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Effects of thermal discomfort in an office on perceived air quality, SBS symptoms, physiological responses, and human performance

Abstract The effects of thermal discomfort on health and human performance were investigated in an office, in an attempt to elucidate the physiological mechanisms involved. Twelve subjects (six men and six women) performed neurobehavioral tests and tasks typical of office work while thermally neutral (at 22°C) and while warm (at 30°C). Multiple physiological measurements and subjective assessment were made. The results show that when the subjects felt warm, they assessed the air quality to be worse, reported increased intensity of many sick building syndrome symptoms, expressed more negative mood, and were less willing to exert effort. Task performance decreased when the subjects felt warm. Their heart rate, respiratory ventilation, and end-tidal partial pressure of carbon dioxide increased significantly, and their arterial oxygen saturation decreased. Tear film quality was found to be significantly reduced at the higher temperature when they felt warm. No effects were observed on salivary biomarkers (alpha-amylase and cortisol). The present results imply that the negative effects on health and performance that occur when people feel thermally warm at raised temperatures are caused by physiological mechanisms.

L. Lan[1,2], P. Wargocki[2], D. P. Wyon[2], Z. Lian[1]

[1]Institute of Refrigeration & Cryogenics, Shanghai Jiao Tong University, Shanghai, China, [2]International Centre for Indoor Environment and Energy, DTU Civil Engineering, Technical University of Denmark, Kongens Lyngby, Denmark

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L. Lan
Institute of Refrigeration & Cryogenics, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
Tel.: +86-21-3420-4263
Fax: +86-21-3420-6814
e-mail: lanli_tty@hotmail.com

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Practical Implications

This study indicates to what extent elevated temperatures and thermal discomfort because of warmth result in negative effects on health and performance and shows that these could be caused by physiological responses to warmth, not by the distraction of subjective discomfort. This implies that they will occur independently of discomfort, i.e. even if subjects have become adaptively habituated to subjective discomfort. The findings make it possible to estimate the negative economic consequences of reducing energy use in buildings in cases where this results in elevated indoor temperatures. They show clearly that thermal discomfort because of raised temperatures should be avoided in workplaces.

Introduction

Indoor environments should safeguard and enhance occupant's health, comfort, and productivity, as people spend around 90% of their lives indoors. Roelofsen (2002) suggests that indoor environmental quality (IEQ) is more important for the performance of office workers than job satisfaction and job stress. Occupants who experience even subclinical symptoms such as headache and fatigue because of poor IEQ are less likely to be comfortable and also less likely to be productive. Thermal environment is one of the most important indoor environmental factors that affect health and human performance (Kosonen and Tan, 2004). Several studies have investigated the effects of the thermal environment on human performance (Wargocki and Wyon, 2007; Wyon and Wargocki, 2006), but little is known regarding the mechanisms behind these effects.

Quantitative estimates of the effects of thermal environment in non-industrial indoor environments on work can be made by associating the performance of office work to indoor air temperatures and/or by associating thermal sensation with human performance. The former approach was used by Seppänen et al. (2006) who used the results of published studies, many of which were summarized by Wyon and Wargocki (2006), to derive a relationship between temperature and performance. When using this approach, it should however be carefully considered whether air temperature can be used to estimate the effects of thermal environment on performance. This consideration should take into account the results of Wyon et al. (1975) who showed that the mental performance of subjects who were clothed for comfort at two different temperatures of 18.7 and 23.2°C was unaffected, implying that the state of heat balance is the driving factor, rather than air temperature per se. The latter approach was used by Roelofsen (2001). To create the relationship, he reanalyzed the results of Berglund et al. (1990) in which the performance of wireless navy telegraph operators was measured at temperatures above 29°C, which are much higher than the temperatures that normally occur indoors. The relationship derived by Roelofsen is based on too few experimental data to be a valid alternative. In addition, with a few exceptions (e.g. Witterseh et al., 2004), published studies show that the performance of office work is not affected by thermal discomfort (Haneda et al., 2009; Lan and Lian, 2009b; Lan et al., 2009a; Tanabe and Nishihara, 2004). This is in spite of the potentially negative effects of warmth, which has been shown to decrease arousal, exacerbate sick building syndrome (SBS) symptoms, and have negative effects on mental work (Wyon and Wargocki, 2006). Understanding the mechanisms by which performance is affected would help us to better understand earlier findings on the effects of thermal environment on performance and to decide how these effects can be predicted in the form of a quantifiable relationship, as well as how thermal conditions indoors should be controlled.

Relatively few studies have investigated the mechanisms by which IEQ factors may affect human performance (Wargocki, 2010). Tanabe and Nishihara (2004) measured cerebral blood oxygenation as an indicator of the rate of cognitive work. They reported that subjects worked harder to maintain their work performance when IEQ (moderately high temperature and lighting condition under 3 lux) was suboptimal. As a consequence of this additional work, the subjects became fatigued. Wargocki et al. (2000) reported that in air polluted by the emissions from typical building materials and bioeffluents from humans, the rate of metabolic CO_2 production of subjects performing typical office work was lower, which suggests that they exerted less effort. Bakó-Biró et al. (2005) reanalyzed the results of Wargocki et al. (2000) and other studies and created a relationship showing that metabolic CO_2 production is lower when the air quality becomes poorer. They hypothesized that this is the result of shallow breathing (hypoventilation) in poor air, causing the CO_2 level in the blood to increase (respiratory acidosis), which is known to cause headaches. They hypothesized that this could be one of the mechanisms explaining why exposure to air of poor quality reduced performance. Biomarkers in saliva were used to examine mechanisms by which thermal environment affects performance; salivary alpha-amylase reflects stress-related changes in the autonomic nervous system (Nater and Rohleder, 2009), while salivary cortisol indicates the hypothalamus–pituitary–adrenal axis (HPAA) adaptation to stress (Hellhammer et al., 2009). Willem (2006) and Tham and Willem (2010) found that salivary alpha-amylase level increased when tropical subjects were exposed to moderately cold environments (20 and 23°C compared with 26°C) and that lower temperatures reduced the concentration of salivary cortisol. Higher alpha-amylase suggested activation of the sympathetic nervous system as a response to cold. This was accompanied by higher mental arousal as indicated by lower scores in a Tsai–Partington test, suggesting that salivary alpha-amylase can be used as an objective indicator of the level of mental arousal associated with thermal exposures. Lower cortisol levels suggested better stress relief at the lower temperature that had resulted in a lower level of psychological stress. These two biomarkers were also used by Wargocki et al. (2009) who exposed non-tropical subjects to moderately elevated temperatures (29°C compared with 23.5°C). Higher temperatures gave rise to thermal discomfort because of warmth and caused salivary alpha-amylase and cortisol to decrease.

The objectives of this study were to investigate whether warmth affects mental performance, and if so, to elucidate the mechanisms behind this effect and whether thermal discomfort is in the chain of causation.

Methods

Approach

The subjects were exposed in an office to two thermal conditions created by setting the temperature at 22 and 30°C; the clothing level of the subjects was 0.9 clo at both temperatures. The clothing level was selected to keep the subjects thermally neutral at 22°C. To make sure that the two thermal conditions were sufficiently different, 30°C was selected, as the relationship derived by Seppänen et al. (2006) suggests that a temperature of 22°C creates conditions for optimal performance while performance should be considerably reduced at 30°C. A noise level of 50 dB(A) (with no occupants in the office) and a ventilation rate of 10 l/s per person were kept constant independently of the temperature in the office. During each exposure in the office, the subjects performed tasks typical of office work and neurobehavioral tests designed to assess different skills. Physiological parameters and biomarkers were measured several times during the exposure to explore the mechanisms by which raised temperatures affect performance. The subjects reported perceived air quality, thermal comfort, SBS symptoms, willingness to exert effort while working, emotion, fatigue, and workload on several occasions during each exposure in the office.

