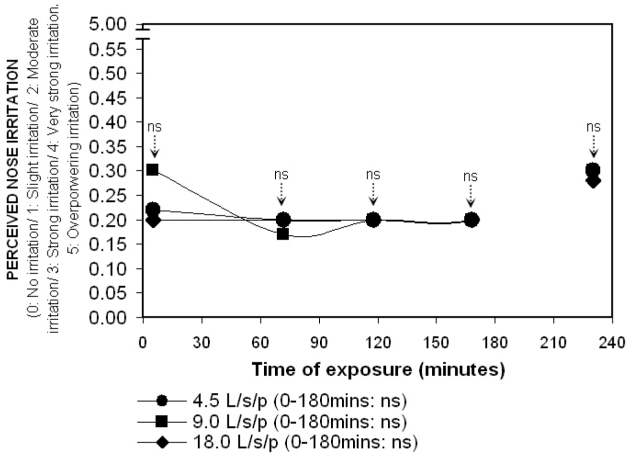

Figure 6.8 Perceived nose irritation as the function of time of exposure at three outdoor air supply rates

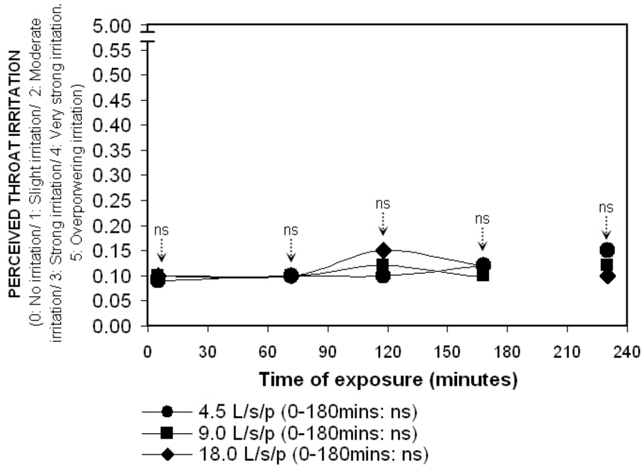

Figure 6.9 Perceived throat irritation as the function of time of exposure at three outdoor air supply rates

Immediately after entering the office, subjects perceived the inhaled air thermal sensation at 4.5 and 9.0 L/s/p close to "neutral", while at 18.0 L/s/p, it was perceived to be slightly cool (P<0.001) (Figure 6.10). There was no apparent reason to the difference since air temperature and relative humidity were constantly maintained at c.a. 23.0°C and 60.0%Rh, respectively. The positive effects on perceived odor through the olfactory system may improve perceived air fresher, and subsequently, influenced perception of inhaled air thermal sensation. This implied that respiratory cooling sensation was not only affected by thermal properties of the air but also was influenced by the olfactory senses. Similar trend were observed during the 2nd (P<0.007) and 4th (P<0.03) surveys.

In the first two-hour, inhaled air thermal sensation decreased monotonically to "slightly cool". The most drastic change occurred within the first hour of exposure (P<0.0001). The subjective vote thereafter remained almost constant. This result replicated previous finding from the effects of air temperature (section 5.4.2.B.). As a follow up to the earlier explanation for the results of acceptability vote, the change of respiratory cooling sensation between the first and the last surveys, i.e. from neutral to slightly cool, was likely to affect subjects' acceptability at the end of the four-hour exposure.

Time-course analysis revealed that the body thermal sensation decreased over the exposure period (Figure 6.11). The change reflected that of inhaled air thermal sensation reported above. However, effects of outdoor air supply rate on the body thermal sensation was not profoundly and consistently observed throughout the surveys, except during the second survey in which subjects perceived a slightly higher body thermal sensation at 4.5 L/s/p (P<0.04). There was no apparent reason for this observation and this should not be considered seriously in the light of perceptual affects of outdoor air supply rates. Further analysis of thermal comfort vote supported this notion. Figure 6.12 suggests no differences of thermal comfort for the three outdoor air supply rates. Despite the reduction of body thermal sensation during the first half of exposure, thermal comfort remained constant throughout the 4-hour exposure.

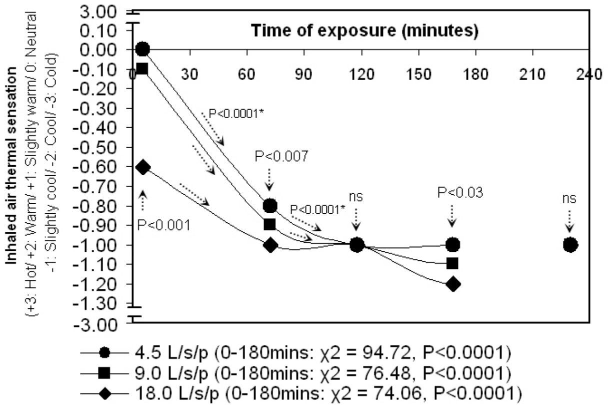

Figure 6.10 Inhaled air thermal sensations as the function of time of exposure at three outdoor air supply rates

*Note: * statictics applicable to changes at all outdoor air supply rates*

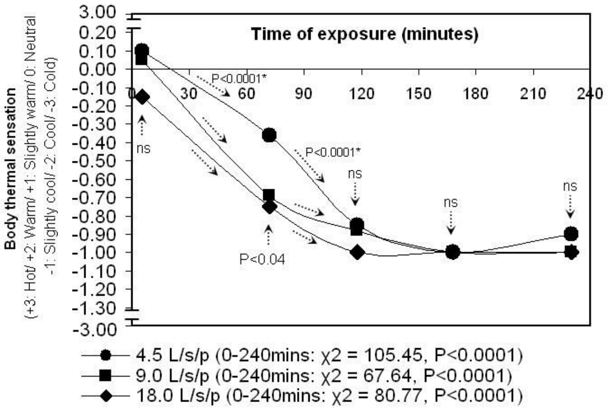

Figure 6.11 Body thermal sensations as the function of time of exposure at three outdoor air supply rates

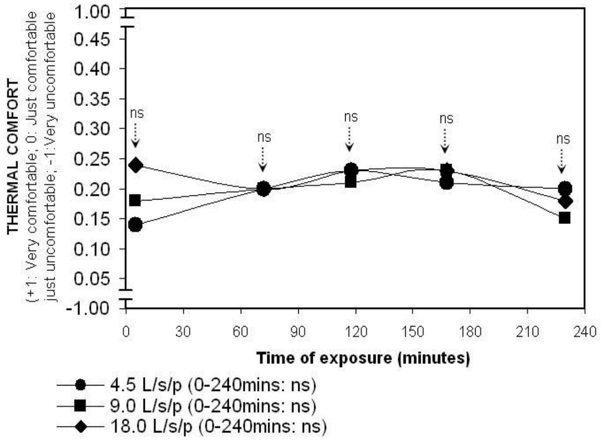

Figure 6.12 Thermal comfort as the function of time of exposure at three outdoor air supply rates

6.4.2. B. Perceptions of indoor environmental conditions

Perceptions of indoor environmental conditions were surveyed on three occasions, at 5th, 118th and 230th minute in the 4-hour session. The subjective responses were analyzed for the effects of outdoor air supply rate and the duration of exposure. The results are presented in Table 6.3. Of the six parameters, significant positive effects of outdoor air supply rates were observed for air stuffiness and stillness. Upon entering the office, air stuffiness tended to decrease as outdoor air supply rate increased ($P<0.06$, one-tailed) and the same tendency was observed in the final survey ($P<0.07$). Subjects also perceived significantly more stagnant air at 4.5 L/s/p during the first survey ($P<0.0001$), although objective measurements did not show any differences in terms of air velocity at different conditions.

Perception of air humidity was lowered as the exposure progressed ($P<0.0001$ at 4.5 L/s/p and $P<0.005$ at 18.0 L/s/p). This change may be associated with the trend of cooling thermal sensation. Air stuffiness also decreased with time but only when subjects were exposed to 4.5 L/s/p outdoor air supply rate ($P<0.04$). Similarly, subjects perceived more air movement after longer exposure in the office only at the lower outdoor air supply rate ($P<0.0001$). These effects of time of exposure signified the role of adaptive olfaction on the perceptual responses, particularly when subjects were exposed to lower outdoor air supply rate.

Table 6.3 Effects of outdoor air supply rate and exposure time on perceptions of the indoor environmental parameters

Perceptual responses	Intensity score (effects of outdoor air supply rate (L/s/p))												Effects of time of exposure (P)		
	1st survey (5')				3rd survey (118')				5th survey (230')						
	4.5	9.0	18.0	P	4.5	9.0	18.0	P	4.5	9.0	18.0	P	4.5	9.0	18.0
Air humidity (0: air too dry - 100: air too humid)	48	48	50	ns	44	44	44	ns	45	46	46	ns	<0.0001	ns	<0.005
Air stuffiness (0: air fresh - 100: air stuffy)	54	47	44	<0.06*	44	43	43	ns	49	48	47	<0.07	<0.04	ns	ns
Air stillness (0: air too drafty - 100: air too still)	**60**	**52**	**52**	**<0.0001**	51	50	51	ns	53	52	50	ns	<0.0001	ns	ns
Room illuminance (0: too bright - 100: too dark)	46	45	46	ns	44	46	46	ns	45	46	47	ns	ns	ns	ns
Room noisiness (0: too noisy - 100: too quiet)	46	48	46	ns	46	46	46	ns	47	48	48	ns	ns	ns	ns
Room dustiness (0: office clean - 100: office dusty)	33	35	29	ns	31	29	26	ns	32	29	28	ns	ns	ns	ns

Note: * statistics based on one-tailed analysis

Table 6.4 summarized the effects of outdoor air supply rate and the time of exposure on the intensity of SBS symptoms. Tendency of increased flu-like symptoms at higher outdoor air supply rate was observed in the final survey (P<0.09). Higher intensity of nose blocked symptoms were reported at 18.0 L/s/p consistently in all surveys and this reached formal significance at the start of exposure (P<0.03). Changing outdoor air supply rate appeared to cause little or no influence on dryness-related symptoms. On the contrary, subjects' reported higher intensity of eyes-related symptoms, namely eyes aching and watering eyes, consistently at higher outdoor air supply rate and this was significant in the first survey for watering eyes (P<0.01) and approached significance in the last survey for eyes aching (P<0.08) and watering eyes (P<0.08). Eyes aching symptom was significantly intensified with time at all outdoor air supply rates. The results of eyes-related symptoms are in good agreement with the effects of outdoor air supply rate on eyes irritation.

There was no significant influence of changing outdoor air supply rate on thermal-related symptoms, i.e. cold hand and cold feet symptoms. Nevertheless, these symptoms were intensified throughout the prolonged exposure in the office independent of the outdoor air supply rate setting. The difference of symptoms' intensity between the first and final surveys was approximately 50 on the 0-100 intensity scale and the magnitude of progressive increase of symptoms' intensity was similar under any of the experimental conditions.

The neurobehavioral-related symptoms, namely intensity of headache, fatigue, difficulty to concentrate, and depression, varied significantly with outdoor air supply rate. These effects were exhibited after at least c.a. 2-hour exposure, indicating that the neurobehavioral-related symptoms began to develop later in the session. Consistently, doubling outdoor air provision from 4.5 to 9.0 L/s/p reduced intensity of symptoms. However, increasing outdoor air supply rate by another factor of two from 9.0 to 18.0 L/s/p reversed the positive effects and aggravated the symptoms. All the neurobehavioral-related symptoms were progressively increased throughout the 4-hour exposure and most profoundly at 4.5 and 18.0 L/s/p.

Some observations of the present result appeared to defy the common understanding of lower symptom intensity with elevated fresh air provision. Of the three outdoor air supply rates, 4.5 and 18.0 L/s/p seemed to cause detrimental effects on intensity of SBS symptoms. While the negative effects of low fresh air provision were expected, the negative effects at higher outdoor air supply rate were uncommon and required further explanations. One possible reason to this effect was that higher outdoor air supply rates elevated the ozone concentration passing through the filters, causing surface- and gas-phase chemistry across and downstream of the used filters (c.a. 5 months). This would increase the risk of exposures to higher concentration of radicals in the air. Evidence of increased irritation to the mucous membrane of the eyes as well as higher intensity of eyes aching and watering eyes under exposure to higher outdoor air supply rate supported this postulation. In contrasts, improved perceptions of air quality, i.e. acceptability of air quality and perceived odor, with higher fresh air provision was related to olfaction rather than chemesthesis (irritation) effects.

Table 6.4 Effects of outdoor air supply rate and exposure time on intensity of SBS symptoms

Note: * statistics based on one-tailed analysis

Intensity of SBS symptoms	Intensity score (effects of outdoor air supply rate (L/s/p))												Effects of time of exposure		
	1st survey (5')				3rd survey (118')				5th survey (230')						
	4.5	9.0	18.0	P	4.5	9.0	18.0	P	4.5	9.0	18.0	P	4.5	9.0	18.0
Nose dryness (0: nose running – 100: nose dry)	67	64	67	ns	65	65	67	ns	63	66	62	ns	ns	ns	ns
Nose blocked (0: nose clear – 100: nose blocked)	**10**	**7**	**13**	**P<0.03**	9	9	15	ns	12	8	15	ns	ns	ns	ns
Flu-like symptoms (0: no flu-like symp– 100: flu-like symp)	5	3	5	ns	6	5	5	ns	3	4	7	<0.09	ns	ns	ns
Throat dryness (0: throat not dry – 100: throat dry)	39	48	46	ns	48	52	55	ns	47	50	50	ns	ns	ns	ns
Mouth dryness (0: mouth not dry – 100: mouth dry)	39	51	49	ns	50	56	53	ns	50	57	52	ns	<0.03	<0.02	ns
Lips dryness (0: lips not dry – 100: lips dry)	53	57	56	ns	63	67	60	ns	67	67	66	ns	<0.0001	<0.04	<0.05
Skin dryness (0: skin not dry – 100: skin dry)	47	45	45	ns	51	50	49	ns	47	50	48	ns	ns	ns	ns
Eyes dryness (0: eyes not dry – 100: eyes dry)	50	50	53	ns	52	56	64	ns	51	56	66	ns	ns	ns	ns
Eyes aching (0: eyes not aching – 100: eyes aching)	18	19	21	ns	52	44	51	ns	42	44	49	<0.08	<0.0001	<0.06	<0.0001
Watering eyes (0: eyes not watering – 100: eyes watering)	**7**	**6**	**9**	**<0.01**	5	5	7	ns	8	6	10	<0.08	ns	ns	ns
Cold hand (0: hand not cold – 100: hand cold)	18	21	28	ns	51	56	54	ns	69	68	70	ns	<0.0001	<0.0001	<0.0001
Cold feet (0: feet not cold – 100: feet cold)	14	21	17	ns	41	50	48	ns	66	61	65	ns	<0.0001	<0.0001	<0.0001
Chest tightness (0: breathing easily – 100: chest tight)	16	16	16	ns	17	19	15	ns	22	15	20	ns	<0.05	ns	ns
Headache (0: no headache – 100: severe headache)	9	5	9	ns	10	13	18	ns	**17**	**7**	**12**	**<0.007**	<0.05	<0.001	<0.005
Difficulty to think (0: head clear – 100: difficult to think)	22	23	26	ns	38	38	37	ns	32	28	28	ns	<0.03	ns	<0.002
Dizziness (0: not dizzy – 100: dizzy)	11	13	9	ns	19	15	17	<0.08	18	14	21	<0.06*	<0.07	ns	<0.04
Feeling/ mood (0: feeling good – 100: feeling bad)	30	35	33	ns	38	42	43	ns	37	33	35	ns	<0.04	ns	<0.004
Fatigue (0: rested – 100: tired)	45	43	44	ns	**52**	**55**	**65**	**<0.04**	**59**	**50**	**61**	**<0.007**	<0.003	<0.0001	<0.0001
Difficulty to concentrate (0: easy to concentrate – 100: difficult to concentrate)	38	36	38	ns	**48**	**46**	**48**	**<0.03**	50	37	47	<0.06*	<0.0001	<0.0001	<0.0001
Depression (0: positive – 100: depressed)	32	29	34	ns	34	36	38	ns	**34**	**26**	**38**	**<0.04**	<0.03	ns	ns
Sleepiness (0: alert – 100: sleepy)	56	54	52	ns	64	68	74	ns	58	60	60	ns	<0.02	<0.007	<0.0001
Tension (0: relaxed – 100: tensed)	27	32	29	ns	33	38	32	ns	30	31	29	ns	<0.02	ns	ns

The individual subjective responses of the final survey were subjected to principal component analysis. It is pertinent to reiterate that the last survey was selected to realistically model the subjective perceptual constructs under prolonged exposure. Ten subjective factors were extracted from the analysis, each representing a coherent structure of subjective responses (Table 6.5).

