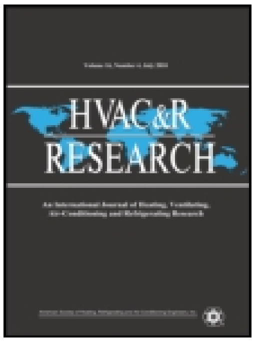

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Occupant Responses and Office Work Performance in Environments with Moderately Drifting Operative Temperatures (RP-1269)

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This paper is based on findings resulting from ASHRAE Research Project RP-1269.

Fifty-two experimental subjects (50% female) were seated in a climate chamber and exposed to operative temperature ramps with different slopes, directions, and durations during two related experiments. The first experiment covered a temperature range of 22°C–26.8°C (71.6°F–80.2°F) and subjects wore light clothing (0.5 clo). The operative temperature was increased in rates of 0.6 K/h (1.1°F/h) (for 8 h), 1.2 K/h (2.2°F/h) (for 4 h), 2.4 K/h (4.3°F/h) (for 2 h), and 4.8 K/h (8.6°F/h) (for 1 h), respectively. In one session, subjects were exposed to a constant temperature of 24.4°C (75.9°F) (for 4 h). The second experiment covered a temperature range of 17.8°C–25°C (64°F–77°F), and subjects wore heavier clothing (0.7 clo). Temperature ramps of 0.6 K/h (1.1°F/h) (for 8 h), 1.2 K/h (2.2°F/h) (for 6 h), 0.6 K/h (–1.1°F/h) (for 8 h), and –1.2 K/h (–2.2°F/h) (for 6 h) and exposure to a constant temperature of 21.4°C (70.5°F) (for 6 h) were examined. Subjects assessed their thermal sensation, acceptability of the thermal environment, perceived air quality, and intensity of sick building syndrome (SBS) symptoms. Subjects' performance was measured by simulated office work, including tasks such as addition, proofreading, reading and comprehension, and text typing. Results of the experiments showed that even moderately changing operative temperature ramps were sensed by sedentary subjects when exposure times exceeded 4 h. No significant effects on SBS symptoms related to local irritation of mucous membranes were found, while intensity of headache, concentration ability, and general well-being were significantly affected in most of the ramps. Linear dependence of perceived air quality on operative temperature was noted. No significantly consistent effects of individual temperature ramps on office work performance were found.

INTRODUCTION

About 40% of the primary energy production in developed countries is consumed by heating, ventilating, and air conditioning residential and nonindustrial buildings (EU 2006). Consequently, a very important goal is to develop new climate systems or indoor climate control strategies that may reduce this high energy consumption. One potential solution is the utilization of a building's thermal mass in combination with night cooling/heating, or cooling by pipes embedded in floors, walls, or ceilings (Meierhans 1993). Such systems are often associated with indoor temperatures

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that drift somewhat during the day (Olesen and Dossi 2004). Allowing indoor temperatures to drift rather than maintaining constant levels, which is common in most air-conditioned buildings, may be a feasible means of reducing building energy demand. However, the current basis for assessing the effects of drifting temperatures on building occupants, as included in standards *ANSI/ASHRAE Standard 55, Thermal Environmental Conditions for Human Occupancy* (ASHRAE 2004) and *ISO 7730: 2005, International Standard: Ergonomics of the Thermal Environment-Analytic Determination of Thermal Comfort by Using Calculations of the PMV and PPPD Indices and Local Thermal Comfort Criteria* (ISO 2005), is founded on the application of engineering judgment, and to some extent, earlier thermal comfort research, but does not account for responses related to health or work performance.

ASHRAE Standard 55 (ASHRAE 2004) describes temperature drifts and ramps as steady, monotonic and not cyclic operative temperature changes. Drifts refer to passive, uncontrolled temperature changes, while ramps refer to actively controlled temperature changes. The recommended maximum rate of temperature change allowed during a specified period of time is defined in Table 1.

The allowed operative temperature changes defined in Table 1 should be applied so that limits for all defined time periods are satisfied. For example, the operative temperature may not change more than 2.2 K/h (4°F/h) during a 1 h period, but at the same time, it may not change more than 1.1 K/h (2°F/h) during any 1/4 h period within that 1 h period.