Facilities

The study was carried out in an office (with floor area of 18 m^2 and a volume of 55 m^3) adapted for experimental purposes (Toftum et al., 2004). Six workstations were set up in the office. Each workstation consisted of a table, a chair, a desk lamp, and a laptop. Webcameras were installed at each workstation to monitor the subjects. The air temperature in the office was maintained at the intended level by controlling the temperature of the air supplied to the office by the central ventilation system, using a PID controller connected to a calibrated temperature sensor located centrally in the space occupied by the subjects. The room was ventilated by 100% outdoor air using the mixing principle.

Subjects

Six women and six men with an average age of 23 ± 2 years were randomly selected from those that could be recruited from a group of 30 subjects who had participated in another experiment using similar experimental procedures that had taken place immediately prior to the present study (Skwarczynski et al., 2009). The subjects selected were all Caucasian students from the Technical University of Denmark but of different nationalities; all tests were therefore presented to them in English. The subjects were recruited based on the following criteria: familiarity with computers, impartiality to the office in which the study was carried out, and absence of chronic diseases, asthma, allergy, hay fever, and color blindness. The information was obtained from a questionnaire distributed during recruitment; none was examined medically.

During the week preceding the experiment, the recruited subjects attended a 1-h practice and instruction session at 22°C. During this session, they rehearsed the experimental procedure. They performed neurobehavioral tests and tasks simulating office work similar to those used in the subsequent experiment. They were instructed on how to fill out the questionnaires used for collecting subjective responses. All of the physiological measurements were explained to them. During this session, the subjects were asked to adjust their clothing so as to feel thermally neutral. They were then instructed to wear the same clothing in the subsequent experiments. The subjects were also instructed what not to do on the experimental day and on the day prior to each exposure (e.g. drinking alcohol, overexertion, late to bed).

The subjects were paid a salary for participating in the experiment at a fixed rate per h; they did not receive any bonuses. All subjects except one who missed one session completed all experimental sessions.

Measurements

Physical measurements. The temperature and relative humidity, illuminance level, and concentration of CO_2 in the room were continuously recorded with HOBO data loggers at each workstation and at the center of the room. The HOBO data logger has a built-in temperature (range: −20 to +70°C, accuracy: ±0.7°C), humidity (range: 0–95%, accuracy: ±5%), and light intensity (range: 0.1–200000 lux, accuracy: ±1 in last digit) sensors and was also connected to a Vaisala CO_2 instrument (range: 0–2000 ppm, accuracy: 40 ppm + 2% of measured value). Operative temperature was measured continuously using a VIVO meter (Dantec Dynamics A/S, accuracy: ±0.5°C) located at the center of the office. The ventilation rate and ventilation effectiveness were measured during each experiment using a LumaSense monitor (Innova 1312 photoacoustic multi-gas monitor, accuracy: ±1%); tracer gas (sulfur hexafluoride, SF_6) and constant dosing were used. The noise level was measured repeatedly with an Extech sound level meter [range: 35–130 dB(A), accuracy: ±2 dB(A)] during the experiment. All of these instruments had been calibrated.

Subjective measurements. A questionnaire was used that included questions regarding perceived air quality, thermal comfort, SBS symptom intensity, emotion, and willingness to exert effort while working. The perceived air quality and thermal comfort were assessed using continuous scales describing the acceptability of air quality and the acceptability of and satisfaction with the thermal environment (Wargocki et al., 1999). A 7-point continuous scale was used to register thermal sensation (ASHRAE 2005). SBS symptom intensity was assessed using visual analogue scales (VAS)—horizontal lines without graduation with two vertical dash lines marking the extreme points of the scale, each with end labels (Wargocki et al., 1999). Willingness to exert effort while working was assessed using a VAS that increased from 0 (low motivation) to 100 (high motivation). Different versions of the Tsai-Partington test were used to assess changes in the level of arousal (Witterseh et al., 2004). All of these scales were presented to subjects on a PC (Toftum and Wyon, 2005).

The profile of mood states. Emotion was investigated with the profile of mood states short form (POMS-SF) presented on a PC (McNair et al., 1992).The mood states included tension, depression, anger, vigor, fatigue, and confusion, scoring on a 5-point Likert-type scale ranging from 0 (not at all) to 4 (extremely). The total mood disturbance (TMD) was computed by adding the scores for tension, depression, anxiety, fatigue, and confusion, with vigor scores subtracted; the higher the TMD score, the more negative the mood.

Subjective symptoms of fatigue. To evaluate the pattern of fatigue, subjects completed a questionnaire presented on a PC (Tanabe and Nishihara, 2004). The questionnaire consists of three groups of questions. Group I consists of 10 questions describing 'drowsiness and dullness'. Group II consists of 10 questions describing 'difficulty in concentration'. Group III consists of 10 questions describing 'lack of physical integration'. The questions are presented to subjects in random order. The rate of complaints was calculated for each group based on Yoshitak's method (Yoshitak, 1973) and used to estimate the pattern of fatigue.

Mental workload. The NASA- Task Load Index (TLX) for evaluating work load was measured using a questionnaire presented on a PC (Hart and Wickens, 1990). It consists of six linear scales (similar to VAS) describing 'mental demand', 'physical demand', 'temporal demand', 'performance', 'effort', and 'frustration level'. The endpoints of the scales are marked low and high, and only in the case of performance are they marked good and poor. They are normally coded 0–100. The responses on each scale were analyzed separately. An overall estimate of mental workload, Raw TLX (RTLX), was also calculated by averaging the scores describing each of the six components (Miyake and Kumashiro, 1993).

Physiological measurements

Finger skin temperature. Finger skin temperature was measured with the Fluke 65 Hand-held Infrared Thermometer (Fluke Europe B.V, The Netherlands, accuracy: ± 0.5°C). The infrared thermometer was in a position perpendicular to the left hand with fingers held together, at a distance of about 3–5 cm. As the optical resolution for this device is 8:1, a distance of 3 cm corresponds to a sampling area with a diameter of <0.5 cm. Typical skin temperature for the human body in thermal equilibrium is about 32–33°C.

Heart rate and respiration ventilation. Heart rate and the *r–r* intervals (the time interval between two heartbeats in milliseconds) were measured with a commercial heart rate monitor (Sunnto Inc., Vantaa, Finland), which consisted of a chest strap with electrodes. Via the docking station, the heart rate and the *r–r* intervals data were transferred to a computer for further analysis. The *r–r* intervals were used by the built-in analysis software (Firstbeat technologies Ltd., Jyväskylä, Finland) to calculate the respiratory ventilation rate (the amount of air breathed per min). Typical healthy resting heart rate in adults is 60–80 bpm. Changes in heart rate (driving the blood supply and related to metabolic heat production) can be used to estimate metabolic rate (ISO 8996, 1989).

End-tidal partial CO_2 ($ETCO_2$) and arterial blood oxygen saturation (SPO_2). The concentration of end-tidal partial CO_2 ($ETCO_2$), the partial pressure of carbon dioxide at the end of an expiration, was monitored with a non-invasive capnographic monitor (LifeSense LS1; MedAir AB Inc., Hudiksvall, Sweden). Measuring $ETCO_2$ can be used to approximate arterial CO_2 non-invasively (Wientjes et al., 1998).The normal values of $ETCO_2$ are 35–45 mmHg.

Arterial blood oxygen saturation (SPO_2) was measured with a monitor for pulse oximetry (LifeSense LS1; Medair AB Inc). A special finger probe (REF 210; Medair AB) was attached to the subject's finger.