The cumulative explained variance indicated that 72% of total variance in the subjective data was accounted by the extracted subjective factors. The first subjective factor, i.e. the neurobehavioral-related symptoms, explained most of the variance in the subjective responses, while the equivalent factor in the previous experiment for air temperature was the cluster of local cooling thermal sensations. The difference confirmed that the most dominant subjective factor in each perceptual construct varied relative to the independent variable. In the present experiment for the outdoor air supply rate, neurobehavioral-related symptoms were apparently more dominant than thermal-related responses.

In the present experiment, the subjective factors are described as follows:

a) SF1: Intensity of neurobehavioral-related symptoms. The subjective factor was positively loaded with the state of feeling/ mood, level of depression, difficulty to think clearly and difficulty to concentrate, intensity of headache and dizziness, the level of fatigue and depression. Mood and depression had the highest loadings on the subjective factor, suggesting the greater influence of psychological stress. Furthermore, subjects associated symptoms related to the nervous system such as dizziness, headache and abilities to think and concentrate to those of psychological/ behavioural measures such as tension, depression, and mood. Based on the factor loading, higher factor scores indicated the increase of neurobehavioral-related symptoms.
b) SF2: Local thermal sensation. Thermal sensation responses of the forehead, neck, body torso, upper and lower arms formed the next subjective factor. The positive loadings of all variables suggested that cooler thermal sensation is related to higher factor scores.
c) SF3: Local thermal sensation and intensity of thermal-related symptoms. The subjective factor was an extension of SF2, in which the local thermal sensation of the body extremities, such as lower arm, hand, thigh, calf and feet were clustered and associated with cold hand and cold feet symptoms intensity. The lower the factor score of SF3, the higher the sensation of cooling of the extremities and the intensity of cold hand and cold feet symptoms.
d) SF4: Perceived odor and irritation. Both olfaction and chemestesis responses were clustered as one subjective factor. Increased perceived odor was associated with increased irritation, as indicated by higher factor score. The factor loading of perceived odor indicated that olfactory system was superior over the irritation responses. This could be linked associated with the perceivable changes in odor level during the re-evaluation of the air quality among the various exposures of outdoor air supply rate while effects of irritation were not clearly observed.
e) SF5: Intensity of dryness symptoms. Intensity of dryness to the mucous membrane and skin surfaces were positively loaded on SF5. Higher factor score on the subjective factor implied the increase in perceived dryness.

f) SF6: Perceptions of air quality. The subjective factor distinctively singled out subjects' perceptions of air stuffiness and the stillness of air and further associated these perceptions with the acceptability of air quality. Previous principal component analysis had demonstrated that subjects/ occupants often linked acceptability of air quality with thermal-related responses. In the present analysis, the separation of subjects' perceptions of air quality from thermally-induced responses highlighted the differentiation of the various subjective traits pertaining to interventions to the outdoor air supply rate.

g) SF7: Self-assessed productivity and effort. An increased amount effort was associated with more productive work, which was indicated by lower factor score of SF7.

h) SF8: Intensity of breathing system-related symptoms. The subjective factor comprised of nose dryness, intensity of blocked nose and flu-like symptoms. As expected, intensity of nose dryness was inversely related with intensity of blocked nose and flu-like symptoms. A higher factor score would indicate increased nose dryness and lowered intensity of blocked nose and flu-like symptoms.

i) SF9: Thermal comfort & thermal sensation. Both the body and inhaled air thermal sensations loaded positively and highly on the subjective factor and were clustered with the perception of thermal comfort. While direct linkage between body thermal sensation and thermal comfort had been shown, the presence of inhaled air thermal sensation on this subjective factor was unexpected and could be suggestive of the influence of respiratory cooling effect on overall thermal comfort of tropically acclimatized subjects.

j) SF10: Perceived illuminance & noise. The last subjective factor served as indicator of other perceptual responses, i.e. the sufficiency of lighting level and the presence of noise problem. The clustering of these responses suggested the separation of both perceptions of lighting and noise from other subjective perceptions related to thermal environment and indoor air quality.

Effects of outdoor air supply rates on the factor scores of each subjective factor are summarized in Table 6.6. Increasing outdoor air supply rate from 4.5 to 9.0 L/s/p reduced SF1 (intensity of neurobehavioral-related symptoms). However, a reversed trend occurred when outdoor air supply rate was further increased to 18.0 L/s/p ($P<0.0001$). The breathing system-related symptoms (SF8) also worsened with higher outdoor air supply rate ($P<0.04$). Subjects experienced higher intensity of nose blocked and flu-like symptom but reduced nose dryness as more outdoor air was introduced to the office. These results reiterated the adverse effect of introducing higher outdoor air supply rate when the increment, in turn, polluted the supply air in the downstream of the used filters. On the contrary, higher outdoor air supply rate was beneficial in reducing the perceived odor and irritation (SF4) with a more pronounced shift in factor score occurring between the settings of 9.0 and 18.0 L/s/p. Likewise, subjects perceived lower air stuffiness, more air movement and more acceptable air quality with increased outdoor air supply rate. It should be reiterated here that subjective responses of the SBS symptoms were taken towards the end of the four-hour exposure prior to the re-entering procedures whilst perceptions of odor and irritation as well as the acceptability rating were made after subjects re-enter the office.

Table 6.5 Extracted subjective factors and the corresponding factor loadings from principal component analysis on subjective responses recorded after 4-hour exposure in the office under the three outdoor air supply rates. Results shown for absolute factor loadings greater than 0.5.

Perceptual responses and intensity of SBS symptoms	SF1	SF2	SF3	SF4	SF5	SF6	SF7	SF8	SF9	SF10
	20%	16%	8%	6%	5%	4%	4%	3%	3%	3%
State of feeling/ mood	0.96									
Level of depression	0.90									
Difficulty to think clearly	0.89									
Difficulty to concentrate	0.86									
Intensity of headache	0.85									
Intensity of dizziness	0.81									
Level of fatigue (tiredness)	0.70									
Level of tension	0.59									
Thermal sensation: Neck (front side)		0.91								
Thermal sensation: Neck (back side)		0.91								
Thermal sensation: Chest		0.90								
Thermal sensation: Back		0.90								
Thermal sensation: Forehead		0.85								
Thermal sensation: Upper arms		0.80								
Thermal sensation: Lower arms		0.57	-0.50							
Thermal sensation: Feet			-0.94							
Thermal sensation: Calf			-0.87							
Intensity of cold feet			-0.71							
Thermal sensation: Thighs			-0.69							
Thermal sensation: Hands			-0.64							
Intensity of cold hand			-0.50							
Odor level				0.90						
Eyes irritation				0.89						
Nose irritation				0.75						
Throat irritation				0.63						
Intensity of mouth dryness					1.02					
Intensity of throat dryness					1.01					
Intensity of lips dryness					1.01					
Intensity of skin dryness					0.73					
Intensity of eyes dryness					0.55					
Air stillness level						-0.77				
Air stuffiness level						-0.71				
Acceptability of air quality						0.62				
Self-perceived productivity							-0.81			
Self-perceived effort							-0.73			
Intensity of nose dryness								0.79		
Intensity of blocked nose								-0.74		
Intensity of flu-like symptoms								-0.62		
Thermal sensation: Body									0.93	
Thermal sensation: Inhaled air									0.91	
Thermal comfort									0.53	
Illuminance level (darkness)										-0.86
Noise level (noisiness)										-0.64

Table 6.6 Effects of outdoor air supply rate on factor score derived for each subjective factor (SF) extracted by the principal component analysis

	Factor scores				
Subjective factors (SF)	4.5 L/s/p	9.0 L/s/p	18.0 L/s/p	Statistics	Score description
SF 1: INTENSITY OF NEUROBEHAVIORAL-RELATED SYMPTOMS	**0.05**	**-0.15**	**0.11**	**P<0.001**	Higher score indicates higher intensity of the symptoms (refer to Table 6.5)
SF 2: LOCAL THERMAL SENSATION	-0.05	-0.01	0.04	ns	Higher score indicates cooler local thermal sensation
SF 3: LOCAL THERMAL SENSATION & INTENSITY OF THERMAL-RELATED SYMPTOMS	-0.02	0.02	-0.08	ns	Higher score indicates lower intensity of cold hand and feet symptoms and warmer local thermal sensation of the body extremities.
SF 4: PERCEIVED ODOR & IRRITATION	**0.08**	**0.03**	**-2.00**	**P<0.0001**	Higher score indicates higher odor and perceived irritation
SF 5: INTENSITY OF DRYNESS SYMPTOMS	0.10	0.02	0.12	ns	Higher score indicates higher perceived dryness
SF 6: PERCEPTIONS OF AIR QUALITY	**-0.14**	**-0.01**	**0.10**	**P<0.02**	Higher score indicates lower perceived stuffiness, more air movement, and more acceptable air quality
SF 7: SELF-ASSESSED PRODUCTIVITY & EFFORT	0.05	-0.03	-0.04	ns	Higher score indicates less effort and less productive completion of tasks
SF 8: INTENSITY OF BREATHING SYSTEM-RELATED SYMPTOMS	**0.06**	**0**	**-0.11**	**P<0.04**	Higher score indicates lower intensity of nose blocked and flu-like symptoms but increased intensity of nose dryness
SF 9: THERMAL COMFORT & THERMAL SENSATIONS	0.06	0.02	-0.05	ns	Higher score indicates better thermal comfort and warmer body and inhaled air thermal sensations
SF 10: PERCEIVED ILLUMINANCE & NOISE	-0.07	-0.02	-0.05	ns	Higher score indicates brighter and less noisy environment

6.4.3. Physiological (biomarker) responses

Salivary Cortisol concentrations of samples collected before and after the 4-hour exposure of three outdoor air supply rates are shown in Figure 6.13. The background levels of salivary Cortisol prior to the exposure (samples collected upon entering the office) were not statistically different across the conditions. The basal level was c.a. 5.5 nmol/l. Lower concentrations were consistently recorded in the samples collected at the end of exposure. The after-exposure salivary Cortisol levels were c.a. 0.4, 0.6 and 0.7 times the background levels in the exposure to 4.5, 9.0, and 18.0 L/s/p, correspondingly. It is also worth noting that the same trend was obtained from previous experiments for air temperature. The reductions of salivary Cortisol concentration at the end of exposure may be related to the diurnal pattern of Cortisol secretion. This result also suggests that subjects were gradually relieved from the workload and thus led the HPA axis to relax the neuro-endocrine system voluntarily.

There were significant effects of outdoor air supply rates on the salivary Cortisol level. Salivary Cortisol secretion increased significantly with higher outdoor air supply rate after the exposure (P<0.001), indicating higher HPA activation level with the increase of outdoor air supply rate. This significant result was attributable to higher Cortisol at 9.0 L/s/p (P<0.02) and 18.0 L/s/p (P<0.001) when compared with the concentration at 4.5 L/s/p. There was, however, no further increase of Cortisol level when outdoor air supply rate was doubled from 9.0 to 18.0 L/s/p. The result of exposure to 18.0 L/s/p is in good agreement with the higher neurobehavioral-related symptoms, suggesting an elevated physio-psychological stress at 18.0 L/s/p. However, this explanation could not be applied to the observed increased of salivary Cortisol at 9.0 L/s/p. Another possible explanation to this effect may be related to the gradual increase of breathing system-related symptoms with higher outdoor air supply rate, which corresponded well with the magnitude of change in salivary Cortisol concentrations across the three outdoor air supply rates.

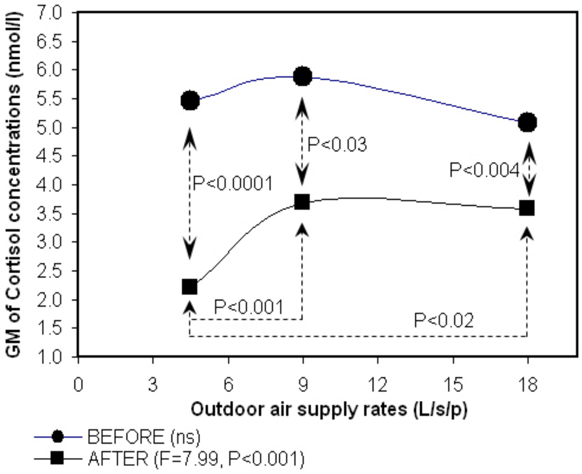

Figure 6.13 Geometric means of salivary Cortisol concentrations as the functions of outdoor air supply rates (before and after 4-hour exposure in the FEC)

Analysis of salivary α-Amylase concentrations showed no significant differences among the three outdoor air supply rates at the start of exposure (Figure 6.14). The biomarker levels, however, consistently increased after the four-hour exposure (P<0.0001). Least activation of the sympathetic nerves was seen under the exposure to higher outdoor air supply rate at 18.0 L/s/p, while greater increases of the norepinephrine indicator (indicating higher activation) were observed at 4.5 and 9.0 L/s/p. Further analysis revealed a significantly lower salivary α-Amylase concentration induced by doubling outdoor air supply rate from 9.0 to 18.0 L/s/p (P<0.005). Based on the results, subjects appeared to have lower arousal at 18.0 L/s/p, plausibly related to the reduced mental alertness following the increased neurobehavioral-related symptoms.

Figure 6.15 highlights the results of immunoglobulin-A analysis in the saliva samples collected after the four-hour exposure. Due to the limited amount of analysis kit during quantification process and based on observations from other biomarkers, a decision was made to focus on samples taken after the 4-hour exposure under the various outdoor air supply rates. The analysis revealed that sIgA levels decreased gradually with increased outdoor air supply rates. A 15% decrease of sIgA concentrations was observed when outdoor air supply rate was elevated from 4.5 to 18.0 L/s/p (P<0.005). In conjunction with the results of salivary Cortisol, there seemed to be the suppression of sIgA level when the HPA axis was activated, increasing susceptibility of the immune system at the mucosal surfaces, through which infections may be initiated. Another observation of increased breathing system-related symptoms (SF8) also supported this postulation.