ISO 7730 (ISO 2005) also deals with non-steady-state thermal environments. If the maximum peak-to-peak variation of the temperature is less than 1 K/h (1.8°F/h) there will be, according to the standard, no influence on thermal comfort and the recommendations for steady state may be used. For temperature drifts and ramps, the standard recommends using the steady-state evaluation method if the temperature change is less than 2 K/h (3.6°F/h).

The results of previous studies suggest that slow temperature ramps up to ±0.5 K/h (±0.9°F/h) (in the range 23°C–27°C [73.4°F–80.6°F]) have no influence on the width of the comfort zone, as established under steady-state conditions (Hensen 1990). Based on their studies, Berglund and Gonzalez (1978a) concluded that the temperature limits for 80% thermal acceptability, particularly the upper limit as defined in ASHRAE Standard 55 (ASHRAE 2004), might be conservative in the case of drifting temperatures. In a subsequent study, Berglund and Gonzalez (1978b) showed that subjects dressed in summer clothing (0.5 clo) and performing office work preferred a temperature ramp at low humidity (0.6 K/h [1.1°F/h]), from 23°C (73.4°F) to 27.8°C (82°F), dew point 10°C (50°F) to a constant temperature environment (25°C [77°F], dew point 10°C [50°F]). Knudsen et al. (1989) addressed the possibility of using the predicted mean vote/predicted percentage of dissatisfied (PMV/PPD) model developed and intended for use mostly under steady-state conditions to predict thermal sensation during temperature ramps up to ±5 K/h (±9°F/h) (Fanger 1970).

Increased indoor temperatures have been shown to increase the intensity of symptoms of fatigue, headache, and difficulty in thinking clearly (Fang et al. 1998). Also, a field study

Table 1. Limits of Operative Temperature Drifts and Ramps (ASHRAE 2004)

Time Period	0.25 h	0.5 h	1 h	2 h	4 h
Maximum Operative Temperature Change Allowed	1.1°C (2.0°F)	1.7°C (3.0°F)	2.2°C (4.0°F)	2.8°C (5.0°F)	3.3°C (6.0°F)

by Mendell et al. (1999) showed significant effects of temperature on the prevalence of sick building syndrome (SBS) symptoms, even within the temperature comfort zone. In a field study conducted in a call center, lowering the temperature by 2K (3.6°F) from 24.5°C (76.1°F) resulted in an increase in the operators' performance by approximately 5%, even though they were more thermally comfortable at the higher temperature (Tham et al. 2003). Likewise, a temperature-intervention study carried out in an office building found a significant negative effect on the performance of workers completing an addition task after the room temperature setpoint was raised from 20°C–22°C (68°F–71.6°F) to 24°C–26°C (75.2°F–78.8°F) (Toftum et al. 2005). In view of the fact that employees' salaries exceed building energy and maintenance costs by a factor of 80 to 100, it becomes clear that reduced energy consumption should not be achieved at the expense of occupants' comfort, productivity, or health (Clements-Croome 2006). Mental work performance was examined in relation to cyclic temperature changes (swings) by Wyon et al. (1971, 1973), who concluded that large temperature swings could have a positive effect on performance, but they could also increase discomfort, and should thus be self-controlled. Another study by Wyon et al. (1975) clearly showed that it was the resulting thermal state of the occupant, not the environmental temperature itself, that affected performance.

Although previous studies conducted in climate chambers examined a large range of temperature ramps from ±0.5 K/h to ±5 K/h (±0.9°F/h to ±9°F/h), their focus was mostly on establishing temperature limits for acceptable thermal comfort associated with temperature ramps. Thus, knowledge is needed to describe how symptoms, perception of air quality, and the performance of office work are affected by moderate and long-term temperature changes. This paper reports on two human subject experiments conducted as a part of ASHRAE RP-1269 to validate the scientific basis of the recommendations on drifting temperatures as stated in current standards and to extend their scope to cover not only thermal comfort, but also health-related effects and performance.