Biomarkers in saliva (alpha-amylase and cortisol). A non-stimulated passive drool salivary sampling procedure was applied to measure the salivary level of alpha-amylase and cortisol in the saliva of subjects. Subjects were asked not to eat or drink for half an hour prior to the collection of saliva. They were also instructed to swallow or clear their mouth of any excessive saliva prior to collection of saliva samples. Subjects then started to accumulate and expel saliva into a labeled sampling tube for about 5 min to provide about 4 ml of saliva. The samples were then centrifuged for 15 min at 1305 *g* and placed for 1 h in a freezer at −20°C. After this time, the samples were centrifuged for 15 min again at 1305 *g*. They were then frozen and stored in a freezer at −20°C before being sent for analysis. The analysis was performed by an external specialized laboratory using a kinetic colorimetric method to determine salivary alpha-amylase and cortisol concentration in the saliva. The accuracy of alpha-amylase analysis was as follows: intra-assay (within run variation) $<1.5\%$; inter-assay (between run variation) $<1.5\%$; recovery: $100 \pm 6.3\%$. The accuracy of cortisol analysis was as follows: intra-assay (within run variation) $<7\%$; inter-assay (between run variation) $<9.3\%$; recovery: $100 \pm 6.3\%$. In US Army research, concentrations of salivary amylase >600 units/ml are considered 'high stress' and 400–600 units/ml are considered 'moderate stress' (Morrison et al., 2003). The secretion of cortisol usually increases profoundly in the morning, after awakening, and then reduces slowly during the afternoon and evening hours (Clow, 2004). The diurnal rhythm of alpha-amylase is characterized by a strong decrease after waking up and gradually increasing levels with peaks in the late afternoon (Rohleder and Nater, 2009).

Tear film quality. Samples of tear film mucus were taken as an indicator of subjects' ability to maintain tear film quality. The subjects collected tear film mucus from the inside of the lower eyelid with a glass rod (while looking into a mirror) and deposited it onto a microscope slide. After drying the slide for 1 h, it was photographed under the microscope and the images obtained were used to classify the samples. The samples were classified independently, by three evaluators using four categories according to the closeness and branching frequency of the ferning patterns (Rolando, 1984). Type I with uniform structures without spaces among the ferns indicates healthy, well-moistured eyes. Type II having abundant ferning but with small spaces appearing between the ferns indicates good tear film mucus. Type III with large spaces between the ferns and with poorer branching indicates that the mucus may not be able to perform its function. Type IV with no visible ferning structure indicates an altered state of mucus that is typical for people with dry eye syndrome.

Blink rate. During the experiment, webcameras placed on every workstation recorded continuous video images of the face of each subject. These recordings were used to estimate the blink rate. The number of blinks that occurred during a 5-min period was counted after 80 min of exposure. This period was used as the subjects were looking at the computer screen with little head movement so that an eye blink could be clearly observed. Most people blink about 15 times a min.

Measurement of performance. During the exposure in the office, the subjects performed neurobehavioral tests and tasks typical of office work. The latter included *text typing* and *addition* (Wargocki et al., 1999); the tasks were presented on a PC (Toftum and Wyon, 2005). The former was a neurobehavioral test battery (Lan and Lian, 2009b; Lan et al., 2009a) including seven computerized tests presented to subjects in the following order: *Mental reorientation* (a spatial orientation test), *Grammatical Reasoning* (a logic reasoning task), *Digit Span Memory* (a traditional test of verbal working memory and attention), *Visual Learning Memory* (a picture memory task measuring spatial working memory), *Number Calculation* (a mental arithmetical test in which the subject has to add, subtract, or multiply numbers), *Stroop* (a test of attentional vitality and flexibility owing to perceptual/linguistic interference), and *Choice Reaction Time* (a sustained attention task measuring response speed and accuracy to visual signals).

The tasks were presented on a PC and were self-paced; the reaction/processing time was recorded by the computer clock. All tasks were presented to subjects without feedback, i.e. they did not receive any information on their performance and performed each task until it was completed. Speed (response time) and accuracy (% of corrects) were used as measures of performance of tasks completed without feedback. In this case, a performance index (PI) was computed separately for each task to describe the mean processing/reaction time divided by the accuracy of responses (e.g. correct characters typed per min or correct units added per min). For the two memory tests, *Digit span* and *Visual learning*, performance was in terms of accuracy, i.e. digit span (the maximum number of digits the subject could correctly learn and recall) and memory capacity (percentage of correctly recalled nonsense designs), respectively (Lan et al., 2009a). *Text typing*, *addition*, *Stroop,* and *Number Calculation* were also presented to subjects with feedback about their performance, i.e. they could not continue until they corrected the error. Speed (response time including the time spent for error correction) was used as a measure of performance of tasks completed with feedback. In this case, the PI was calculated as the reciprocal of processing/reaction time. The tasks were always performed in the same order independently of the condition. Four sets of tasks with similar level of difficulty were prepared and randomly assigned to subjects in a design that was balanced for order of presentation.

Experimental procedure

The subjects were divided into two groups of six persons (three men and three women). Each group was exposed to each temperature twice in a repeated measures design balanced for order of presentation, i.e., one group was exposed in 22-30-30-22 order and the other group in the following order: 30-22-22-30. The exposures took place in two successive weeks of March 2009 from Monday to Thursday in the afternoon from 13:00 to 17:30; the actual exposure in the office lasted 4.5 h. Each group was exposed twice a week (Group 1 on Mondays and Wednesdays and Group 2 on Tuesdays and Thursdays) and on the same weekdays in the subsequent weeks. Although only 12 subjects participated, the repeated measures design with repetition ensured that the statistical power of the study was similar to the statistical power of the previous comparable studies on the effects of IEQ on performance in which 30 subjects were normally recruited, and the repeated measures design was used without repetition (e.g. Wargocki et al., 2000); the statistical power for both designs is 0.96 with the sphericity assumption and assuming equal medium effect size (ES = 0.25) (Faul et al., 2007).

Figure 1 shows the schedule for each experimental session. Prior to entering the office, the subjects assembled in a waiting room (in which the temperature was about 22°C) where they stayed for approximately 10 min. During this time, they rated emotion, fatigue, and willingness to exert effort. They also put on the chest belt for continuous measurement of heart rate