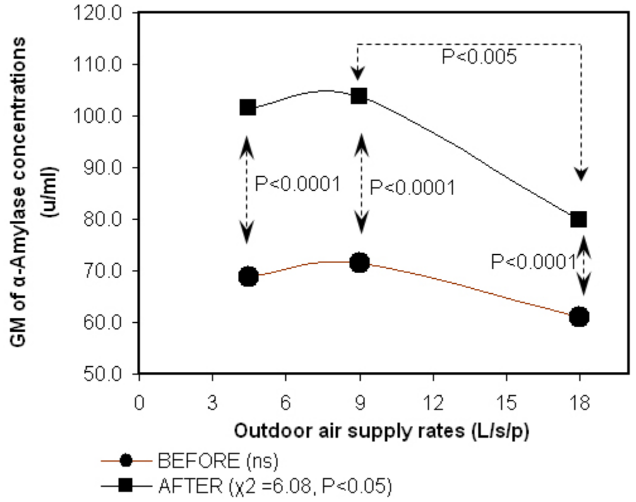

Figure 6.14 Geometric means of salivary α-Amylase concentrations as the functions of outdoor air supply rate (before and after 4-hour exposure in the FEC)

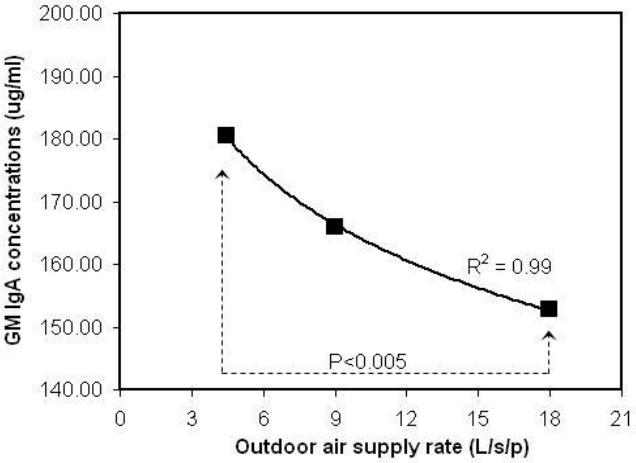

Figure 6.15 Geometric means of salivary sIgA concentrations as the functions of outdoor air supply rate (after 4-hour exposure in the FEC)

An additional analysis based on the mass-balance model of measured indoor carbon dioxide level, measured outdoor carbon dioxide concentration, and the outdoor air supply rates (ASHRAE, 2004) revealed that there was a marked decrease of carbon dioxide production rate when the subjects were exposed to higher outdoor air supply rate (Figure 6.16). Assuming that indoor air pollution level was elevated at 18.0 L/s/p, this result supported the postulation that in the event of higher pollution, subjects would unconsciously alter their breathing pattern, causing them to breathe shallowly and thus, reducing the carbon dioxide generation rate.

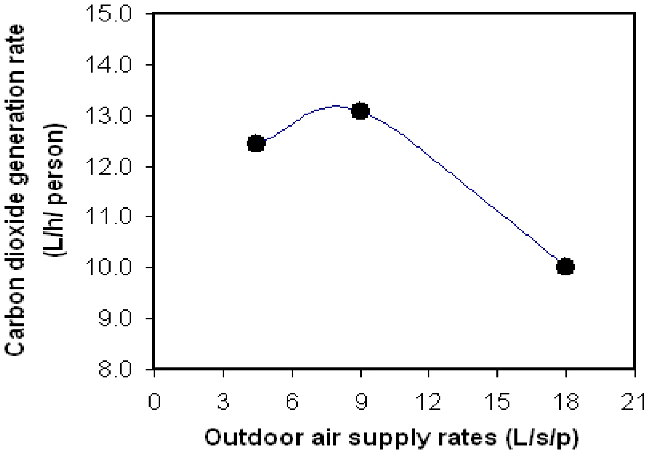

Figure 6.16 Estimated carbon dioxide generation rates as the functions of outdoor air supply rate. Calculation was based the projected steady-state carbon dioxide concentrations.

6.4.4. Performance measures

The four-hour occupation was completed by the subjects while performing various tasks of mental performance and other simulated office work such as proofreading, numerical addition, and text-typing. The results of the mixed model analysis adjusted for time-related effects and subjects' gender, when these effects were present, following the procedures described in sections 4.6.2 and 5.4.4 are presented in the following section. Results of analysis for performance tests conducted during the first and second halves of the experimental session was reported together with separate analysis on performance data collected from morning and afternoon sessions.

6.4.4. A. Mental performance tests

Table 6.7 summarizes the subjects' mental performance under the exposures to three outdoor air supply rates. The evaluation was made based on speed and accuracy measures for each task, except for the creativity test, which employed the creativity score. The analysis revealed that performance accuracy was not affected across the range of mental performance tests. The speed of work of two tasks, namely numerical reasoning and creativity, was significantly improved at higher outdoor air supply rate. There was also the tendency of faster speed of work during alphabetical reasoning and concentration endurance tests at higher outdoor air supply rates, although these did not reach the formal significance level.

Table 6.7 Speed and accuracy of mental performance tests at three outdoor air supply rates. Results obtained from mixed model estimated marginal means.

Mental performance	Speed*					Accuracy*				
	4.5 L/s/p	9.0 L/s/p	18.0 L/s/p	P**	unit	4.5 L/s/p	9.0 L/s/p	18.0 L/s/p	P**	unit
Numerical reasoning	2.7	2.8	2.9	<0.03	rows/min	21.3	20.5	21.8	ns	% error
Alphabetical reasoning	24.8	25.3	25.2	ns	units/min	1.4	1.2	1.4	ns	% error
Concentration	159.1	159.9	163.5	<0.06^{+}	characters/min	2.4	2.2	2.1	ns	% error
Arousal	17.7	17.7	17.6	ns	links/min	2.4	2.5	2.9	ns	% error
Creativity$^{\#}$	6.7	7.3	7.8	<0.02	bits					

Notes: *: values are geometric means, **: based on mixed model fixed (main) effects statistics, $^{\#}$: data shown for C-score, $^{+}$: one-tailed statistics

Figure 6.17 depicts the speed (rows/min) and accuracy (percentage error) of numerical reasoning performance. Subjects performed the numbers sequencing task faster at 18.0 L/s/p than at 4.5 L/s/p (P<0.02), which was equivalent to c.a. 7.1% increase in speed of work (each row of ten 2-digit numbers required approximately 21 seconds for re-sequencing). There was no significant difference of performance accuracy of numerical reasoning at different conditions of outdoor air supply rate. Improved reasoning performance, however, could not be associated with the intensity of SBS symptoms or physiological measure of salivary Cortisol level. It had been shown before that higher outdoor air supply rate increased intensity of symptoms and psychological stress. As the nature of the task required subjects to work within a reasonable short duration, i.e. 8 minutes, the time pressure coupled with task difficulty would demand better attention and lower optimum arousal for performance. The concentration endurance test result shown in Table 6.7 indicated the tendency of higher concentration at 18.0 L/s/p (P<0.06, one-tailed). Moreover, the result of salivary α-Amylase indicated lower activation (arousal) level at higher outdoor air supply rate, although the Tsai-partington test did not successfully detect any change in arousal level.

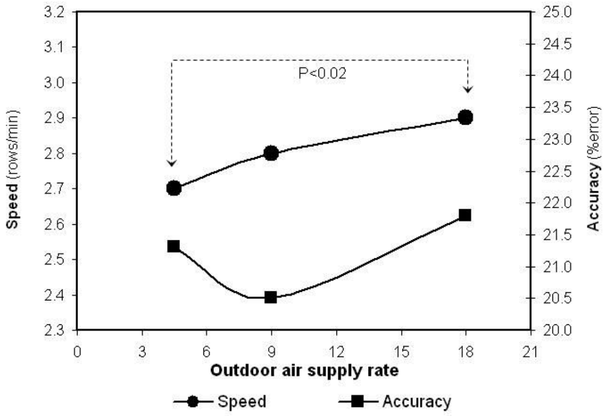

Figure 6.17 Geometric means of speed and accuracy measures of numerical reasoning as the function of outdoor air supply rate

The numerical reasoning test was performed once at the beginning of the session, and therefore, no comparison could be made between performance during the first and second halves of the session. Subjects who attended the afternoon sessions performed significantly faster at higher outdoor air supply rates (P<0.0001), while subjects in the morning were able to maintain their working speed (Table 6.8). The mixed model analysis revealed that subjects in the morning groups made significantly higher percentage error than those in the afternoon groups (P<0.001), which accounted for 4-6% reduced percentage errors consistently.

Table 6.8 Speed and accuracy of numerical reasoning tests during first and second half of session Results obtained from mixed model estimated marginal means.

Mental performance	**Speed** (characters/min)				**Accuracy** (% error)			
	4.5 L/s/p	9.0 L/s/p	18.0 L/s/p	P	4.5 L/s/p	9.0 L/s/p	18.0 L/s/p	P
Numerical reasoning (morning)	2.7	2.7	2.7	ns	23.4	23.2	24.9	ns
Numerical reasoning (afternoon)	2.7	2.8	3.0	<0.0001	19.3	17.7	18.9	ns

Increasing outdoor air supply rate significantly improved creative thinking (P<0.02). There was a difference of c.a. 1.1 bit based on the computed C-score between subjects' creative thinking under the exposure to 4.5 and 18.0 L/s/p (P<0.02), indicating subjects' better ability to provide unique ideas to the application of the simple object in the open-ended question (Figure 6.18). Based on this result, the higher psychological stress (Cortisol level) and intensity of neurobehavioral-related symptoms (SF1), seemingly, did not pose detrimental effects on the creative thinking, particularly during the first half of the session as seen in results of independent analysis of first- and second-try of the task (Table 6.9). Subjects performed generally worst under exposure of 4.5 L/s/p during both tries and the effects of outdoor air supply rate produced the significant effects only in the first-try of the creativity task (P<0.009).

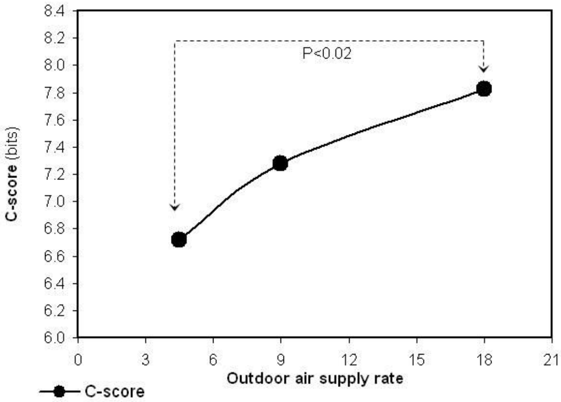

Figure 6.18 Geometric means of C-score of creativity task as the function of outdoor air supply rate

A more detailed analysis showed that subjects made significant improvements between the first- and second-try (P<0.01). There was also significant interactions between exposure conditions and time of test (P<0.05), indicating that subjects made the most improvement of C-score between the first- and second-try at lower outdoor air supply rate (ΔC-score$_{4.5L/s/p}$: 1.9 bits) and that the magnitude of change in C-score decreased as the outdoor air supply rate increased (ΔC-score$_{9.0L/s/p}$: 1.7 bits, ΔC-score$_{18.0L/s/p}$: 0.6 bits). The gradual increase of neurobehavioral-related symptoms over the time of exposure at 18.0 L/s/p could be the plausible explanation for the diminishing benefit of increasing outdoor air supply rate (with the presence of carpet and used filter) on creative thinking performance.

Subjects in morning groups performed significantly more creative when outdoor air supply rate was increased from 4.5 to 9.0 or 18.0 L/s/p (P<0.03), while in the afternoon groups, similar trend was observed between C-scores obtained at 4.5 and 18.0 L/s/p (P<0.04, one-tailed).

Table 6.9 C-score of open-ended creative thinking task a) during first and second half of session b) between morning and afternoon sessions. Results from mixed model estimated marginal means.

Mental performance	**C-score** (bits)			
	4.5 L/s/p	9.0 L/s/p	18.0 L/s/p	P
a) Creativity (1st-try)	5.9	6.5	7.6	<0.009
Creativity (2nd-try)	7.8	8.3	8.2	ns
b) Creativity (morning)	6.8	8.2	8.0	<0.03
Creativity (afternoon)	6.7	6.5	7.7	<0.04*

*Note: * = one-tailed statistics*

6.4.4. B. Simulated office tasks

The simulated office tasks included both arithmetic and language-processing skills. Table 6.10 summarizes the findings based on the mixed model analysis and the statistics shown here had been adjusted for time-related influences and gender effects, if any. The speed and accuracy of numeric addition, accuracy of proofreading, and speed of text-typing were significantly influenced when outdoor air supply rates were modified.

Table 6.10 Speed and accuracy of simulated office tasks at three outdoor air supply rates. Results obtained from mixed model estimated marginal means.

Mental performance	**Speed***					**Accuracy***				
	4.5 L/s/p	9.0 L/s/p	18.0 L/s/p	P**	unit	4.5 L/s/p	9.0 L/s/p	18.0 L/s/p	P**	unit
Numeric addition	28.2	29.0	28.9	<0.04	units/min	0.7	1.0	0.9	<0.04	% error
Proof reading	21.1	21.4	21.2	ns	lines/min	54.5	54.0	57.3	<0.002	% error
Text-typing (words)	31.7	32.1	30.4	<0.003	words/min	0.8	0.8	0.9	ns	% error
Text-typing (characters)	192.5	197.6	187.4	<0.0001	characters/min					

Notes: *: values are geometric means, **: based on mixed model fixed (main) effects statistics

The number of units added per minutes (P<0.04) and the percentage errors (P<0.04) of numeric addition performance varied between the exposures to the three outdoor air supply rates. The significant differences were, as shown in Figure 6.19, contributed by the increase of speed (P<0.05) at the expense of higher percentage errors (P<0.04) between exposures to 4.5 and 9.0 L/s/p, while speed at 18.0 L/s/p did not differ significantly from other conditions and the percentage error were only marginally lower than the errors committed under the exposure to 9.0 L/s/p. These latter effects were not statistically significant. The main effects of outdoor air supply rate on numerical addition agreed well with the results of numerical reasoning measurement. However, the advantage of faster work compromised the level of accuracy in the addition task. Taken together, the speed and accuracy analysis suggested an increase of numerical addition performance by c.a. 2.5% of average 229 units added with the doubling of outdoor air supply rate from 4.5 to 9.0 L/s/p.

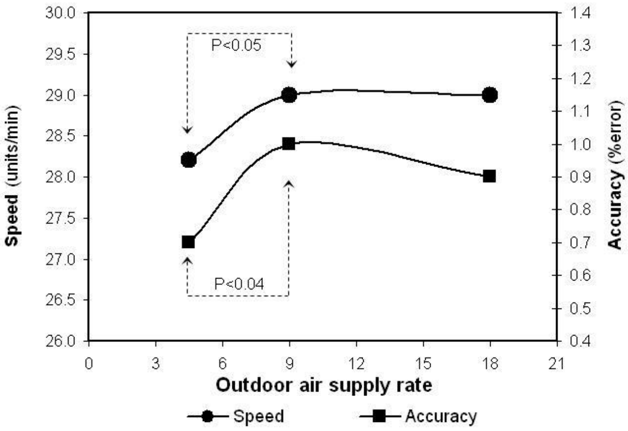

Figure 6.19 Geometric means of speed and accuracy measures on numeric addition task as the function of outdoor air supply rate

Subjects performed the numerical addition task faster at 9.0 and 18.0 L/s/p in both first- and second- try (Table 6.11). This trend was significant during the second-try (P<0.04), while the differences in accuracy in the second-try was not significantly difference. Subjects performed significantly faster during the second-try (P<0.0001) and more so with the increase of outdoor air supply rate (P<0.05). On the other hand, accuracy was affected during the first attempt of the task at P<0.007. Combined with mental performance of numerical reasoning, it is clear that short-term arithmetic performance was not affected by the change of neurobehavioral-related symptoms. There was no difference in terms of accuracy or percentage error between first and second attempts and likewise, on the magnitude of changes at the three outdoor air supply rates. Additionally, subjects' performance in the morning groups was significantly affected by outdoor air supply rate for both the speed (P<0.03) and accuracy (P<0.05) measures.