METHODS

Climate Chamber

The climate chamber (5 m [16.4 ft] wide, 6 m [19.7 ft] long, and 2.5 m [8.2 ft] high) was developed to accurately control the thermal environment (Kjerulf-Jensen et al. 1975). The temperature in the climate chamber could be regulated between 5°C (41°F) and 50°C (122°F), with an accuracy of ±0.2°C (±0.4°F), and between 20% and 100% relative air humidity (RH) with an accuracy of 0.25 g/kg (0.55×10^{-3} lb/lb). The control system was modified to provide steady changes of the temperature setpoint necessary to establish the planned temperature ramps. The climate chamber walls consisted of vinyl sheets, which were separated from the solid outer chamber walls by an air space of approximately 16 mm (0.63 in.). A fraction of the air supplied to the chamber flowed behind the vinyl sheets, ensuring that air and mean radiant temperatures were equal during both steady and thermal transients. Air and operative temperatures, air velocity, and air humidity were measured continuously at the center of the chamber at 0.6 m (23.6 in.) above the floor.

Conditions Tested

The first experiment (Experiment 1) addressed the summer conditions zone and covered a temperature range of 22°C–26.8°C (71.6°F–80.2°F), while the second experiment (Experiment 2) addressed the winter conditions and covered a temperature range of 17.8°C–25°C (64°F–77°F). The water vapor pressure of 1.53 kPa (0.22 PSI) (corresponding to 50% RH at 24°C [75.2°F]) was maintained constant during all exposures. Thus, the relative humidity varied with the changing temperatures during ramp exposures. Conditions examined in both experiments are summarized in Tables 2a and 2b.

Table 2a. Experimental Conditions and Results of the Physical Measurements in SI Units

Experimental Design				Physical Measurements			
Temperature Ramp, K/h	Temperature Range, °C	Clothing Insulation, clo	Exposure Duration, h	Initial Operative Temperature,[1] °C	Final Operative Temperature,[1] °C	Humidity Ratio,[2] g/kg	Measured Clothing Insulation,[1] clo
Pre-session (Experiment 1)							
0.0[2]	24.4	0.5–0.6	2	24.4 ± 0.07	—	9.2 ± 0.2	0.54 ± 0.18
Experiment 1							
0.0[2]	24.4		4	24.4 ± 0.05	—	9.5 ± 0.7	0.55 ± 0.17
2.4			2	22.2 ± 0.17	26.4 ± 0.08	9.2 ± 0.2	0.53 ± 0.13
1.2	22.0–26.8	0.5–0.6	4	22.2 ± 0.09	26.4 ± 0.08	9.2 ± 0.2	0.56 ± 0.13
0.6			8	22.2 ± 0.03	26.8 ± 0.02	9.2 ± 0.2	0.54 ± 0.17
4.8			1	22.1 ± 0.12	26.4 ± 0.05	9.2 ± 0.3	0.52 ± 0.13
Pre-session (Experiment 2)							
0.0[2]	21.4	0.9–1	2	21.4±0.07	—	9.1 ± 0.2	0.78 ± 0.19
Experiment 2							
0.0[2]	21.4	0.9–1	6	21.5 ± 0.08	—	9.5 ± 0.2	0.74 ± 0.18
0.6	19.0–23.8		8	19.2 ± 0.15	23.7 ± 0.02	9.0 ± 1.5	0.75 ± 0.20
1.2	17.8–25.0		6	18.3 ± 0.26	24.8 ± 0.06	9.5 ± 0.4	0.74 ± 0.17
–0.6	23.8–19.0		8	23.7 ± 0.32	19.9 ± 0.07	9.5 ± 0.2	0.73 ± 0.18
–1.2	25.0–17.8		6	25.2 ± 0.21	19.2 ± 0.19	9.4 ± 0.3	± 0.17

[1] Mean ± SD

[2] Mean ± SD for the duration of the experimental session

Table 2b. Experimental Conditions and Results of the Physical Measurements in I-P Units