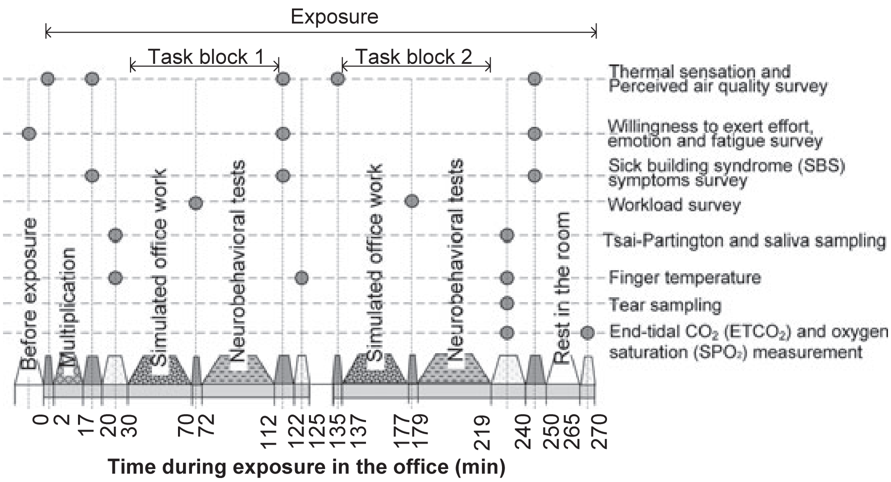

Fig. 1 Experimental procedure

and respiration parameters. The subjects then entered the office, approached their workstations and evaluated their thermal comfort and the perceived air quality. They performed a multiplication task for 15 min; this period was used to allow subjects to adapt to conditions. The performance of the multiplication task was not analyzed. After the multiplication task, subjects assessed the air quality and their thermal comfort, and indicated their SBS symptoms followed by sampling of saliva and the measurements of finger temperature. Subjects then performed the Tsai-Partington test followed by a period of 40 min during which they performed *text typing*, *addition*, *text typing with feedback,* and *addition with feedback*; each task took 10 min to complete. Upon completing the tasks, subjects evaluated work load using the NASA-TLX, which was followed by a 40-min period during which they performed neurobehavioral tests with and without feedback; the test without feedback took 30 min to complete, while *Stroop* and *Number Calculation* took in all about 10 min. They then evaluated the air quality and their thermal comfort and indicated their SBS symptoms, emotion, fatigue, and motivation. This was followed by a 10-min break during which the subjects could leave the office if necessary, but were asked to stay inside the office. After the break, the above experimental plan was repeated (Figure 1). Toward the end of each exposure, after the subjects had completed the neurobehavioral tests with feedback, finger temperature, $ETCO_2$, and SPO_2 were measured, and samples of tear film mucous and saliva were taken. This was followed by another evaluation of air quality and thermal comfort, SBS symptoms, emotion, fatigue, and motivation. The subjects then remained in the office for 15–20 min without performing any tests (resting). After this period, the $ETCO_2$ and SPO_2 were measured again.

All protocols were approved by the ethics review board and conformed with the guidelines contained in the Declaration of Helsinki. Verbal and written informed consent was obtained from subjects prior to their participation in the experiment.

Statistical analysis

The SPSS 13.0 (SPSS Inc., Chicago, IL, USA) program was used to perform the statistical analysis. The measured data were subject to analysis of variance (ANOVA) in a repeated measures design; Huynh–Feldt statistics was used to adjust the violation of sphericity. The significance level was set to be 0.05 ($P < 0.05$). In some cases, a paired t-test was used. It should be noted that it is effect size (ES) instead of P-value that measures the difference between the true value and the value specified by the null hypothesis and hence indicates whether the difference is of practical importance (Lan and Lian, 2010). In this article, ES was calculated and reported. Effect sizes with values of 0.1, 0.25, and 0.4 for the ANOVA indicate small, moderate, and large changes, while for the t-test, the corresponding effect sizes are 0.2, 0.5, and 0.8. (Cohen, 1988).

Results

Average values of the physical parameters describing the indoor environment in the office are shown in Table 1; the operative temperature did not deviate from the intended levels. The CO_2 levels measured at each workstation with the Vaisala CO_2 transmitter increased with the air temperature. There were very small variations between the conditions within each experimental condition; thus, the conditions for different groups of subjects and during each repetition can be considered as similar.

The thermal sensation reported by the subjects was neutral (mean thermal sensation votes = 0.01) at 22°C and warm (mean thermal sensation votes = 2) at 30°C

Table 1 Physical measurements (mean ± s.d.) describing the office environment under the two conditions

Condition (intended temperature)	Air temperature (°C)	Operative temperature (°C)	Relative humidity (%)	Light (lux)	CO_2 (ppm)	Noise (dBA)
22°C	23.3 ± 0.8	22.6 ± 0.6	21 ± 7	241 ± 60	801 ± 70	56 ± 5
30°C	31.1 ± 1.3	29.4 ± 1.2	22 ± 3	225 ± 64	1047 ± 145	55 ± 4

Table 2 Subjective assessments on thermal sensation and perceived air quality at two thermal conditions; the results shown are averages and standard deviations (in brackets)

Exposure time in the room (min)	0–2	17–20	112–122	135–137	240–250
Thermal sensation [hot(3); warm(2); slightly warm(1); neutral(0); slightly cool(−1); cool(−2); cold(−3)]					
22°C	0.42	0.30	−0.20	−0.39	−0.07
30°C	2.17	2.08	2.28	2.16	2.00
P	<0.001**	<0.001**	<0.001**	<0.001**	<0.001**
Perceived air quality (clearly acceptable(1); clearly unacceptable(−1))					
22°C	0.70	0.81	0.74	0.71	0.79
30°C	−0.11	−0.06	−0.22	−0.15	−0.08
P	<0.001**	<0.001**	<0.001**	<0.001**	<0.001**
% dissatisfied with air quality (Gunnarsen and Fanger, 1992)					
22°C	2	1	2	2	1
30°C	60	54	64	65	57

**Significant differences ($P < 0.05$) between conditions observed.

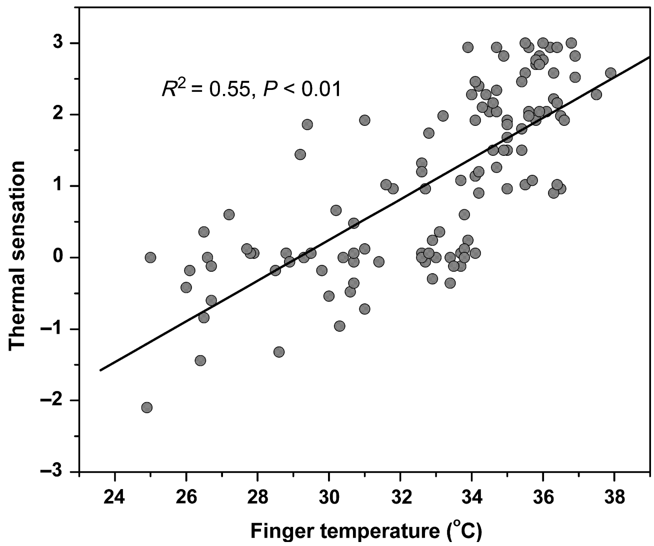

Fig. 2 Thermal sensation votes as a function of finger temperature

(Table 2). Subjects were significantly more satisfied with the thermal environment at 22 than at 30°C ($P < 0.001$, ES = 3.20). Subjects reported that the air quality was significantly less acceptable at 30°C compared with 22°C (Table 2). Although the subjects entered the office at 30°C from the 22°C waiting area, their assessments of the perceived air quality and thermal sensation made during the course of exposure at this condition did not differ much from the assessments made immediately upon entering the office (Table 2). Upon reentering the office after exposure, subjects reported that the air quality was less acceptable at 30°C than at 22°C; the estimated % dissatisfied with air quality (Gunnarsen and Fanger, 1992) corresponded to 65% and 2% respectively. Measured finger temperatures significantly correlated with thermal sensation votes; they increased with higher thermal sensation vote, as expected (Figure 2).

The general rate of complaints of fatigue was very low and was similar in both conditions prior to exposure (Table 3). During and after exposure, the subjects displayed a pattern of fatigue that is typical for mental work; the rate of complaints was higher at 30°C than at 22°C.

Subjects experienced more negative moods and lower vigor when exposed at 30°C compared with 22°C; there were no differences in emotions prior to exposure (Table 4).

The SBS ratings were subject to paired *t*-tests as there was missing data for one group at both 22 and 30°C. Except for the intensity of dry nose, dry skin, dry eyes, and headache, which did not change significantly, the intensity of all other SBS symptoms was higher at 30°C compared with 22°C, especially halfway through the exposure (after 112–122 min of exposure) (Table 5). The subjects indicated that they were significantly less able to perform their work in the 30°C condition compared with the 22°C condition. Subjects indicated that they felt more fatigue at 30°C after they completed the tasks (Table 5), which is consistent with the subjectively rated complaints of fatigue (Table 3 and 4).

Figure 3 shows that the subjects were less willing to exert effort while working at 30°C compared with 22°C, both after exposure for 112 min ($P < 0.01$; ES = 1.45) and for 240 min ($P < 0.05$; ES = 0.65); there were no differences in motivation prior to exposure.