Table 6.11 Speed and accuracy of numeric addition task
a) during first and second half of session b) between morning and afternoon sessions.
Results obtained from mixed model estimated marginal means.

Mental performance	**Speed** (lines/min)				**Accuracy** (% error)			
	4.5 L/s/p	9.0 L/sp	18.0 L/s/p	P	4.5 L/s/p	9.0 L/sp	18.0 L/s/p	P
a) Numeric addition (1st-try)	27.6	28.1	27.9	ns	0.9	1.2	1.0	<0.007
Numeric addition (2nd-try)	28.9	29.9	30.0	<0.004	0.8	0.8	0.9	ns
b) Numeric addition (morning)	27.7	28.0	28.8	<0.03	0.9	1.2	1.1	<0.05[+]
Numeric addition (afternoon)	28.1	29.4	28.4	ns	0.7	0.9	0.8	ns

Note: [+]: one-tailed statistics

The proofreading speed of subjects did not vary when exposed to various outdoor air supply while the accuracy levels or percentage errors (based on unidentified intentional errors) were significantly affected (P<0.0002). A significantly higher percentage error in the highest outdoor air supply rate was obtained from the analysis (Figure 6.20), which may be the consequence of higher psychological stress, lower arousal, and increased neurobehavioral-related symptoms. Proofreading performance as a multi-paradigm task would generally require high attention and ability to think clearly. In the light of various detrimental factors induced by elevated outdoor air, it seemed that the subliminal mental performance for proofreading performance could not be attained.

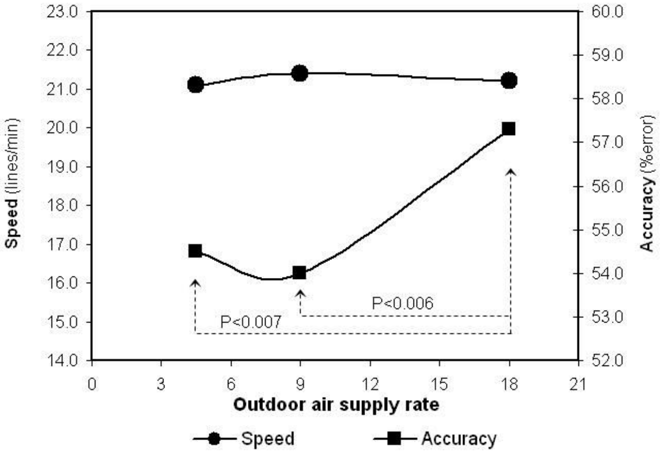

Figure 6.20 Geometric means of speed and accuracy measures on proofreading task as the function of outdoor air supply rate

Analysis based on first- and second-try on proofreading as well as morning and afternoon groups confirmed that speed of reading was unaffected (Table 6.12). The effects on proofreading accuracy were consistent for both attempts. Further analysis also revealed that differences between percentage errors during first- and second- try gradually increased with higher outdoor air supply rates (P<0.02). Subjects missed significantly more intentional errors in the second-try (P<0.001) and in the afternoon sessions (P<0.001).

Table 6.12 Speed and accuracy of proof reading task
a) during first and second half of session b) between morning and afternoon sessions.
Results obtained from mixed model estimated marginal means.

Mental performance	**Speed** (lines/min)				**Accuracy** (% error)			
	4.5 L/s/p	9.0 L/sp	18.0 L/s/p	P	4.5 L/s/p	9.0 L/sp	18.0 L/s/p	P
a) Proofreading (1st-try)	20.9	21.3	21.5	ns	57.7	56.7	59.5	$<0.05^{+}$
Proofreading (2nd-try)	21.3	21.5	20.8	ns	57.1	58.2	61.6	<0.02
b) Proofreading (morning)	21.2	21.7	22.4	ns	53.7	52.2	54.3	ns
Proofreading (afternoon)	21.0	21.3	20.0	ns	55.6	56.0	60.9	<0.0001

Note: $^{+}$: one-tailed statistics

Subjects performed the first typing tasks for 48 minutes starting from the 18th minute (first-try) and 176th minute (second-try). The combined and adjusted mixed model analysis revealed significant differences of typing speed in terms of number of words per minute (P<0.003) and number of characters per minute (P<0.0001), while no significant difference was associated with accuracy of text-typing. The difference in terms of characters typed per minute, which also reflected the change of words typed per minute is shown in Figure 6.21. Subjects typed significantly slower at 18.0 L/s/p when compared with speed at 9.0 (P<0.0001) and 4.5 L/s/p (P<0.08). Under normal office working day, Burr (2000) estimated that about 1.8 hours were spent on text-typing related activities assuming that worker spent 65% of their office hours working with computer and 35% of this duration for typing.

Based on this assumption and the effect on text-typing speed in the present study, exposure to higher outdoor air supply rate led to a loss of c.a. 1.4% of total working time in a day. The same negative factors affecting proofreading task may be extended to explain the present results on text-typing. Text-typing is generally a more complex task that it involves cognitive skills, manual dexterity and visual attention, all of which must be sustained over a longer duration of work. The lack of effects on accuracy of text-typing in the present experiment as well as that of previous results from air temperature interventions suggests that subjects consistently checked and corrected errors in the text (proofread) as part of the text-typing routines.

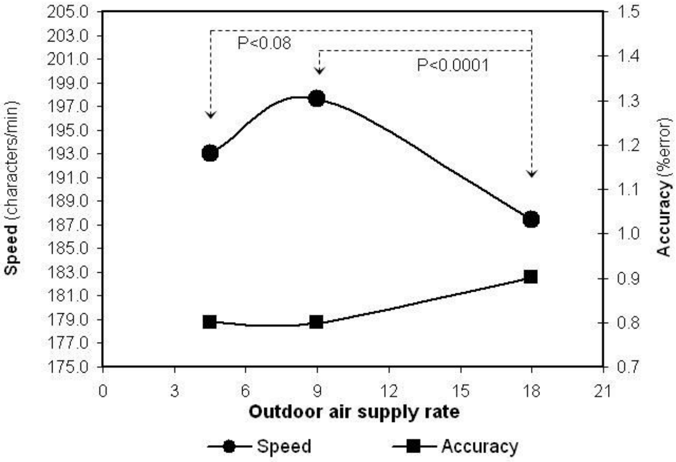

Figure 6.21 Geometric means of speed (characters per minutes) and accuracy measures on text-typing task as the function of outdoor air supply rate

Speed measures of text-typing (defined by words/min and characters/min) were significantly higher in the second-try (P<0.0001) (Table 6.13). The exposures to various outdoor air supply rates did not affect the changes between first and second text-typing tasks. Nevertheless, the significant difference of text-typing speed under exposures to the conditions was seen in the first-try (P<0.002). In the second-try, the trend approached significance at P<0.08. Likewise, the same effect on text-typing speed was observed within the morning groups (P<0.0001), while in the afternoon, the similar trend did not achieved the formal significance level. No significant effects on percentage text-typing errors were observed from the time-related comparative analysis.

Table 6.13 Speed and accuracy of text-typing task
a) during first and second half of session b) between morning and afternoon sessions.
Results obtained from mixed model estimated marginal means.

	Speed								**Accuracy** (% error)			
	(words/min)				(characters/min)							
Mental performance	4.5 L/s/p	9.0 L/sp	18.0 L/s/p	P	4.5 L/s/p	9.0 L/sp	18.0 L/s/p	P	4.5 L/s/p	9.0 L/sp	18.0 L/s/p	P
a) Text-typing (1st-try)	29.2	30.6	28.6	<0.002	183.2	193.2	180.0	<0.002	0.9	0.9	1.0	ns
Text-typing (2nd-try)	34.6	34.6	33.8	<0.06*	204.4	205.1	199.4	<0.08	0.7	0.7	0.8	ns
b) Text-typing (morning)	31.0	32.1	29.1	<0.0001	188.4	196.0	177.8	<0.0001	0.8	0.8	1.0	ns
Text-typing (afternoon)	32.0	32.4	31.8	ns	195.5	197.7	194.2	ns	0.8	0.8	0.9	ns

6.4.4. C. Self-evaluation of performance

The subjective responses for self-evaluation of performance, namely self-perceived effort and productivity, were not significantly affected by outdoor air supply rate interventions. A more detail analysis showed that subjects felt more productive at the end of exposure with the greater improvement reported under exposure of 18.0 L/s/p ($P<0.0001$). There was no significant difference of perceived effort between the 118th – 230th minute. Overall, the self-evaluation of performance did not reflect the effects observed for other subjective affects as well as the objective measures of performance.

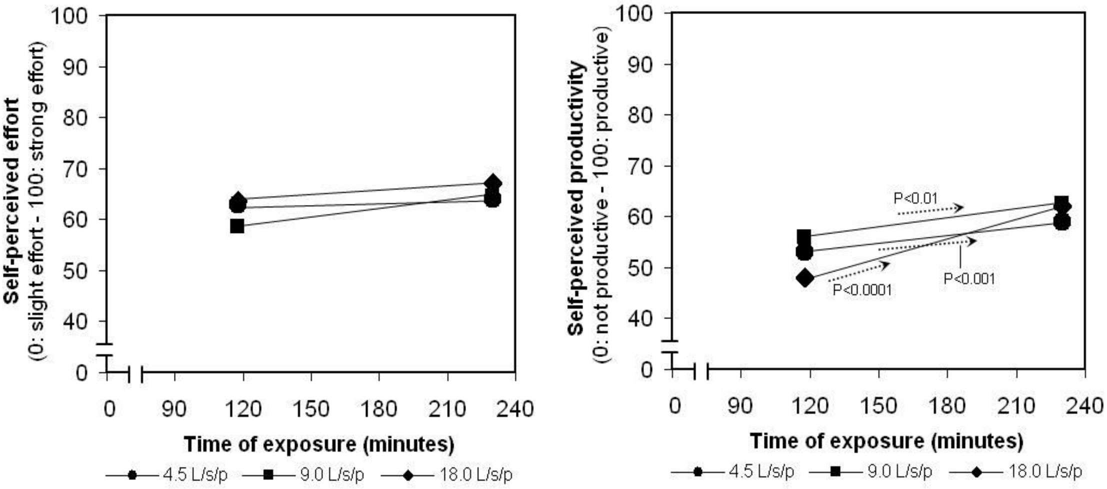

Figure 6.22 Self-perceived effort (left) and productivity (right) as the function of time of exposure

6.5. Structural equation model

Figure 6.23 shows the final structural model derived from the methods described in section 5.5. The statistical modeling procedures started from fitting the smaller subsets of latent structures to identify the effects of interventions to the amount outdoor air on various perceptual, physiological and performance variables. In the present study, the latent components tested independently are "percept" representing perceptual constructs of the subjective responses with four factors (CFI: 0.97, RMSEA: 0.03), "physio" representing physiological responses to the atmospheric changes with two factors (CFI: 0.96, RMSEA: 0.05) and "perform" representing four performance variables (CFI: 0.98, RMSEA: 0.03). Of particular importance to note in the final model is the exclusion of the sIgA concentrations data, which was not found to be a statistically significant factor to physiological latent structure and appeared to weaken the statistical fit, due to its relatively small loading. Upon evaluation of the smaller subsets of hypotheses, they were combined following the postulated structural model depicted in Figure 6.1. The final model was derived from the theoretical constructs and postulated mechanisms derived from previous results. It is the equivalent of the MPIESM developed for the effects of air temperature. The numeric values shown in Figure 6.23 are the significant standardized coefficients (based on standard deviations) of the direct relationships or the covariance between two variables.

The final model produced a reasonably good fit to the overall data with $X^2 = 29.2$ (df=25, N=285, $P<0.25$) after 11 iterations using the maximum likelihood estimation. Other goodness-of-fit criteria used in the evaluation of the model fit also suggested that the model sufficiently predicted the postulated relationships among the parameters with CFI=0.98 (a value greater than 0.95 often indicative of good-fitting models (Hu and Bentler, 1999)) and RMSEA=0.03 (a value larger than 0.10 indicates a poor-fitting model relative to the model degrees of freedom (Browne and Cudeck, 1999)). Test for skewness of data did not revealed any significant deviations, while three outliers were detected based on the Mahalanobis distance and Mardia's coefficient criteria at $P<0.0001$ due to extremely high factors scores on SF4 and SF8. These outliers were subsequently deleted from the input data. The recursive model (one-directional) comprises of 24 variables with 11 observed and 13 unobserved variables. The solution of the model with various restrictions (covariations) was based on 66 distinct sample moment and 41 parameters to be estimated (df=25).

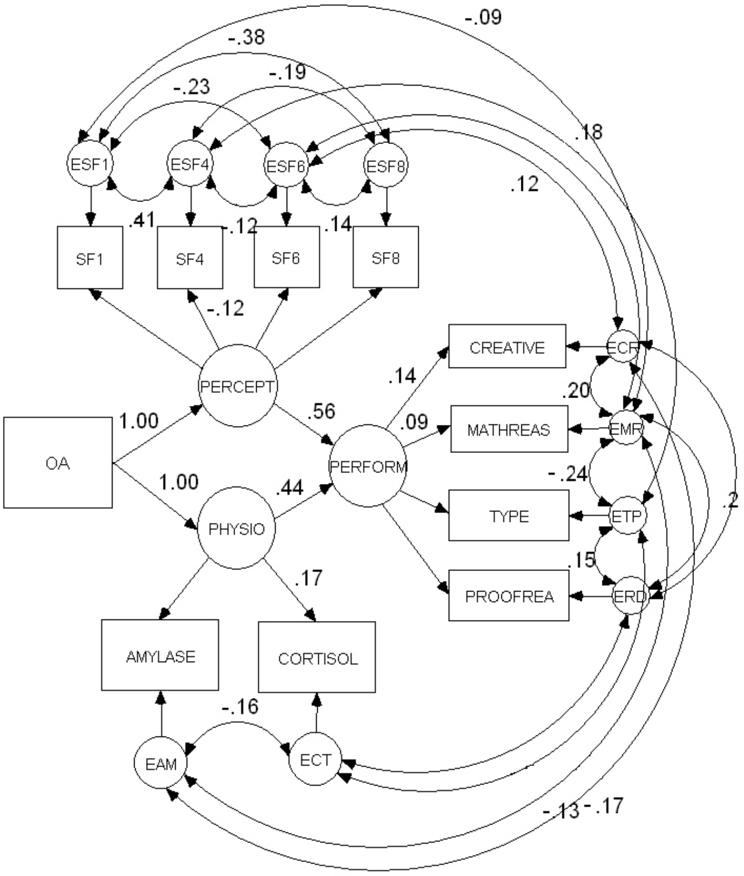

Figure 6.23 Man-performance-indoor environment structural model (MPIESM) for effects of outdoor air supply rate. Figure taken from AMOS™ 5.0 SEM program.

The basic latent structure of the MPIESM consists of two main pathways, namely a) outdoor air supply rate – perceptual responses – performance measures and b) outdoor air supply rate – physiological responses – performance measures. Both links were found to be the significant predictors of work performance. The significant direct effects of outdoor air supply on "percept" and "physio" (standardized coefficient/ SC=1.00) show that the environmental parameter was a good predictor of perceptions to air quality and physiological responses. Progressively, "percept" and "physio" also served as predictors of "perform" latent variable, with SC=0.56 and =0.44, respectively. The model also indicates that the measured or derived variables associated with the latent components were not always significantly loaded. The subjective factor, SF4, negatively loaded on "percept" (SC=-0.12) while the rest did not reach the formal significance (SF6 and SF8 was significant loaded at $P<0.07$ for one-tailed statistics). Likewise, only salivary Cortisol level served as significant predictor of "physio" at SC=0.17. Subjects' performance as delegated by "perform" latent variable was predicted by the C-score of creativity task ("creative") and the numerical reasoning task ("mathreas"), while the other simulated office tasks did not load significantly on the latent variable. Further observations reveal that the model has greater reliance on the covariances among the variables (represented by double-headed arrows). These covariances (or correlations when expressed as standardized coefficients) indicate the direct relationships between variables of perceptual responses and performance measures, between variables of physiological responses and performance measures, as well as between variables within each latent construct.

The significant correlations of residuals between EAM and ECR as well as between EAM and EMR show plausible predictive ability of the salivary α-Amylase on both mental performance. Higher salivary α-Amylase indicating lower mental alertness (SAM activity) would provide a better mental state for creativity and numerical reasoning. The modification indices indicated that allowing for residuals of salivary Cortisol and both simulated office task to covary would improve the model estimation. If realized, salivary Cortisol as a correlate of stress-response could be a useful indicator for text-processing tasks such as text-typing and proofreading. There were significant negative correlations between EMR and ETP (speed) as well as positive correlation between EMR and EPR (accuracy) which indicated that better numerical reasoning is associated with lower text-typing and proofread performance. There was no apparent explanation for these relationships, except that both tasks were influenced by the same mechanism of mental activation and stress response in different directions and thus, allowing the negative correlation of the performance variables.

Perceptual responses expressed as subjective factors (SF) that were derived from the principal component analysis have been shown in the model as plausible predictors of various performance measures: a) ESF1 (neurobehavioral-related symptoms) was negatively correlated with EMR (numerical reasoning), b) ESF4 (perceived odor and irritation) was positively correlated with ETP (text-typing), and c) ESF6 (perceptions of air quality) was positively correlated with ECR (creativity thinking). These model correlations imply that higher neurobehavioral-related symptoms would lower the numerical reasoning ability, stronger odor and irritation would reduce typing performance, and finally, perceived stuffy air and poor acceptability of air quality would adversely affect creative thinking.

6.6. Discussions

The present experiment was devised to investigate the effects of changing outdoor air supply rates on subjects' perceptions, stress-related biomarkers, intensity of SBS symptoms and work performance within the tropical context. The range of outdoor air supply rate studied was common to the air-conditioned office premises, i.e. between 4.5-18.0 L/s/p, in the tropics (Sekhar et al, 2002 and Tham et al, 2002) and around the world (Sundell, 1994, Bluyssen et al, 1996). It was found that increasing outdoor air supply rates would gradually improve the sensory evaluation of indoor air quality by means of reducing perceivable odor, lowering perceived air stuffiness and air stillness, and improving acceptability (and thus lowering percentage dissatisfied) of the tropically acclimatized subjects. Introducing higher amount of outdoor air supply rates above 9.0 L/s/p in conjunction with used ventilation filters further increased the risk of aggravating the intensity of neurobehavioral-related symptoms and other breathing system-related symptoms, and would tend to elevate irritation to the eyes.

The present results suggest that various physiological attributes were sensitive to changes of indoor air quality. The biomarkers quantification revealed that higher salivary Cortisol and reduced salivary α-Amylase and sIgA levels were exclusively related to air quality at 18.0 L/s/p. Gradual improvements of creativity and numerical reasoning with increasing outdoor air supply rate were observed, while multi-paradigm and complex simulated office tasks, i.e. proofreading and text-typing, were impaired at 18.0 L/s/p. These findings indicated that while increasing outdoor air supply rates improved perceptual responses of air quality and performance, it might also cause adverse effects of the intensity of SBS symptoms and other tasks. In the present study, the latter effects were presumably related to higher concentration of indoor air pollutants. The presence of used ventilation filters in the air distribution system was identified as a major source of pollution load, particularly when the amount of outdoor air passing through it was increased substantially. Finally, the practical usefulness of the objective measures of psycho-physiological biomarkers and the subjective evaluation of perceptions and SBS symptoms in explaining some plausible mechanisms was demonstrated.

6.6.1. Perceptual and sensory responses of the indoor air quality

One of the main hypotheses in the present study that increasing outdoor air supply rate would lead to better acceptability of air quality and reduction of perceived odor and irritation was accepted, except for the effects on irritation, which mostly did not exhibit improvements with outdoor air supply rate. Improved acceptability of air quality with higher ventilation rates reconfirmed the effects observed in the call center studies, in particular, the consistent effects in Call center B. The main effects of outdoor air supply rate on two subjective factors, i.e. SF6 (perceptions of air quality) and SF4 (perceived odor and irritation), which represents the clusters of perceptual responses related to sensory assessments, confirmed the positive implications of increasing outdoor air supply rate. Wargocki et al (2000) reported the monotonic improvements of perceived air quality and correspondingly the reduction in percentage dissatisfied with increasing ventilation rate based on subjective assessments of thirty female subjects made upon entering and re-entering the simulated office. In their study, subjects also perceived the air quality to be markedly worse upon re-entering the room at lower outdoor air supply rates suggesting the strong influence of accrued bio-effluents due to low ventilation rate. Although the effects of increasing outdoor air supply rate was seen in the present study, the latter effect due to increased perceivable bio-effluents was not obvious and significant on both acceptability of air quality and perception of odor. The effect of prolonged respiratory cooling effects as observed from the inhaled air thermal sensation vote at 23°C on perceived air quality even after refreshing outside the office may have potentially altered the negative effects of the accumulated bio-effluents generated by the subjects. This finding is also supported by the result from previous experiment for the effects of air temperature, although the previous study did not include carpets as additional pollution load (see Chapter 5). Maintaining the level of outdoor air supply rate sufficient to dilute pollutants from material emissions and other gaseous by-products of oxidation processes while maintaining optimum thermal sensation for comfort is therefore of practical significance as was previously suggested by Gunnarsen and Fanger (1992).

The present experiment was conducted in the well-controlled simulated office environment and the indoor environmental parameters achieved the quasi-steady state condition before subjects entered the room, except for the built-up of pollutants associated with subjects' activity and the bio-effluents. The positive effects of outdoor air supply rate at the onset of experiment were therefore solely attributable to the air quality polluted by the air distribution system including the presence of used filters, the carpets, and office appliances such as computers and printers. Towards the end of session, presence of bio-effluents introduced additional load to subjects' perceptual (olfactory) senses but was confounded by the respiratory cooling sensation. This result is in good agreement with finding in another study by Molhave et al (1993) which demonstrated that acceptability of air quality and perceived odor in the presence of various levels of VOC is influenced by room air temperature. Odor perception habituated almost immediately during the first hour, after which no observable changes occurred. On the contrary, sensory irritation to the eyes was elevated during the first hour and remained higher throughout the habituation period with tendency of more irritation in the higher ventilation. The results suggest that irritation effects may exhibit a longer latency than the olfactory senses on odor. The increase eyes irritation may be partially caused by the VDU-related tasks performed in the office. Various studies have suggested the benefits of increasing outdoor air supply rates in reducing the indoor air pollution levels. However, this may not be the case when used/ loaded filters were installed. Alm et al (2000) and Størm-Tejsen et al (2003) have shown that increasing ventilation rates within and above the normal ventilation rates, when coupled with used ventilation filters elevated the sensory pollution load following a linear function. The pollution source strength of loaded filters could also increase with operating time (Pejtersen, 1996). With the total air flow through the used ventilation filter kept constant, Wargocki et al (2004) further argued that higher proportion of outdoor air in the upstream of the filter would lead to lower retention of pollutants on the filter's dust cake and thus higher emissions and concentrations of pollutants transported to the occupied space. In the present study, higher dust particulate levels in terms of number and mass concentration of particles at 18.0 L/s/p were registered, which may be an indicator of deterioration of air quality. These consistent findings could be a plausible explanation to the negative effects on the mucous membrane of the eyes with increasing outdoor air supply rate and the elevated intensity of SBS symptoms.

Previous studies on the effects of outdoor air supply rate on indoor air contaminants generation and sensory mechanisms were mostly conducted without air recirculation, which could be an important determinant factor for the overall air quality in offices in the tropics, where recirculation is part of the air conditioning system. The present study was performed using the close air distribution system with recirculation. A recent study by Zuraimi et al (2005) in the same laboratory set-up concluded that increased ozone and SOA (secondary organic aerosols) deposition on surfaces due to thinner surface boundary layer occurred at higher recirculation rates, and thus reduced significantly the amount of particles in the air. However, this study was conducted without ventilation filters and only at one constant outdoor air supply rate. With loaded filters installed and higher amount of outdoor air passing through, the ozone consumption across the filters would likely be increased as suggested by Bekö et al (2006), resulting in plausibly higher gas-phase ozone-initiated indoor chemistry or oxidation downstream the filters (Hyttinen et al (2003)).

Another possible explanation was related to the presence of carpet in the office. Wargocki et al (1999) have demonstrated that air quality with the presence of carpet reduced perceived air quality, increased irritation and SBS symptoms and worsened performance. The emission of pollutants from carpet in the present study could also increase the irritants or by-products generation in the air catalyzed and aggravated by ozone and higher desorption from indoor surfaces at higher outdoor air supply rate. The sensory pollution load calculated for three outdoor air supply rates were higher at 18.0 L/s/p indicating higher pollutants emission. Knudsen et al (1997) and Wargocki et al (2000) had also reported the same tendency in the previous studies.

The preceding discussions implied that increasing outdoor air supply rate with loaded filter and presence of carpet seemingly caused detrimental effects on air quality, particularly during the quasi-steady state conditions or long-term exposure. In addition, due to accruing pollution load in the longer exposure, the adverse effects on irritation and other symptoms could still be present despite lower perceived odor and improved acceptability of air quality due to olfactory adaptation. It is important to note that a clear distinction must be maintained between perceptual responses during immediate exposure as opposed to that of habituation period. In the later, perceived odor and therefore, acceptability of air quality may not elicit the actual exposure-response caused by indoor air pollution. In a review, Köster and Degel (2001) concluded that weak or unnoticed odor could even exert stronger effects on human behavior than those perceivable ones. The applicability of the concepts of indoor chemistry in the system with air recirculation and the dichotomous effect on olfaction and sensory irritation remain to be investigated in carefully designed and controlled experiments, preferably, involving human subjects.

6.6.2. Intensity of SBS symptoms and subjective factors

It seems prudent to maintain an outdoor air supply rate of 10.0 L/s/p or higher (Sundell et al, 1994, Jaakkola and Miettinen, 1995), to select low emission material and equipment (Norbäck et al, 1990, Skov et al, 1990) and to clean or replace filters (Clausen et al, 2002, Wargocki et al, 2000) to eradicate or reduce the prevalence or intensity of SBS symptoms. In the present study, the benefits of increasing outdoor air supply rate on the intensity of SBS symptoms were seemingly confounded with the presence of used ventilation filters in the air distribution system. Thus, there appeared to be mixed implications of increasing outdoor air supply rate on the intensity of SBS symptoms. Moreover, the effects were not observed for many symptoms, which could be partially attributable to the relatively short duration of exposure, i.e. 4 hours, in contrast to the eight or more hours of continuous exposures the office workers would have experienced in the real office.

In addition to the tendency of higher eyes irritation in the higher outdoor air supply rate, subjects also perceived the intensity of eyes ache and eyes watering to be gradually higher with increasing outdoor air supply rate, both when they first entered and before they left the office. Tasks involving sustained visual attention such as text-typing and proofreading elevated the symptoms within the 4-hour session. They experienced the worst nose blocked symptom at 18.0 L/s/p, followed by exposure in the 4.5 L/s/p and the least symptoms at 9.0 L/s/p. The difference between responses at 4.5 and 9.0 L/s/p was not significant. The symptoms confirmed some adverse effects of higher outdoor air supply rates on the mucous membrane, presumably related to higher indoor air contaminants or irritants. The non-linear tendency in the nose-blocked symptoms was also reflected by several neurobehavioral-related symptoms such as headache, dizziness, fatigue, difficulty to concentrate, and depression with highest intensity generally observed at 18.0 L/s/p. Clausen (2002) demonstrated that the presence of used filters in the air conditioning system could have negative effects on the intensity of SBS symptoms. This is in addition to the perceptions of poor air quality. The negative effects of introducing used filters at higher outdoor air supply rate on irritation to the eyes and nose have also been confirmed in the real office setting (Wargocki et al, 2004). Likewise, the presence of carpet was also considered a risk factor of SBS symptoms prevalence (Norbäck and Torgén, 1989).

The lack of noticeable effects of outdoor air supply rate on the individual SBS symptoms suggested that when considered singly, these symptoms might not produce any practical significance in the interpretations. The subjective factors, on the other hand, provide better interpretation of subjects' perceptual constructs by forming stronger clusters of SBS symptoms and other sensory responses. Further analysis of factor scores therefore is more sensitive if indeed outdoor air supply rate imposed any short-term health effects. It is worth reiterating that neurobehavioral-related symptoms (SF1) accounted for most of the subjective data variance. This indicates that the subjective factor is most crucial in defining the relationship between indoor air quality (as determined by amount of outdoor air supply) and the subjective affects. This result could explain why several intervention studies either in laboratory or real office settings in the past consistently reported significant effects on SBS symptoms such as headache, dizziness, ability to think clearly, ability to concentrate, fatigue, and state of feeling/ mood. Wyon (2004) concisely reported these studies in a recent review on the effects of indoor air quality on work performance.

The subjective factor representing the neurobehavioral-related symptoms was significantly different for the three outdoor air supply rates with the highest median factor score (highest intensity of symptoms) at 18.0 L/s/p ($P<0.001$). The effect reflected the observations from the individual symptoms, but as a cluster, it appeared to be more profound and significant. Neurobehavioral-related symptoms (SF1) was significantly lower at 9.0 L/s/p which may suggest that the increase of indoor air pollutants in the office as discussed in section 6.6.1 did not overcome the benefit of improving sensory responses. Moreover, measured dust concentration did not indicate substantial increment between 4.5 and 9.0 L/s/p settings, indicating that indoor air pollution may not be deteriorated when outdoor air supply rate did not exceed 9.0 L/s/p. Similar pattern was reflected in the estimated carbon dioxide generation rate, which in accord with postulated mechanism by Bakó-Biró et al (2005) suggested lower carbon dioxide content in the blood and thus, reduce the intensity of neurobehavioral-related symptoms such as headache, dizziness, etc. Another subjective factor, i.e. the intensity of breathing-related symptoms (SF8), was significantly higher at 18.0 L/s/p. Together with the lower sIgA level when subjects were exposed to higher ventilation, these indicators seemed to indicate higher susceptibility of the upper respiratory tracts to indoor air pollutants.