Table 6 summarizes the effects of conditions on mental work load and the six-component scales of the NASA-TLX. Subjects indicated that the mental workload was significantly higher at 30°C. Subjects indicated also that the mental and physical demand and the feeling of disappointment increased at 30°C compared to 22°C.

The performance of simulated office work and of the neurobehavioral tests is summarized in Table 7. Except for the performance of the *text typing* task, the

Table 3 The complaints of subjective symptoms of fatigue in the two thermal conditions

Exposure time in the room (min)	Condition	Complaint rates Group I	Group II	Group III	The order among three categories	Pattern of fatigue
Before exposure	22°C	5.8	4.2	6.3	III > I > II	Fatigue for mental work
	30°C	4.8	5.2	3.0	II > I > III	N/A
After block 1 (112)	22°C	22.1	18.3	9.2	I > II > III	Fatigue for mental work
	30°C	43.5	42.9	17.1	I > II > III	Fatigue for mental work
After block 2 (240)	22°C	25.6	21.1	12.2	I > II > III	Fatigue for mental work
	30°C	47.4	41.7	24.3	I > II > III	Fatigue for mental work

Table 4 Average and standard deviation (in brackets) of emotion scores under different conditions; higher score of total mood disturbance (TMD) and the negative moods, such as tension, depression, anger, fatigue, and confusion, indicates higher negative emotion, while the higher score of vigour indicates higher positive emotion; effect sizes (ES) with values of 0.1, 0.25, and 0.4 indicate small, moderate, and large changes, respectively

Time during exposure (min)	17–20				112–122				240–250			
Temperature	22°C	30°C	ES	*P*	22°C	30°C	ES	*P*	22°C	30°C	ES	*P*
TMD	−0.7 (5.8)	−1.0 (7.3)	0.08	0.82	9.3 (10.1)	19.2 (15.6)	1.23	<0.01**	12.1 (9.9)	19.3 (13.8)	0.93	0.02
Tension	0.9 (0.9)	0.8 (1.7)	0.03	0.93	2.2 (2.0)	3.3 (2.3)	0.62	0.08*	2.7 (2.2)	3.3 (2.2)	0.38	0.29
Depression	1.0 (1.5)	1.2 (2.3)	0.10	0.77	2.2 (2.2)	4.1 (3.4)	0.87	0.02**	2.3 (2.2)	3.7 (3.00)	0.69	0.07*
Anger	1.3 (1.8)	0.9 (1.5)	0.23	0.49	2.7 (2.3)	4.5 (3.5)	1.02	0.01**	2.8 (2.2)	4.0 (3.2)	0.71	0.06*
Vigor	11.0 (2.9)	10.5 (3.9)	0.18	0.58	5.7 (3.2)	4.2 (3.4)	1.25	<0.01**	3.8 (2.6)	3.5 (3.5)	0.42	0.24
Fatigue	3.8 (1.2)	4.0 (1.0)	0.13	0.70	4.92 (3.23)	7.5 (4.05)	1.24	<0.01**	5.71 (3.23)	8.49 (4.13)	1.37	<0.01**
Confusion	3.3 (1.4)	2.7 (0.9)	0.64	0.07*	3.0 (2.3)	3.9 (2.3)	0.47	0.17	2.4 (2.3)	3.3 (2.4)	0.47	0.19

*Differences approaching significance ($0.05 < P < 0.10$).
**Significant differences ($P < 0.05$) between conditions observed.

Table 5 Average and standard deviation (in brackets) intensity of sick building syndrome symptoms under different conditions in the office; coding of the scales is indicated in the table; effect sizes (ES) with values of 0.2, 0.5, and 0.8 indicate small, moderate, and large changes, respectively

Time during exposure in the office (min)	17–20				112–122				240–250			
Temperature	22°C	30°C	ES	*P*	22°C	30°C	ES	*P*	22°C	30°C	ES	*P*
Dry nose (100) Runny nose (0)	59.8 (25.5)	52.3 (30.3)	0.41	0.18	50.5 (25.3)	56.7 (26.0)	0.13	0.67	54.8 (25.4)	54.5 (30.9)	0.05	0.87
Dry throat (100) Not dry throat (0)	34.1 (30.2)	53.0 (37.8)	0.43	0.17	36.5 (28.6)	53.9 (30.9)	1.00	0.01**	42.4 (34.5)	57.5 (30.1)	0.85	0.02**
Dry mouth (100) Not dry mouth (0)	46.5 (33.9)	57.4 (37.2)	0.56	0.08*	39.5 (28.2)	57.5 (36.1)	1.05	<0.01**	50.9 (32.2)	55.9 (35.8)	0.50	0.11
Dry skin (100) Not dry skin (0)	31.1 (29.6)	35.0 (29.7)	0.24	0.43	27.0 (24.9)	33.2 (29.3)	0.39	0.20	29.8 (27.5)	31.5 (25.1)	0.20	0.51
Dry eyes (100) Not dry eyes (0)	29.2 (26.5)	34.7 (29.3)	0.46	0.14	34.8 (28.7)	50.3 (33.4)	0.40	0.19	45.0 (30.7)	53.6 (31.8)	0.47	0.13
Severe headache (100) No headache (0)	9.7 (18.7)	13.9 (18.9)	0.15	0.60	16.9 (22.3)	22.9 (27.0)	0.24	0.42	17.3 (24.9)	27.0 (30.1)	0.46	0.14
Difficult to concentrate (100) Easy to concentrate (0)	20.2 (19.2)	44.7 (27.6)	0.75	0.03**	36.3 (19.6)	69.9 (23.3)	1.80	<0.01**	41.0 (24.8)	65.1 (20.8)	0.95	0.01**
Feeling good (100) Feeling bad (0)	82.4 (13.5)	56.1 (28.0)	0.99	0.01**	67.9 (22.2)	36.1 (24.1)	1.42	<0.01**	66.5 (19.5)	39.7 (20.6)	1.12	<0.01**
Sleepy (100) Rested (0)	33.7 (23.0)	39.0 (27.0)	0.18	0.54	51.2 (23.9)	74.1 (24.9)	1.13	<0.01**	60.8 (20.9)	69.6 (20.0)	0.47	0.14
Hard to think (100) Easy to think (0)	19.7 (14.3)	45.4 (27.4)	1.45	<0.01**	37.6 (23.6)	69.8 (25.4)	1.39	<0.01**	44.4 (24.2)	65.1 (19.1)	0.79	0.02**
In a good mood (100) Depressed (0)	81.2 (15.9)	66.7 (24.2)	1.24	<0.01**	76.7 (16.9)	54.7 (19.5)	1.06	<0.01**	71.9 (16.0)	55.0 (19.0)	1.04	<0.01**
I am able to work 0–100	80.3 (9.3)	65.9 (17.2)	1.52	<0.01**	68.1 (16.5)	46.1 (20.3)	1.33	<0.01**	64.5 (17.7)	47.1 (20.7)	0.88	0.02**

*Differences approaching significance ($0.05 < P < 0.10$).
**Significant differences ($P < 0.05$) between conditions observed.