6.6.3. Stress-related biomarkers and their associations with perceptual responses

Expressing the associations between intensity of SBS symptoms, particularly those identified as non-specific symptoms, and workers' performance, may be challenged with the lack of clear evidence of physiological activation (or deactivation). Moreover, measuring intensity of SBS symptoms by means of surveys on subjective perceptions could be confounded by various psychosocial factors, particularly in observational studies. In the present experiment, the application of salivary biomarkers for measuring mental activation association with the brain and nervous system, and even, the immunological response has shown great potential to address the above issues.

Perception of odor intensity is the resultant of olfactory system. Inhaled air molecules including gaseous indoor air contaminants that pass through the nose activates the epithelium, which subsequently sends the signal to the olfactory bulb through olfactory nerves. The mitral cells in the olfactory bulb, in turn, project their axons to the various parts of the brain and nervous system, including the medial amygdala. Combined information from the olfactory system in the brain is subsequently transduced into perception of odor and its intensity. These processes involve the ability to distinguish immediately the differences in present odor as contrast with the background environmental odor (Buck and Axel, 1991 and Shepherd, 2003). As the activation of the amygdala is linked with sympathetic nervous system (explained in section 5.6.6), salivary α-Amylase could therefore be a good correlate for olfactory system responses (perceived odor). The application of the biomarker as the surrogate indicator of perceived air quality is therefore a viable option. Furthermore, lower salivary α-Amylase, as the measure of adrenergic activity related to activation of SAM axis, also indicated a lower mental activation during the higher outdoor air supply rate, which could be beneficial for task performance with lower optimum arousal.

As an established biomarker for stress-responses related to the activation of the HPA axis, salivary Cortisol concentration provides the measure of etiological factors that could be responsible in the effects of outdoor air supply rate on neurobehavioral responses. In the present results, based on samples taken after the 4-hour occupation, doubling outdoor air supply rate from 4.5 to 9.0 L/s/p significantly elevated salivary Cortisol level by c.a. 60%, while further increased from 9.0 to 18.0 L/s/p did not yield any meaningful changes. The four-hour exposure consistently reduced salivary Cortisol concentration partly due to the diurnal variation. The salivary Cortisol increased monotonically while the neurobehavioral-related symptoms increased markedly only when outdoor air supply rate was highest (18.0 L/s/p). The discrepancy at 9.0 L/s/p, i.e. higher salivary Cortisol but lower reported neurobehavioral-related symptoms, could be attributable to the improved subjective perceptions of air quality and that increase of pollution load caused nontrivial effects only when outdoor air supply rate was kept at 18.0 L/s/p with used filters. In another result, the sIgA level decreased monotonically as the consequence of increasing outdoor air supply rate ($R^2=0.99$). An estimated 15% reduction of salivary IgA level is attributable to the quadrupling of outdoor air supply rate between 4.5 and 18.0 L/s/p. Activation of HPA axis could lead to the suppression of immunoglobulin hormone, which may lead to increased susceptibility of the immune system and detrimental health effects of the sensitive/ atopic subjects.

6.6.4. Effects of outdoor air supply rates on work performance and the mechanisms

The present results testify to the mixed implications of increasing outdoor air supply rate on work performance when used ventilation filter was present instead of new or clean ones and when carpet was included as an additional pollution source. Wargocki et al (2004) has demonstrated the negative implications of increasing outdoor air supply rate between 2.5 and 25.0 L/s/p when used filters were installed on the performance of call center operators with call handling performance decreased by 8.0%, while on the contrary, in the new filters call-handling performance would be improved by an estimated 6.0%. The latter positive effect was also observed in the call center studies in the tropics elaborated in Chapter 2. In earlier laboratory studies, Wargocki et al (1999) demonstrated that in office without carpet, performance in terms of speed of work on numerical addition and text-typing were 3.8% and 6.5% better than in the office with carpet; and subsequently, every doubling of outdoor air supply rate above 3.0 L/s/p was found to improve text-typing speed by c.a. 1.1% and tended to increase speed of addition and proofreading by c.a. 2.1% (Wargocki et al, 2000). The results of the latter study were however not confirmed on simulated office tasks such as text-typing and proofreading but consistent with mental performance tasks of the present experiment.

Mental performance gradually improved when outdoor air supply rate was increased. Subjects performed better in numerical reasoning (7.1%) and had better creativity (16.4%) when outdoor air supply rate was quadrupled from 4.5 to 18.0 L/s/p. Lower mental activation or arousal and improved perceptions of air quality may lead to the improvements in the various mental performance tasks conducted over a short period. This postulation has been confirmed in the MPIESM, which highlights significant covariance between ESF6 (perceptions of air quality) and the mental performance as well as between EAM (α-Amylase) and the mental performance. These effects and correlations have been suggested in previous studies elsewhere. Wolkoff et al (2006) suggested in their review as follows: "mood and alertness influence the mental and cognitive state and perhaps mental creativity". Another study in favor of this postulation (Wargocki et al, 2000) found that better creative thinking occurred when outdoor air supply rate was increased by three folds from 10.0 to 30.0 L/s/p ($P<0.05$, one-tailed). Further analysis revealed that the positive effects on mental performance were obtained almost exclusively during the first-try (first half of session), which may indicate that the positive effects of sensory responses is reduced once they reached the quasi-steady state level. Danuser (2001) and Danuser et al (2003) suggested that productivity reduction caused by indoor air contaminants may be encumbered by behavioral responses linked with perception of odor and that this influence may be temporary.

Except for numerical addition which improved by c.a. 2.5% with doubling of outdoor air supply rate between 4.5 and 9.0 L/s/p, other more complex and prolonged tasks involving language processing were negatively affected when subjects worked in the higher outdoor air supply rate (18.0 L/s/p). Subjects missed c.a. 3.0% intentional errors in the proofreading task and typed c.a. 1.4% slower during text-typing. With higher neurobehavioral symptoms (SF1), higher psychological stress (salivary Cortisol) and longer task durations, the multi-paradigm tasks requiring sustained coordination among various mental skills and manual dexterity are likely to be impaired at higher outdoor air supply rate, which in the present experiment, was related with higher indoor air pollution. Due to the differences in indoor air quality (pollution load), any direct comparisons on the effects of increasing outdoor air supply rate between the present experiment and the field study in the call centers would be confounded. Nevertheless, these studies were in agreement with previous findings reported elsewhere.

Finally, the findings of this experiment indicate that effects of outdoor air supply rate are intricately complex and should be evaluated in conjunctions with other determinants of indoor air quality such as the thermal environment and the presence of pollution sources in the air distribution system or the occupied areas. The physiological indicators, i.e. the salivary biomarkers, which express the mental activation state, psychological-stress level and health-related status, and the subjective evaluation of the air quality and the intensity SBS symptoms have potentially provided compelling evidences of the various mechanisms between indoor air quality and work performance.

7

CONCLUSIONS AND RECOMMENDATIONS

In conclusion, the objectives of the present thesis have been achieved. It has been demonstrated that work performance of tropically acclimatized people is affected by thermal environment and indoor air quality following the interventions to the air temperature and outdoor air supply rate, respectively. Performance of tropically acclimatized office worker in the real office settings is affected by changing air temperature within the range of 22.5-24.5°C and/or doubling the outdoor air supply rate. The main findings are subsequently explored and reconfirmed by the results of studies conducted in the field environmental chamber using tropically acclimatized subjects. There are strong evidences that these effects are associated with and preceded by the changes of perceptual responses, intensity of SBS symptoms and/or physiological measures; and that two mechanisms, i.e. perceptual constructs as well as psycho-physiological measures, could be applied in deriving the plausible effects on work performance. These mechanisms are further transduced into a structural model, termed as the Man – Performance - Indoor Environment Structural Model (MPIESM). Cost-benefit analysis based on the percentage of improvements achieved in the call centers and data on local energy consumption and workforce statistics shows that the projected economical gain is very large when optimum air temperature or increased ventilation, which results in optimum thermal environment and improved air quality for performance, is provided to the office workers. The following summarizes the conclusions or main outcomes of the present thesis for the effects of air temperature and outdoor air supply rate.

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7.1. Effects of air temperature

7.1.1. Field study in the call centers

a) Decreasing air temperature from c.a. 24.5 to 22.5°C with subjects clothed above c.a. 0.6 clo shifted workers' thermal sensation from slightly warm to slightly cool ranges, lowered perceived sweating (humid skin) intensity, improved perceptions of air quality, reduced dryness intensity and decreased neurobehavioral-related symptoms.
b) Decreasing air temperature from c.a. 24.5 to 22.5°C with subjects clothed above c.a. 0.6 clo improved call handling performance by 5.7%.

c) Decreasing air temperature from c.a. 24.5 to 22.5°C with subject clothed below c.a. 0.5 clo reduced workers' thermal sensation from slightly cool towards cool ranges, reduced thermal comfort and acceptability to air quality, reduced perceived humid skin, markedly elevated cold hand and cold feet symptoms, and reduced dryness intensity.
d) Increasing air temperature from c.a. 22.5 to 24.5°C with subject clothed below c.a. 0.5 clo improved call handling performance by 3.0-5.3%.

e) Reducing air temperature by c.a. 1.5-2.0°C in a small scale office with 50 workers clothed above c.a. 0.6 clo in the tropical context could yield productivity gain that exceed cost for increased energy consumption by a factor of 17, not including other potential benefits related to improved thermal perceptions.

f) Performance improvements due to increased outdoor air supply rate diminish exponentially with the higher range of outdoor air supply rates (R^2=0.99).

7.1.2. Simulated office environment

a) Subjects' body thermal sensation increased with room air temperature at 20.0, 23.0 and 26.0°C but decreased monotonically with time under all exposure conditions, despite clothing adjustments for maintaining the thermal neutrality.
b) Subjects' thermal comfort was consistently highest at 23.0°C throughout the 4-hour exposure. At 20.0°C, thermal comfort decreased sharply during the first hour of exposure and eventually arrived at "just uncomfortable" after 4 hours, while at 26.0°C, thermal comfort increased gradually during the first 3 hours before reaching a plateau close to that of 23.0°C.
c) Subjects' body thermal sensation was correlated with thermal comfort following an inverted-U function (R^2=0.92). The estimated room air temperature for comfort was 24.2°C (corresponding to thermal sensation of -0.40 or below thermal neutrality).
d) Mean skin temperature varied with air temperature in the expected direction and gradually decreased within the 4-hour exposure.
e) Body thermal sensation was linearly correlated with mean unweighted skin temperature (R^2=0.95).

f) Local cooling sensations at various locations of the body increased with decreasing air temperature. Local cooling sensation also increased during the 4-hour exposure at 20.0°C (all locations) and at 23.0°C (all locations, except the chest and the back).
g) Intensity of cold hand and cold feet symptoms increased following the trends of local cooling sensation at the hands and the feet as concluded in point d).
h) Hand and foot skin temperatures decreased over time and were consistently lowest at 20.0°C reflecting the intensity of cold hand and cold feet, but remained almost unchanged at 26.0°C.

i) Air quality was consistently the least acceptable at 26.0°C during immediate exposures (upon entering the office and during re-entering at the end of exposure). No significant differences between acceptability of air quality at 20.0 and 23.0°C during immediate exposures were observed. During habituation period, there were no significant effects of air temperature on acceptability of air quality.
j) There was a moderately strong association between acceptability of air quality and inhaled air thermal sensation (R^2=0.83). Air quality at 23.0°C with inhaled air thermal sensation corresponding to slightly cool was most acceptable.
k) Perceived air stuffiness and air stillness increased with room air temperature suggesting the influence of respiratory cooling sensation.

l) Intensity of dryness symptoms (SF4: mouth, throat, lips, and skin dryness) tended to be higher at 20.0°C.
m) Intensity of neurobehavioral-related symptoms increased gradually over time but did not differ significantly across the air temperature range
n) The local thermal sensation responses accounted for most of variance in the subjective responses data.

o) Salivary Cortisol concentrations after 4-hour exposure to 23.0 and 26.0°C were 1.6 times higher than the concentration under exposure to 20.0°C indicating the under-stimulation of HPA axis of the nervous system or increase of negative psychological affects during moderate warm exposure.

p) Salivary α-Amylase concentrations after 4-hour exposure linearly increased with lowering air temperature, indicating higher mental activation or adrenergic activity at lower air temperatures.

q) Concentration endurance was significantly worse in the higher air temperature (26.0°C). Subjects' skipped fewer characters in the search task but worked slower at 20.0°C and performed faster but with higher error at 23.0°C. Given the nature of concentration-related tasks, a slower but more accurate work at 20.0°C would be preferred.

r) Arousal level decreased progressively when room air temperature was increased from 20.0 to 26.0°C. The result is consistency with measure of mental activation based on salivary α-Amylase biomarker level.

s) Performance of simulated office work, i.e. proofreading, was better at 20.0°C with higher reading speed and the tendency for identifying more text-embedded errors. This could be related to better mental performance (higher activation and concentration) and improved perceptions of air quality. Subjects may also change their cognitive strategies in dealing with higher stress level and lower activation at 26.0°C and thus, worked faster but performed poorly for the error search.

t) Performance of another simulated office task, i.e. text-typing, was 3.8 and 3.2% faster under moderate cool stress at 20.0°C than speed at 23.0 and 26.0°C, respectively. This result highlights the relatively negligible effects of local cooling of the hand but greater reliance on the better mental state as induced by lower air temperature during performance of a complex and multi-paradigm task such as text-typing.

u) The MPIESM has demonstrated the direct and indirect predictive effects of air temperature on various aspects of human responses that eventually affected work performance.

7.2. Effects of outdoor air supply rate

7.2.1. Field study in the call centers

a) Doubling outdoor air supply rate led to the following positive effects: reduction of intensity of neurobehavioral-related symptoms, improvement of acceptability of air quality, lower perceived odor, lower perceived nose and throat irritations, reduction of perceived air stuffiness, office perceived less dusty; but caused the following negative effects only in one call center: higher perceived odor, increased intensity of aching eyes, and more fatigue.

b) Benefit of increasing (doubling) outdoor air supply rate on call handling performance diminished as the range of outdoor air supply rate increases following an exponential decay function (R^2=0.99).
c) Increasing outdoor air supply rate from 3.0 to 6.0 L/s/p improved call handling performance by 8.2%.
d) Increasing outdoor air supply rate from 6.0 to 12.0 L/s/p improved call handling performance within 6.0-10.9%
e) Increasing outdoor air supply rate from 9.0 to 18.0 L/s/p improved call handling performance by 5.1%

f) Increasing outdoor air supply rate in a small scale office with 50 workers in the tropical context could yield productivity gain that exceed cost for increased energy consumption by a factor of 16-36, not including other potential benefits related to the improved indoor air quality.