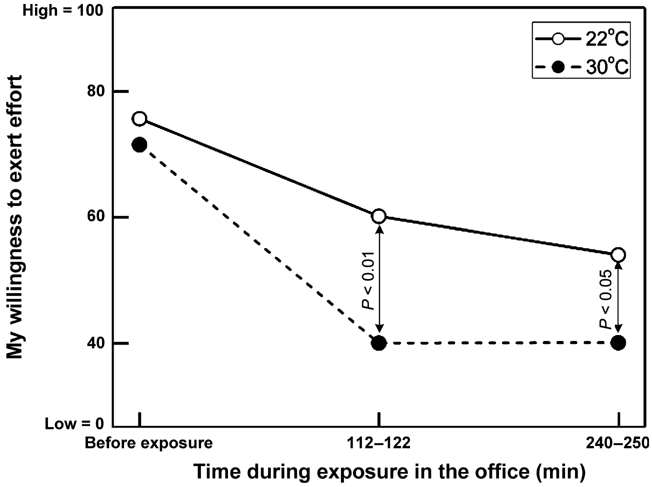

Fig. 3 Subjectively assessed willingness to exert effort while working as a function of time during exposure in the office

performance of the tasks decreased at 30°C compared with 22°C, although for some tasks, the decrease was not significant. The effect size was in many cases at least moderate, indicating that the observed effects were of practical importance. The performance of tasks presented with feedback was affected to a higher degree than that of the tasks presented without feedback, especially in the condition with a temperature of 30°C. In the case of *text typing without feedback*, the subjects input more characters at 30°C but at the same time, they also made more errors; the effect size was small in this case, and the effect was insignificant suggesting that the observed effects occurred by chance and had no practical importance. When *text typing with feedback* was presented, the subjects performed less well at 30°C compared with 22°C. The effect was not statistically significant although the effect size was in this case moderate.

No significant effects of thermal environment or exposure time were observed on the performance of the Tsai-Partington tests.

Based on the continuous measurements of heart rate and the *r–r* intervals, the average heart rate and respiratory ventilation rate for five different periods during exposure was calculated: when subjects were performing the tasks typical of office work (during exposure in the office from 30 to 70 min); when subjects were performing the neurobehavioral tests (from 72 to 112 min); when they were performing tasks typical of office work and the neurobehavioral tests separately again (from 137 to 177 minand 179 to 219 min, respectively); and finally when they rested while remaining in the room (from 250 to 265 min). Heart rate was lower at 22°C compared with 30°C; it also decreased during the course of each exposure independently of the condition in the office (Table 8). The respiratory ventilation rate was lower at 22°C than at 30°C; it decreased during the course of exposure to 22°C but at 30°C, it first decreased and then increased; the decrement was independent of the condition when the subjects rested in the office (Table 8).

Table 9 shows that the $ETCO_2$ measured immediately after the subjects finished the tasks, i.e. after 219 min of exposure in the office, was significantly higher at 30°C ($P = 0.02$, ES = 0.86). The measurements taken after the 15 min of resting showed that the arterial CO_2 was still higher at 30°C, although the difference had decreased somewhat ($P = 0.08$, ES = 0.63), Table 9. The arterial CO_2 did not change significantly during exposure in either of the two examined temperatures. The SPO_2 measurements taken after 219 min of exposure in the office indicate that arterial oxygen saturation was significantly lower at 30°C compared with 22°C ($P < 0.01$, ES = 1.524), Table 9. Arterial oxygen saturation was still significantly lower at 30°C after the 15-min rest ($P < 0.05$, ES = 0.823). Arterial oxygen saturation did not change significantly between the two periods in which the measurements were taken at 22°C, but it increased significantly after 15 min of resting at 30°C ($P < 0.01$, ES = 1.094).

Table 6 Mental workload (Raw TLX) and the six-component scales of NASA-TLX during exposure in the office at different conditions; the results shown are averages and standard deviations (in brackets); effect sizes (ES) with values of 0.1, 0.25, and 0.4 indicate small, moderate, and large changes, respectively

Time during exposure in the office (min) Temperature	70–72				177–179			
	22°C	30°C	ES	*P*	22°C	30°C	ES	*P*
Mental demand (A lot-100, A little-0)	30.9 (15.8)	40.0 (21.9)	0.96	0.01**	31.0 (14.9)	36.5 (19.1)	0.68	0.06*
Physical demand (A lot-100, A little-0)	14.0 (14.1)	26.3 (16.5)	0.82	0.03**	13.6 (8.4)	23.6 (18.7)	0.72	0.04**
Time stress (A lot-100, A little-0)	37.3 (21.5)	32.3 (20.5)	0.41	0.23	34.4 (23.0)	35.4 (20.5)	0.06	0.85
Performance (Poor-100, Well-0)	27.2 (18.4)	36.5 (24.9)	0.73	0.04**	22.2 (16.2)	33.1 (23.1)	0.79	0.03**
Effort (A lot-100, A little-0)	25.7 (17.8)	24.4 (18.3)	0.12	0.71	26.5 (16.5)	25.5 (16.6)	0.11	0.74
Disappoint (A lot-100, A little-0)	25.1 (18.0)	29.1 (22.2)	0.35	0.30	18.5 (14.0)	29.2 (20.0)	0.92	0.02**
Mental workload (Raw TLX)	26.7 (9.5)	31.4 (14.2)	0.68	0.05**	24.3 (9.0)	30.6 (14.2)	0.77	0.04**

*Differences approaching significance ($0.05 < P < 0.10$).

**Significant differences ($P < 0.05$) between conditions observed.

Table 7 Performance of tasks typical of office work and of the neurobehavioral tasks; a negative relative change in the performance (△) indicates that performance decreased at 30°C compared with 22°C; effect sizes (ES) with values of 0.1, 0.25, and 0.4 indicate small, moderate, and large changes, respectively

Task	Temp. (°C)	Performance index Metrics	Value	△	ES	P
Text typing	22	Char/min	143.6	0.3%	0.11	0.75
	30		144.0			
Text typing with feedback	22	Char/min	133.1	−10.6%	0.40	0.23
	30		120.3			
Addition	22	Units/min	4.67	−11.7%	1.15	0.01**
	30		4.11			
Addition with feedback	22	Units/min	3.02	−8.2%	0.83	0.03**
	30		2.77			
Redirection	22	Units/sec	0.932	−3.0%	0.58	0.10
	30		0.905			
Digit span	22	Span	7.69	−2.8%	0.27	0.44
	30		7.48			
Grammatical reasoning	22	Units/sec	0.165	−25.0%	0.71	0.06*
	30		0.132			
Visual learning	22	Memory	90.0	−1.4%	0.22	0.51
	30	capacity	88.8			
Stroop	22	Units/sec	0.513	−9.5%	0.59	0.09*
	30		0.469			
Stroop with feedback	22	Units/sec	0.517	−11.2%	1.01	0.01**
	30		0.465			
Calculation	22	Units/sec	0.236	−4.6%	0.62	0.08*
	30		0.226			
Calculation with feedback	22	Units/sec	0.225	−9.7%	0.93	0.01**
	30		0.205			
Visual RT	22	Units/sec	1.672	−6.8%	0.86	0.02**
	30		1.566			

*Differences approaching significance (0.05 < P < 0.10).
**Significant differences (P < 0.05) between conditions observed.

Table 8 Heart rate and respiratory ventilation rate as a function of time during exposure in the office; the results shown are averages and standard deviations (in brackets)

Exposure time in the room (min)	30–70	72–112	137–177	179–219	250–265
Heart rate (bpm)					
22°C	73.5 (9.3)	71.2 (8.9)	70.7 (8.6)	69.6 (7.9)	71.0 (8.3)
30°C	78.8 (9.5)	76.9 (8.7)	75.9 (8.8)	75.6 (9.2)	72.7 (8.5)
P	<0.01**	<0.01**	<0.01**	<0.01**	0.05**
Respiratory ventilation (l/min)					
22°C	6.5 (2.1)	6.2 (2.4)	5.9 (2.1)	5.8 (2.0)	5.6 (1.7)
30°C	7.3 (2.1)	6.7 (2.1)	6.7 (2.0)	6.8 (2.1)	5.7 (1.8)
P	0.06*	0.21	<0.01**	<0.01**	0.69

*Differences approaching significance (0.05 < P < 0.10).
**Significant differences (P < 0.05) between conditions observed.

The concentration of alpha-amylase did not change with the temperature; it also did not change between the two measurements taken at two points in time, in either temperature condition (Table 10). No significant change in salivary cortisol was observed between the two thermal conditions, but salivary cortisol decreased significantly during the course of exposure in both conditions ($P < 0.01$), Table 10. The concentration of salivary alpha-amylase correlated positively with cortisol level but with a relatively low correlation coefficient (Spearman's $r = 0.29$). No significant correlation was found between the salivary alpha-amylase level or the cortisol level and the performance of the Tsai-Partington tests.

Table 9 End-tidal partial CO_2 and arterial oxygen saturation measured at the two thermal conditions; the results shown are averages and standard deviations (in brackets)

Exposure time in the room (min)	219–240	265–270
End-tidal partial CO2 (mmHg)		
22°C	38.2 (3.1)	38.3 (3.1)
30°C	40.2 (3.1)	39.8 (2.6)
P	0.02**	0.08*
Arterial oxygen saturation (%)		
22°C	98.0 (0.8)	97.8 (1.2)
30°C	96.6 (0.7)	96.9 (0.7)
P	<0.01**	0.03**

*Differences approaching significance (0.05 < P < 0.10).
**Significant differences (P < 0.05) between conditions observed.

Table 10 Concentration of salivary alpha-amylase and cortisol during exposure in the office at different conditions; the results shown are averages and standard deviations (in brackets)

Time during exposure in the office (min)	20–30	219–240
Alpha-amylase (IU/ml)		
22°C	98.4 (42.5)	104.9 (54.9)
30°C	97.2 (44.0)	99.6 (58.1)
P	0.81	0.73
Cortisol (ng/ml)		
22°C	5.25 (2.41)	3.02 (1.00)
30°C	4.72 (1.48)	3.29 (0.90)
P	0.38	0.18

Figure 4 shows the results of the tear film mucous quality analysis. There was a significant effect of temperature condition on tear film quality ($P < 0.05$, ES = 0.33). Samples assessed as Type I and Type II were observed to be more frequent when the temperature was 22°C. The increased percentage of Type III and Type IV tear film mucus samples at 30°C indicates that tear film mucous quality was reduced at the raised temperature.

No significant difference in blink rate was found between the 5-min periods after 80 min of exposure during which blink rates were counted (17.89 ± 8.44 blinks/min at 22°C vs. 17.53 ± 8.41 blinks/min at 30°C).

Discussion

The air temperatures of 22 and 30°C were selected to provide two sufficiently different thermal comfort environments. Using measured parameters in the office, assuming an activity level of 1.2 met, it was predicted (Fanger, 1970) that subjects should have been thermally neutral at 22°C and warm at 30°C in clothing with an insulation value of 0.9 clo. The

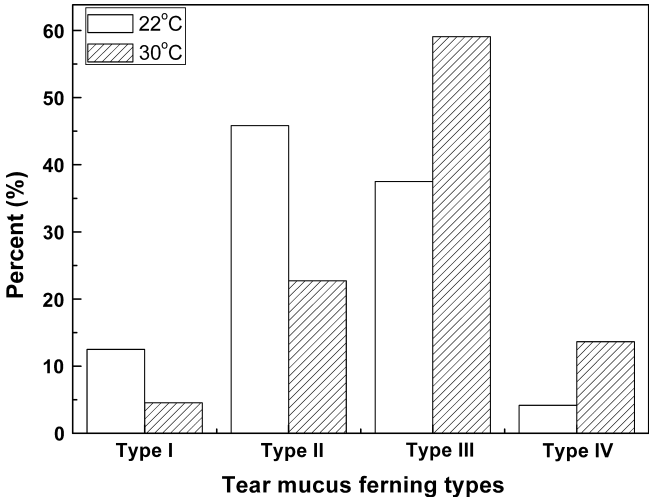

Fig. 4 Tear film quality as a function of the condition in the office; Type I and Type II indicate good efficiency of tear mucus and higher tear film quality while Type III and Type IV indicate problems with mucus and lower tear film quality

corresponding predicted percentage dissatisfied because thermal discomfort was 5% and 69%, respectively (Fanger, 1970). The thermal sensation and thermal comfort responses indicate that the two thermal conditions were as predicted. The correlation between thermal sensation and finger temperature confirms previous findings (Wargocki et al., 2009) and suggests that skin temperature can be used as a simple indicator of thermal discomfort in this thermal range.

The intensity of SBS symptoms, fatigue, and negative mood disturbance increased to a large extent, and the perceived indoor air quality and motivation to exert effort while working decreased, when subjects were exposed at 30°C and felt thermally warm compared with 22°C, at which temperature they felt thermally neutral. These results are consistent with those of previous studies (e.g. Fang et al., 1998; Haneda et al., 2009; Lan and Lian, 2009b; Lan et al., 2009a; Mendell and Mirer, 2009; Tanabe and Nishihara, 2004).

The intensity of SBS symptoms, the negative mood disturbance, and the perceived air quality improved slightly toward the end of the exposure. Similar results were also obtained in previous studies in which subjects were exposed for a period of up to 4.5 h to different air quality and temperature conditions (Fang et al., 2004; Wargocki et al., 1999, 2000). These results could be either because of psychological habituation or because of physiological adaptation. Subjects were aware that they would be leaving the exposure shortly, and this positive emotion might have caused their evaluations to be less critical toward the end of each exposure. This interpretation is supported by the reporting of less negative moods (e.g. less anger, see Table 4). It should also be noticed that subjects did not perform any tasks toward the end of an exposure. Thus, their metabolic rate would have been lower, causing less thermal strain that could also result in less intense symptoms.

The negative effects of moderately elevated temperatures causing thermal discomfort on the performance of tasks typical of office work or neurobehavioral tests examining different skills confirm the results of some of previous studies (e.g. Niemela et al., 2002; Tham, 2004; Wargocki and Wyon, 2007; Witterseh et al., 2004). Some recent laboratory studies did not observe such effects (Haneda et al., 2009; Lan and Lian, 2009b; Lan et al., 2009a; Tanabe and Nishihara, 2004). One possible explanation for this discrepancy may be motivation. In the studies of Lan et al. (2009a) and Lan and Lian (2009b) Haneda et al. (2009), the subjects were told during recruitment that a bonus would be paid to them depending on their performance. This could affect their motivation and the subjects might have exerted more effort to maintain performance independently of the thermal conditions, at the expense of experiencing more symptoms. In the present study, no bonus was offered to the subjects and there is no indication that the subjects exerted more effort in different exposure conditions (Table 6). In fact, Figure 3 shows that the subjects were less motivated to exert effort at 30°C.

According to Heerwagen (1995), the relationship between buildings and worker performance is related to both motivation and ability; an individual must first feel like working and then must be capable of working. When highly motivated by a bonus, people are able to resist the negative effects of thermal discomfort by exerting more effort. This is probably due to the existence of a 'cognitive reserve' (extraneural resources) that allows people to maintain their performance during a short exposure even when indoor conditions are unfavorable (Hocking et al., 2001). Performance can deteriorate when these resources are insufficient to deal with both the task demands and thermal stress. People are then unable to maintain their performance. Exerting extra effort for a short period is probably without long-lasting health consequences; this is an example of human flexibility being able to deal with short-term demands (Johnson and Anderson, 1990). However, prolonged, repetitive, and continuous effort can have negative consequences for health. For example, it has been suggested that repetitive activation of the cardiovascular defense response may lead to hypertension (Johnson and Anderson, 1990). Taking this view, poor indoor environmental conditions, e.g. elevated temperatures and/or thermal discomfort, should be avoided in offices even though increased effort can for a short period counteract the negative effects. This was probably the case in some of the previous studies where no effect of thermal discomfort on performance was observed (e.g. Haneda et al., 2009; Tanabe and

Nishihara, 2004). High motivation to overcome any negative effect of the indoor environment may be difficult to maintain in schools, especially in elementary schools. This is probably the reason why the performance of school work by children is to a much larger extent affected by poor indoor environmental quality compared to the performance of adults in offices (Wargocki and Wyon, 2007).