7.2.2. Simulated office environment

a) Acceptability of air quality was monotonically improved with increasing outdoor air supply rate from 4.5 to 9.0 to 18.0 L/s/p during immediate exposures but did not differ across the three settings during habituation period.
b) Percentage dissatisfied with air quality at 9.0 L/s/p and below was higher than 20% and thus did not comply with recommended level by ASHRAE 55 (2004).
c) Perceived odor decreased monotonically with increasing outdoor air supply rate during immediate exposures. Subjects did not perceived significant difference in odor level during habituation period.
d) Perceived eyes irritation increased and reached the plateau level during the first hour of exposure. The irritation level tended to be higher at higher outdoor air supply rate.
e) Inhaled air thermal sensation was reduced from neutral to slightly cool implying the effects on perceived air quality, e.g. counteracting the negative effects of accumulated bio-effluents in the office.
f) Air quality also reduced perceived air stuffiness and air stillness still with increasing outdoor air supply rate during immediate exposures.
g) The olfactory senses activated SAM axis, which was evident in the positive correlation between the odor perception and salivary α-Amylase as the biomarker of SAM activation. Higher odor perception was associated with higher mental or adrenergic activation.

h) Intensity of neurobehavioral-related symptoms was markedly elevated in the higher outdoor air supply rate, which was presumably related to increased air contaminants when used filter and carpet were presence.
i) Higher salivary Cortisol was associated with increased neurobehavioral-related symptoms at higher outdoor air supply rate, confirming the adverse effects of indoor air at 18.0 L/s/p.
j) Suppression of immunoglobulin A (sIgA) level at higher outdoor air supply rate suggested higher susceptibility of the immune system. Coupled with higher

breathing-related symptoms, the risk of detrimental health effects on sensitive/ atopic people may be increased.

k) Subjects unconsciously reduced metabolic rate at higher outdoor air supply rate (higher air contaminants) as evident from the lower CO_2 generation rate.

l) Creative thinking performance improved monotonically with increasing outdoor air supply rate. Quadrupling outdoor air supply rate from 4.5 to 18.0 L/s/p increased creativity score (C-score) by 16.4%.
m) Numerical reasoning performance improved monotonically with increasing outdoor air supply rate. Quadrupling outdoor air supply rate from 4.5 to 18.0 L/s/p increased speed of work by 7.1%.
n) Both mental performance (conclusion point k) and l)) could be associated with better perceptions of air quality and reduced perceived odor, resulting in optimum mental activation level measured through the human biomarker.

o) Numerical addition performance increased by 2.5% when changing outdoor air supply rate from 4.5 to 9.0 L/s/p.
p) Subjects missed 3.0% more of the text-embedded errors in the proofreading task at 18.0 L/s/p than performance at 4.5 and 9.0 L/s/p. Performance at 4.5 and 9.0 L/s/p did not differ significantly.
q) Subjects typed 1.4% slower in the text-typing task at 18.0 L/s/p than performance at 4.5 and 9.0 L/s/p. Performance at 4.5 and 9.0 L/s/p did not differ significantly.
r) The higher neurobehavioral-related symptoms, subsequently confirmed by the increased salivary Cortisol level as well as reduction in metabolic rate (lower CO_2 generation rate) were postulated as negative affects on the performance of more complex and multi-paradigm tasks such as text-typing and proofreading.

s) The MPIESM has demonstrated the direct and indirect predictive effects of changing outdoor air supply rate on various aspects of human responses that eventually affected work performance.

7.3. Practical implications

In the tropical context, providing optimum thermal conditions for performance within tolerable range or moderate thermal stress would improve work performance and eventually, the productivity. In accord with thermal comfort theory, this optimum condition may be specifically related to the body thermal balance, profoundly affected by occupants' activity and the thermal insulation from their clothing. The preferred room air temperature for the performance of tropically acclimatized subjects should eventually achieve a thermal sensation between neutral and slightly cool. The practical range of room air temperature recommended with subjects clothed in normal office attires (allowed for adjusting their clothing) and performed seated/sedentary tasks is within c.a. 20.0-23.7°C, (between neutral and cool). The upper limit of the recommended range could be further reduced to 22.5°C in considerations of higher activity rates, more clothing insulation, or in the episodes of elevated work-related stress. Lower air temperature within the comfort range has been proven to reduce psychological stress and improved alertness.

Supplying higher outdoor air supply rate without introducing more pollutants in the air stream/ distribution would benefit work performance and thus, overall productivity. Careful attention should be given to the overall maintenance of air conditioning system, in particular, the presence of used ventilation filter that could negate the potential benefit of increasing outdoor air supply rate. In the perspective of present findings, the minimum outdoor air supply rate recommended is c.a. 9.0L/s/p. The value is adopted based on the considerations that benefit of increasing outdoor air supply diminishes at the higher range of outdoor air supply rates and that this level would still benefit mental performance of workers without necessary affecting more complex tasks even with the presence of used filter in the air distribution system. The latter explanation should be viewed in the context of present study in the simulated office. Past researches in the simulated environment have shown higher benefits of increasing outdoor air supply rate up to 30.0 L/s/p when ventilation achieved its intended purpose of reducing indoor air pollution loads.

7.4. Future studies

There are growing evidences of the occurrence of reactive indoor chemistry between gaseous contaminants in the indoor air catalyzed by ozone from the outdoors and the increased risks when filters are loaded and with indoor materials, office appliances and occupants emitting various types and concentrations of contaminants. It is therefore important to implement the latest measurement approaches to estimate these processes and the actual real-time concentrations of indoor air contaminants, especially in the air distribution system with air recirculation. It is recommended to replicate the indoor air pollution load when increased outdoor air supply rate was accompanied by the presence of used filter.

The present study performed in both real offices as well as simulated environment could not be quantitatively compared due to various reasons, of which one of them is the use of different subjects' group. In the call center studies, subjects are generally older, more experienced and under higher work-related stress, while in the laboratory set-up, the participants are young adults recruited among the university students, less experienced and did not work under the same level of stress as in the more complex environment in the actual offices. Identifying, recruiting and measuring the performance of young office workers from real offices and subsequently subjecting this group of workers in the simulated environment while monitoring various parametric measurements is a viable option to be explored in the future. Another viable option is to introduce the Remote Performance Measurement and Survey (RPMS) protocols to measure various office component skills of real office workers and their feedbacks to the indoor air conditions through the internet interfaces to minimize interruptions to the daily work. At the same time, any interventions to the indoor environmental parameters could be conducted blind to the subjects.

In the present study, measures of work performance both in the field studies as well as in the laboratory experiments are limited to several indicators elaborated in previous sections of the thesis. These measures may not be generalized to various types of office environments. More studies involving other types of office performance are therefore crucial to elicit the benefit of improving thermal environment and/or indoor air quality.

Finally, the linkages relating human perceptual responses and other potential psycho-physiological measures to work performance provide, at the present stage of research, suggestive evidences of the effects of thermal environment and indoor air quality on work performance through several plausible mechanisms involving the brain nervous system activation and its association with perceptual responses. The identified basic research required in the furtherance of understanding of occupant – indoor environment interactions are as follows:

a) The application of salivary biomarkers has shown that effects on office workers' performance level are associated with the HPA and SNS activations. This is also supported by the perceptual responses of the occupants. Further confirmation of this result with more samples collected from the office workers is required. As the sampling procedures are relatively simple and non-invasive, collecting more samples with the consent of the office managements would not be a major concern. Another important objective for the next stage is to identify the "window of activation" as the results of indoor environmental conditions, in which the work performance could be maintained at the optimum level. This should be explored on time course basis due to the diurnal patterns of occupants' physiological responses, fluctuations in the daily activities, and the possible integration of various parameters to achieve the optimum condition.

b) The research partner of the National University of Singapore, i.e. the International Center for Indoor Environment and Energy of Technical University of Denmark, has earlier reported and hypothesized that the air quality may affect occupants' physiological state through the interfaces of the lung alveolar gas exchange. The exposure to (hydrophilic) indoor air pollutants that alter the lung surfactants could influence the gas exchange phase and thus elevating the concentration of CO_2 in the blood. The immediate effects are the onset and increased of neurobehavioral-related symptoms such as headache and fatigue, loss of concentration, etc, all of which have been shown to reduce work performance. The mechanism has been partially observed in the present study using the tropically acclimatized subjects as well in the study conducted in Denmark. The generation rate of CO_2 tended to decrease with elevated indoor air pollutants concentration and this effect was consistent with the biomarkers result mentioned in a) and work performance decrements. It is therefore crucial at this stage to study the detailed mechanisms using *in vitro* measurements of the breathing system in the well-controlled laboratory settings. In congruence with the earlier recommendation, the identification of specific indoor air pollutants involved has become even more important.

These detailed mechanisms have not been explored in the past and they are certainly very promising new multidisciplinary research areas to be explored within the progressive effort to identify the healthy, stimulating and productive indoor environment.

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A

Questionnaire Used in Call Center Studies

INDOOR ENVIRONMENTAL SURVEY

Dear Sir/ Madam
Please complete **all** the **vertical and horizontal scales** by giving **a tick mark** at any **one point** within each scale. Only your complete feedback can be processed. We deeply appreciate your effort and cooperation. Thank you.

LOGON ID : ____________________

EXT. NO : ____________________

(Official use only) Ref. no. : M/A__________

How do you assess the **thermal comfort level**?

Pay attention to the distinction between comfortable and uncomfortable

Very comfortable
Just comfortable
Just uncomfortable
Very uncomfortable

How do you assess the **air quality level**?

Pay attention to the distinction between acceptable and unacceptable

Clearly acceptable
Just acceptable
Just unacceptable
Clearly unacceptable

Assess the **odor intensity**:

No odour
Slight odour
Moderate odour
Strong odour
Very strong odour
Overpowering odour

Assess **level of irritation** of the:

Eyes Nose Throat

No irritation
Slight irritation
Moderate irritation
Strong irritation
Very strong irritation
Overpowering irritation

Right now, I feel that **my working environment** is:

Too warm ____________________ Too cold
Too humid ____________________ Too dry
Air stuffy ____________________ Air fresh
Air still ____________________ High air movement
Too dark ____________________ Too bright
Too noisy ____________________ Too quiet
Office dusty ____________________ Office clean

Right now I feel/ experience as follows:

Nose dry	Nose running
Nose blocked	Nose clear
Flu-like symptom	No flu-like symptom
Throat dry	Throat not dry
Mouth dry	Mouth not dry
Lips dry	Lips not dry
Skin dry	Skin not dry
Eyes dry	Eyes not dry
Eyes smarting	Eyes not smarting
Eyes aching	Eyes not aching
Gritty eyes	Eyes not gritty
Cold hand	Hand not cold
Cold feet	Feet not cold
Severe headache	No headache
Difficult to think	Head clear
Dizzy	Not dizzy
Feeling bad	Feeling good
Tired	Rested
Difficult to concentrate	Easy to concentrate
Depressed	Positive
Alert	Sleepy
Tense	Relaxed

How do you rate your **thermal sensation** ?

+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

How do you experience **sweating** or **humid skin**?

Extensively or continuously

Slightly or intermittently

Not at all

How do you rate the **completion of your tasks** today?

Slight effort	Strong effort
Productive	Not productive

B

Main Effects Results of Call Center Surveys

Perceptual and SBS symptoms responses	Intensity score																		Scale description
	Call center A			Call center B												Call center C			
				Section 1			Section 2			Section 3			Section 4						
	T_1^	T_2^	P	T_1	T_2	P	T_1	T_2	P	T_1	T_2	P	T_1	T_2	P	T_1	T_2	P	
Thermal comfort	0.21	0.22		0.16	0.13		0.14	0.13		0.12	0.16		0.13	0.16		0.41	0.52	***	(+1: very comfortable; 0: just comfortable/ just uncomfortable; -1: very uncomfortable)
Acceptability of air quality	0.27	0.24		0.33	0.21		0.22	0.19		0.18	0.24		0.29	0.25		0.47	0.60	***	(+1: very acceptable; 0: just acceptable/ just unacceptable; -1: very unacceptable)
Perceived odor	0.52	0.55		0.36	0.50	*	0.60	0.58		0.50	0.48		0.51	0.54		0.19	0.23		(0: no odor - 1:slight odor - 2: moderate odor - 3: strong odor - 4: very strong odor - 5: overpowering odor
Perceived eyes irritation	0.59	0.50	*	0.50	0.43		0.50	0.60	**	0.67	0.67		0.55	0.52		0.34	0.34		(0: no irritation - 1:slight irritation - 2: moderate irritation - 3: strong irritation - 4: very strong irritation - 5: overpowering irritation
Perceived nose irritation	0.66	0.60		0.47	0.42		0.43	0.52	**	0.54	0.60		0.54	0.59		0.36	0.34		(0: no irritation - 1:slight irritation - 2: moderate irritation - 3: strong irritation - 4: very strong irritation - 5: overpowering irritation
Perceived throat irritation	0.85	0.80	***	0.50	0.73	*	0.54	0.56	*	0.57	0.70		0.60	0.52		0.40	0.44		(0: no irritation - 1:slight irritation - 2: moderate irritation - 3: strong irritation - 4: very strong irritation - 5: overpowering irritation
Air warmness	42	49	***	32	56	***	34	53	***	28	47	***	32	54	***	51	50		(0: too cold - 100: too warm)
Air humidity	40	47	***	42	50	***	46	52	***	43	49	***	43	52	***	47	44		(0: too dry - 100: too humid)
Air stuffiness	45	51	**	38	53	***	43	51	***	40	45	***	40	52	***	51	52		(0: air fresh - 100: air stuffy)
Air stillness	48	55	***	39	53	***	41	51	***	42	49	***	41	53	***	60	52		(0: high air movement - 100: air still)
Room darkness	44	48	**	41	42	*	44	45	**	39	39		44	44		45	45		(0: too bright - 100: too dark)
Room noisiness	48	53		50	50		49	50	*	56	57		50	52		49	49		(0: too quiet - 100: too noisy)
Room dustiness	45	47		38	45	**	44	44		50	48		41	46	***	40	47		(0: office clean - 100: office dusty)
Nose dryness	58	61		64	68		53	55		62	63		59	58	*	56	69	***	(0: nose running - 100: nose dry)
Intensity of blocked nose	58	61		32	35	*	37	40		34	38		42	40		42	45		(0: nose clear - 100: nose blocked)
Intensity of flu-like symptom	37	26		29	29		30	28		35	36		30	30		34	34		(0: no flu-like symptom - 100: flu-like symptom)
Throat dryness	43	54	*	43	51		44	45		43	49		43	39		50	58	**	(0: throat not dry - 100: throat dry)
Mouth dryness	50	55	**	37	51		43	43		48	48		44	39		56	56		(0: mouth not dry - 100: mouth dry)
Lips dryness	56	60		58	58		44	43		51	49		44	38		61	60		(0: lips not dry - 100: lips dry)
Skin dryness	51	51		46	51		43	43		53	51		44	42		51	59	**	(0: skin not dry - 100: skin dry)
Eyes dryness	47	49		40	44		40	42	***	43	43		41	38		49	52		(0: eyes not dry - 100: eyes dry)
Intensity of smarting eyes	46	41		32	34		37	36		38	39		39	37		31	32		(0: eyes not smarting - 100: eyes smarting)
Intensity of aching eyes	39	35		21	22		28	25		36	34		36	33		43	50		(0: eyes not aching - 100: eyes aching)
Intensity of gritty eyes	41	27		22	23		33	29		40	37		30	31		37	49		(0: eyes not gritty - 100:eyes gritty)
Intensity of cold hand	44	40	**	63	38	***	54	42	***	67	46	***	54	35	***	31	36		(0: hand not cold - 100: cold hand)
Intensity of cold feet	49	44	***	63	30	***	51	40	***	62	47	***	60	37	***	47	48		(0: feet not cold - 100: cold feet)
Intensity of headache	31	31		18	23		26	24		31	31		26	25		34	30		(0: no headache - 100: severe headache)
Ability to think clearly	37	35		22	20		26	26		31	30		26	29		31	32		(0: head clear - 100: difficult to think)
Dizziness	22	27		17	19		26	23	**	30	28		25	26		31	33		(0: not dizzy - 100: dizzy)
Feeling/ mood	40	39		26	26		32	30	**	36	36		39	35		38	45		(0: feeling good - 100: feeling bad)
Level of fatigue	52	51		32	35		39	38		43	47	*	34	38	*	49	55		(0: rested - 100: tired)
Ability to concentrate	47	46		28	32		32	37		34	35		34	32		39	45		(0: easy to concntrt. - 100: difficult to concentrt.)
Level of pepression	42	41		25	25		30	28		35	35		32	31		34	40		(0: positive - 100: depressed)
Level of arousal	51	57	*	32	31		51	51		42	43		44	45		51	47		(0: alert - 100: sleepy)
Level of tension	40	45		33	35		36	36		39	41		36	39	**	44	46		(0: relaxed - 100: tense)
Thermal sensation	-0.36	0.19	***	-1.08	-0.40	***	-0.64	-0.39	**	-1.47	-0.72	***	-1.05	-0.15	***	-1.29	-0.90		(-3: cold -- 0: neutral -- +3: hot)
Sweating intensity	24	28	**	26	35	***	28	35	***	18	33	***	22	41	***	28	40	***	(0: no sweat - 100: extensive sweating)
Self-perceived effort	47	51		46	50		45	47	**	49	51		47	50	*	43	47		(0: slight effort - 100: strong effort)
Self-perceived productivity	50	50		65	63		56	54		64	64		63	63		58	60		(0: not productive - 100: productive)