Many countries now mandate that thermostats should be set higher during warm weather than would be required for thermal neutrality to conserve the energy used for cooling buildings, and many 'green' or low-energy buildings are to some extent thermally passive, allowing indoor temperatures to rise when it is warm outdoors. When indoor temperatures increase above what is necessary for thermal neutrality, subjective thermal discomfort is usually reported. People can habituate to endure or even prefer feeling warm rather than neutral at elevated temperatures. Assuming that the distraction of thermal discomfort is the main mechanism, no negative effects on mental performance would be expected to occur at elevated temperatures when people have been able to adapt to new conditions. However, the present study shows that there are other physiological mechanisms by which the thermal discomfort caused by moderately elevated temperatures can affect task performance and SBS symptoms, so habituation to a feeling of warmth may not protect against the negative effects; these plausible mechanisms are discussed in subsequent paragraphs. It should be mentioned that even if habituation was the only mechanism, thermal conditions providing optimum comfort may not give rise to maximum performance. This has already been demonstrated by Pepler and Warner (1968): normally clothed (0.5 clo) young Americans performed mental work at a number of different temperatures (from 21 to 33°C). They were most thermally comfortable at 27°C, the temperature at which they exerted least effort and performed least work, while they performed most work at 21°C, although most of them felt uncomfortably cold under this condition. The percentage error rate was constant throughout.

Higher $ETCO_2$ (indicating higher arterial CO_2 level) and increased heart rate and respiratory ventilation rate were observed at 30°C when subjects felt warm. This suggests that subjects' metabolic rate increased at this condition. This result is as expected—when the body is hot, the rate of heat production will increase because of the increased rate of chemical reaction in the cells of the body (ISO 8996, 1989). The metabolization of fats and carbohydrates leads at the same time to the formation of a large amount of CO_2. When the lungs cannot remove all of the CO_2 produced by the metabolic processes, respiratory acidosis may occur (Seifter, 2007). Studies have shown that respiratory acidosis or an increase in CO_2 concentration in the blood may induce physiological effects that give rise to SBS symptoms such as easy fatigue, sleepiness, and headache (Paulev, 2000; Resta et al., 2000; Seifter, 2007). In the present study, the intensity of SBS symptoms increased when the subjects felt warm at 30°C and at the same time $ETCO_2$ increased. As a natural defense mechanism, the respiration rate (the amount of air breathed per min) increased (see Table 8) to remove excessive CO_2 but the increased respiration was evidently insufficient to remove all excessive CO_2; the discrepancy between required and actual respiratory ventilation rate led to an increased accumulation of CO_2 in the blood.

The CO_2 concentration in room air in the 30°C condition was higher than it was at 22°C (see Table 1). This increase could be the result of increased metabolism at 30°C and increased production of metabolic CO_2. As a result, the concentration of bioeffluents in the room increased in this condition, leading to a reduction in the air quality. Perceived air quality at 30°C may also have occurred because elevated temperatures reduce the capacity of inhaled air to cool mucous membranes in the nose (Fang et al., 1998; Toftum et al., 1998).

Blood oxygen saturation (SPO_2) decreased significantly when the subjects felt warm. This change of SPO_2 could affect the intensity of SBS symptoms and task performance. For example, it has been found that a supply of oxygen reduced the fatigue experienced by drivers (Sung et al., 2005). In the present study, fatigue symptoms increased in the warm condition (see Table 3, 4, and 5) when blood oxygen saturation decreased. Low oxygen saturation has also been shown to be associated with decreased cognitive functions (Andersson et al., 2002; Winder and Borrill, 1998). Brain activity consumes 20–30% of all energy produced in the body. In the process of providing cells with energy, oxygen is consumed (Benton et al., 1996). It has also been shown using brain imaging techniques that the brain increases the uptake of oxygen (and glucose) into active brain areas during cognitively demanding tasks (Andersson et al., 2002). In the present study, reduced task performance (see Table 7) was observed when blood oxygen saturation decreased, which is consistent with the hypothesis that lower oxygen saturation can reduce task performance. Whether the reduced performance occurred because of decreased cognitive functioning of the brain or because of fatigue cannot be determined from the present results. The studies of Nishihara et al. (2008) showed generally no difference between oxygenated and deoxygenated hemoglobin in the brain when subjects were exposed to a temperature range of 25.5–31.5°C. It should be noted that oxygen saturation increased after 15 min of resting toward the end of the exposure at 30°C (Table 9). This could occur because more oxygen was available when subjects were resting and their metabolic rate decreased (see Table 8).

Tear film quality decreased and the intensity of the dry eye symptom increased ($0.4 < ES < 0.5$) when subjects were thermally warm at 30°C (see Table 5). Mendell et al. (2002) reported that a 19% decrease in eye irritation was associated with each 1°C decrease in air temperature in the range from 26 to 22°C. Dry eyes can be defined as a disorder of the tear film because of excessive tear evaporation, which may cause damage to the ocular surface. An increased rate of water evaporation from the tear mucus at the higher air temperature, perhaps because of an increase in eye surface temperature, may thus have contributed to the development of symptoms related to eye irritation; there were no differences in relative humidity between the two conditions (Table 1). A natural body defense mechanism would be to increase the blink rate to refresh the tear film more often, but this was not observed here, possibly because blink rate was evaluated only from a short 'snap shot' of the entire exposure. The fact that the tests were presented to subjects on a PC will inevitably have reduced their blink rate when they were concentrating on the tasks.

No effects of the thermal environment on the level of salivary alpha-amylase and cortisol or on the performance of the Tsai-Partington test were found in the present study. These results may suggest no effects of the thermal environment on arousal and are inconsistent with the results obtained by Tham and Willem (2010) and by Wargocki et al. (2009). The reasons for the inconsistency between these different studies are unclear at present. One reason can be the low level of stress experienced by the subjects in the present study, as the concentrations of salivary amylase obtained in all but two samples were below 200 units/ml (Morrison et al., 2003). A reduction in salivary cortisol during the course of the exposures was observed, independently of conditions, suggesting further relief from stress. This was probably because the subjects worked on self-paced tasks and were acquainted with the experimental procedures before starting the experiment.

A limitation of the present experiment is that only young and healthy college students were recruited and that this is not a representative subpopulation of office workers. In future experiments, a different subpopulation of subjects should be selected in terms of their age, health, and occupation. Validation of the present results is also required in real workplaces and warmer climates, at lower room temperatures and in different seasons of the year.

Conclusions

The perceived air quality was poorer, the intensity of SBS symptoms, fatigue, mental workload, and negative mood disturbance all increased, the subjects were less willing to exert effort while working, and the performance of simulated office work and neurobehavioral tests decreased when they felt warm at 30°C compared with the 22°C condition in which they felt thermally neutral. Heart rate, respiratory ventilation rate, and $ETCO_2$ concentration increased, and SPO_2 concentration decreased, while tear film quality was reduced and eye discomfort was intensified when the subjects felt warm at 30°C compared with the 22°C condition when they felt thermally neutral. No effects of thermal conditions on the concentration of salivary alpha-amylase and cortisol, or on the performance of a Tsai-Partington test, were found. The present results imply that the negative effects on health and performance that are observed when people are thermally warm at raised temperatures are very likely to be caused by physiological mechanisms.

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