Note: *** denotes 0<P≤0.01; ** denotes 0.01<P≤0.05; * denotes 0.05<P≤0.10

^: T_1 indicates lower air temperature (set-point= 22.5°C) and T_2 indicates higher air temperature (set-point= 24.5°C)

C

Subjective Factors of Call Center Surveys

Call center A	Subjective Factor (loading)					
	SF1A	SF2A	SF3A	SF4A	SF5A	SF6A
Variance (%)	31	11	9	7	5	5
Level of depression	0.93					
Feeling/ mood	0.90					
Ability to concntrt	0.89					
Level of tension	0.86					
Level of fatigue	0.82					
Self-percvd prod.	-0.79					
Ability to thk clearly	0.76					
Dizziness	0.64					
Intensity of headache	0.62					
Level of arousal	0.50					
Thermal sensation		0.80				
Air warmness		0.77				
Intensity of cold hand		-0.76				
Intensity of cold feet		-0.75				
Intensity of blck nose			0.86			
Intensity of flu-like			0.82			
Nose dryness			-0.56			
Room darkness				-0.72		
Room noisiness				-0.70		
Room dustiness				-0.68		
Air stuffiness				-0.62		
Air humidness				-0.59		
Perceived odor					-0.70	
Perceived throat irtn.					-0.65	
Perceived eyes irtn.					-0.59	
Sweating intensity					-0.57	
Perceived nose irtn.					-0.54	
Thermal comfort						0.81
Accept. of air quality						0.80

Call center B (Section 1)	Subjective Factor (loading)					
	SF1B1	**SF2B1**	**SF3B1**	**SF4B1**	**SF5B1**	**SF6B1**
Variance (%)	**33**	**16**	**9**	**7**	**5**	**4**
Level of depression	0.87					
Ability to thk clearly	0.85					
Dizziness	0.81					
Level of fatigue	0.80					
Ability to concntrt	0.80					
Level of tension	0.80					
Feeling/ mood	0.77					
Intensity of headache	0.70					
Air warmness		0.84				
Air stillness		0.78				
Air stuffiness		0.76				
Intensity of cold feet		-0.69				
Air humidness		0.67				
Intensity of cold hand		-0.65				
Perceived eyes irtn.			-0.87			
Perceived nose irtn.			-0.83			
Perceived odor			-0.77			
Perceived throat irtn.			-0.76			
Lips dryness				0.92		
Mouth dryness				0.87		
Skin dryness				0.82		
Throat dryness				0.80		
Eyes dryness				0.64		
Thermal comfort					0.84	
Accept. of air quality					0.83	
Thermal sensation						-0.82
Sweating intensity						-0.78

Call center B (Section 2)	**Subjective Factor (loading)**				
	SF1B2	**SF2B2**	**SF3B2**	**SF4B2**	**SF5B2**
Variance (%)	**38**	**16**	**7**	**7**	**5**
Level of fatigue	0.76				
Level of arousal	0.76				
Ability to concntrt	0.75				
Level of tension	0.72				
Level of depression	0.70				
Self-percvd prod.	-0.63				
Feeling/ mood	0.60				
Ability to thk clearly	0.52				
Lips dryness		0.93			
Mouth dryness		0.92			
Skin dryness		0.90			
Throat dryness		0.84			
Eyes dryness		0.79			
Intensity of cold hand			-0.52		
Air stillness			0.82		
Air stuffiness			0.81		
Air warmness			0.78		
Air humidness			0.72		
Perceived nose irtn.				0.71	
Perceived odor				0.70	
Perceived eyes irtn.				0.70	
Perceived throat irtn.				0.69	
Sweating intensity				0.62	
Thermal sensation				0.61	
Thermal comfort					0.85
Accept. of air quality					0.80

Call center B (Section 3)	Subjective Factor (loading)				
	SF1B3	**SF2B3**	**SF3B3**	**SF4B3**	**SF5B3**
Variance (%)	**34**	**15**	**8**	**6**	**4**
Dizziness	0.83				
Intensity of headache	0.77				
Ability to thk clearly	0.77				
Self-percvd prod.	-0.73				
Level of depression	0.72				
Feeling/ mood	0.66				
Ability to concntrt	0.63				
Air warmness		0.90			
Intensity of cold hand		-0.72			
Thermal sensation		0.67			
Air stillness		0.67			
Air humidness		0.64			
Intensity of cold feet		-0.63			
Sweating intensity		0.57			
Air stuffiness		0.51			
Lips dryness			0.93		
Mouth dryness			0.89		
Throat dryness			0.83		
Skin dryness			0.76		
Eyes dryness			0.75		
Perceived nose irtn.				0.83	
Perceived eyes irtn.				0.82	
Perceived odor				0.72	
Perceived throat irtn.				0.67	
Thermal comfort					0.78
Accept. of air quality					0.55

Call center B (Section 4)	Subjective Factor (loading)					
	SF1B4	**SF2B4**	**SF3B4**	**SF4B4**	**SF5B4**	**SF6B4**
Variance (%)	**36**	**12**	**9**	**7**	**5**	**4**
Feeling/ mood	1.02					
Dizziness	1.00					
Ability to concntrt	0.97					
Level of fatigue	0.96					
Intensity of headache	0.95					
Ability to thk clearly	0.91					
Level of tension	0.84					
Level of depression	0.79					
Air warmness		0.86				
Air humidness		0.83				
Air stuffiness		0.82				
Air stillness		0.76				
Mouth dryness			1.13			
Lips dryness			1.08			
Throat dryness			0.99			
Skin dryness			0.97			
Eyes dryness			0.89			
Thermal comfort				0.86		
Accept. of air quality				0.81		
Thermal sensation				0.50		
Perceived nose irtn.					1.04	
Perceived throat irtn.					0.89	
Perceived eyes irtn.					0.81	
Room noisiness						0.97
Room dustiness						0.62
Room darkness						0.62

Call center C	Subjective Factor (loading)				
	SF1C	SF2C	SF3C	SF4C	SF5C
Variance (%)	35	13	12	7	5
Ability to concntrt	0.92				
Feeling/ mood	0.89				
Level of depression	0.88				
Ability to thk clearly	0.84				
Intensity of headache	0.81				
Level of arousal	0.81				
Dizziness	0.80				
Level of tension	0.78				
Level of fatigue	0.73				
Self-percvd prod.	-0.64				
Air warmness		-0.86			
Intensity of cold feet		0.80			
Intensity of cold hand		0.80			
Air humidness		-0.68			
Thermal sensation		-0.67			
Lips dryness			0.88		
Skin dryness			0.85		
Mouth dryness			0.84		
Throat dryness			0.76		
Eyes dryness			0.65		
Perceived eyes irtn.				0.88	
Perceived nose irtn.				0.82	
Perceived throat irtn.				0.72	
Perceived odor				0.69	
Accept. of air quality					0.91
Thermal comfort					0.90

D

Questionnaire Used in Field Laboratory Studies

Imagine that during your daily office work you are exposed to this air.

How do you assess the **air quality**?

(Pay attention to the distinction between ***acceptable and unacceptable****)*

Clearly acceptable

Just acceptable
Just unacceptable

Clearly unacceptable

Assess **odor intensity**:

No odour
Slight odour
Moderate odour
Strong odour
Very strong odour
Overpowering odour

Assess **level of irritation** of the:

Eyes Nose Throat

No irritation
Slight irritation
Moderate irritation
Strong irritation
Very strong irritation
Overpowering irritation

Imagine that during your daily office work you are exposed to this air.

How do you assess the **thermal environment**?

*(Pay attention to the distinction between **comfortable and uncomfortable**)*

Very comfortable

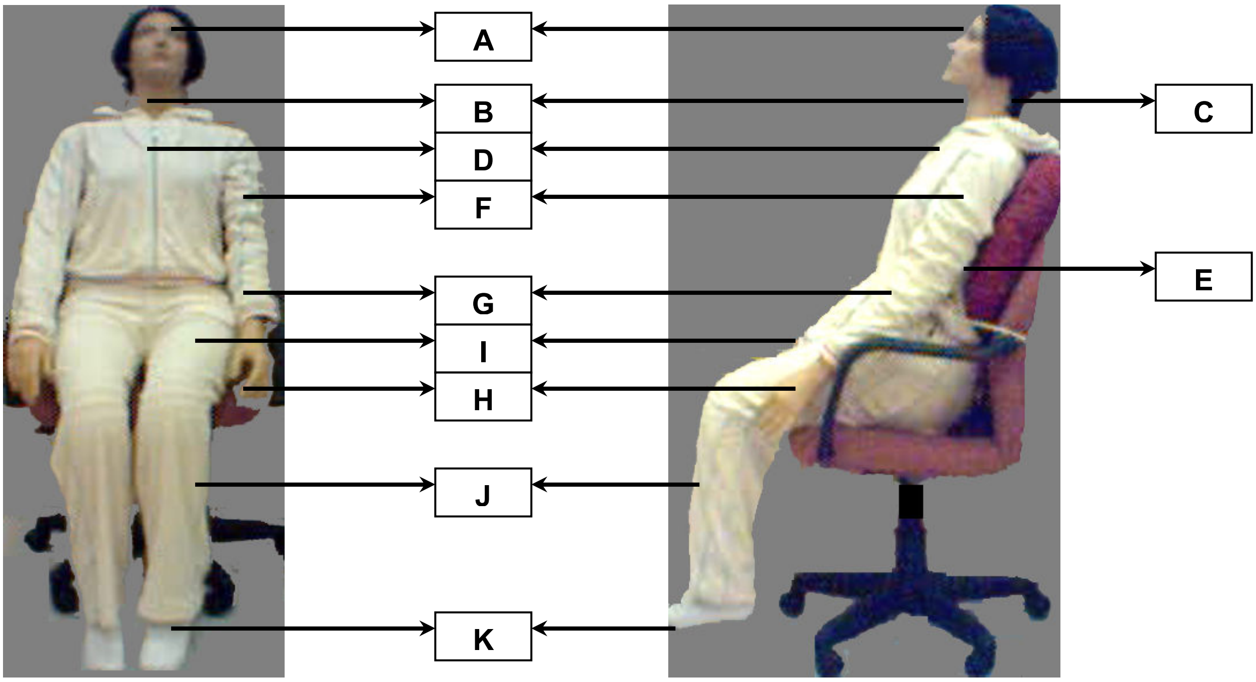
Just comfortable

Just uncomfortable

Very uncomfortable

How do you rate your body thermal sensation?	How do you rate the air that you inhale?
Hot	Hot
Warm	Warm
Slightly warm	Slightly warm
Neutral	Neutral
Slightly cool	Slightly cool
Cool	Cool
Cold	Cold

How do you rate **the thermal sensation at these locations of your body** at the moment?



A (Forehead) Hot ______________________ Cold

B (Front of neck) Hot ______________________ Cold

C (Back of neck) Hot ______________________ Cold

D (Chest) Hot ______________________ Cold

E (Back) Hot ______________________ Cold

F (Upper arms) Hot ______________________ Cold

G (Lower arms) Hot ______________________ Cold

H (Hands) Hot ______________________ Cold

I (Thigh) Hot ______________________ Cold

J (Calf) Hot ______________________ Cold

K (Feet) Hot ______________________ Cold

Right now, I can **describe my working environment** as:

Air too humid ______________________ Air too dry

Air stuffy ______________________ Air fresh

Air too still ______________________ Air too drafty

Too dark ______________________ Too bright

Too quiet ______________________ Too noisy

Dusty ______________________ Clean

Right now, **I feel/ experience** as follows:

Nose dry	Nose running
Nose blocked	Nose clear
Flu-like symptom	No flu-like symptom
Throat dry	Throat not dry
Mouth dry	Mouth not dry
Lips dry	Lips not dry
Skin dry	Skin not dry
Eyes dry	Eyes not dry
Eyes aching	Eyes not aching
Watering eyes	Eyes not watering
Cold hand	Hand not cold
Cold feet	Feet not cold
Chest tightness	Breathing easily
Severe headache	No headache
Difficult to think	Head clear
Dizzy	Not dizzy
Feeling bad	Feeling good
Tired	Rested
Difficult to concentrate	Easy to concentrate
Depressed	Positive
Alert	Sleepy
Tense	Relaxed

How do you rate the **completion of your tasks** today?

Slight effort	Strong effort
Productive	Not productive

Please rate immediately after re-entering your office.

**Imagine that during your daily office work
you are exposed to this air.**

How do you assess the **air quality**?

(Pay attention to the distinction between ***acceptable and unacceptable****)*

Clearly acceptable

Just acceptable
Just unacceptable

Clearly unacceptable

Assess **odor intensity**:

No odour
Slight odour
Moderate odour
Strong odour
Very strong odour
Overpowering odour

Assess **level of irritation** of the:

Eyes Nose Throat

No irritation
Slight irritation
Moderate irritation
Strong irritation
Very strong irritation
Overpowering irritation

Right now, **I am wearing**:

(please tick accordingly)

Shirts and blouses

__ Sleeveless
__ Short sleeved, cotton
__ Long sleeved, cotton
__ Long sleeved, flannel

Dresses and skirts

__ Skirt (thin garment)
__ Skirt (thick garment)
__ Short sleeved shirtdress
__ Long sleeved shirtdress (thin)
__ Long sleeved shirtdress (thick)

Trousers

__ Short shorts
__ Walking shorts
__ Straight trousers (thin)
__ Straight trousers (thick)

Underclothing

__ Men's brief
__ Panties
__ Bra
__ T-shirt
__ Full slip
__ Half slip
__ Long underwear top
__ Long underwear bottom

Vests and jackets

__ Sleeveless vest (thin)
__ Sleeveless vest (thick)
__ Single-breasted suit jacket
__ Double-breasted suit jacket

Sweaters

__ Sleeveless
__ Long sleeved

Footwear

__ Ankle-length socks
__ Calf-length socks
__ Knee socks
__ Panty hose
__ Shoes, thin
__ Shoes, thick
__ Boots

Other clothing/ wardrobes

__ Head scarves
__ Long/ neck scarves