Experimental Design				Physical Measurements			
Temperature Ramp, K/h	**Temperature Range, °F**	**Clothing Insulation, clo**	**Exposure Duration, h**	**Initial Operative Temperature,(1) °F**	**Final Operative Temperature,(1) °F**	**Humidity Ratio,(2) lb/lb**	**Measured Clothing Insulation,(1) clo**
			Pre-session (Experiment 1)				
0.0(2)	75.9	0.5–0.6	2	75.9 ± 0.13	—	$0.02 \pm 0.4 \times 10^{-3}$	0.54 ± 0.18
			Experiment 1				
0.0(2)	75.9		4	75.9 ± 0.09	—	$0.02 \pm 1.5 \times 10^{-3}$	0.55 ± 0.17
2.4			2	71.6 ± 0.30	79.5 ± 0.14	$0.02 \pm 0.4 \times 10^{-3}$	0.53 ± 0.13
1.2		0.5–0.6	4	71.6 ± 0.16	79.5 ± 0.14	$0.02 \pm 0.4 \times 10^{-3}$	0.56 ± 0.13
0.6	71.6– 80.2		8	71.6 ± 0.05	80.2 ± 0.04	$0.02 \pm 0.4 \times 10^{-3}$	0.54 ± 0.17
4.8			1	71.6 ± 0.22	79.5 ± 0.09	$0.02 \pm 0.6 \times 10^{-3}$	0.52 ± 0.13
			Pre-session (Experiment 2)				
0.0(2)	70.5	0.9–1	2	70.5±0.13	—	$0.02 \pm 0.4 \times 10^{-3}$	0.78 ± 0.19
			Experiment 2				
0.0(2)	70.5	0.9–1	6	70.7 ± 0.14	—	$0.02 \pm 0.4 \times 10^{-3}$	0.74 ± 0.18
0.6	60.2–74.8		8	66.7 ± 0.27	74.7 ± 0.04	$0.02 \pm 3.3 \times 10^{-3}$	0.75 ± 0.20
1.2	64.0–77.0		6	64.9 ± 0.47	76.6 ± 0.11	$0.02 \pm 0.9 \times 10^{-3}$	0.74 ± 0.17
–0.6	74.8–66.2		8	74.7 ± 0.58	67.8 ± 0.13	$0.02 \pm 0.4 \times 10^{-3}$	0.73 ± 0.18
–1.2	77.0–64.0		6	77.4 ± 0.38	66.6 ± 0.34	$0.02 \pm 0.7 \times 10^{-3}$	± 0.17

(1) Mean ± SD

(2) Mean ± SD for the duration of the experimental session

Panel of Subjects

A total of 23 and 29 healthy, recruited college subjects were used in Experiments 1 and 2, respectively (Tables 3a and 3b). The subjects were seated in the climate chamber and were exposed to the experimental conditions. In both experiments, subjects were divided into groups of six. Each group participated in the experiment on the same weekday over five successive weeks. Each group experienced one test condition per week in a randomized order, using Latin Square Design (Montgomery 2005), to minimize any bias caused by the order of exposure.

Experimental Procedure

The intention was to simulate an activity pattern that would be typical for office employees. At the same time, data analysis required a regular and systematic sequence of activities on each experimental day. Subjects entered the climate chamber at 9 a.m. and were seated at separate workstations consisting of a desk, a chair, and a PC connected to a local intranet. Initially, subjects spent 30 min in a constant-temperature environment to dissipate any residual metabolic heat resulting from their previous activity, after which the experimental session started. The experimental session was divided into 1 h intervals during which the subjects completed a questionnaire in the first 5 min, and were engaged in a block of simulated office tasks over the

Table 3a. Panel of Subjects—Main Characteristics; Mean ± SD

Gender	Age, yrs	Height, cm	Weight, kg	Number of Subjects
		Experiment 1		
Males	23.6 ± 2.9	184.7 ± 7.1	79.9 ± 10.2	12
Females	24.5 ± 7.7	167.5 ± 4.3	60.5 ± 7.5	11
Total	24.0 ± 5.6	176.5 ± 10.5	71.1 ± 13.3	23
		Experiment 2		
Males	24.1 ± 3.3	182.1 ± 7.7	77.5 ± 9.9	14
Females	22.9 ± 3.1	171.6 ± 5.3	67.5 ± 9.1	15
Total	23.4 ± 3.2	176.7 ± 8.4	72.3 ± 10.6	29

Table 3b. Panel of Subjects—Main Characteristics; Mean ± SD

Gender	Age, yrs	Height, in.	Weight, lb	Number of Subjects
		Experiment 1		
Males	23.6 ± 2.9	72.7 ± 2.8	176.1 ± 22.5	12
Females	24.5 ± 7.7	65.9 ± 1.7	133.4 ± 16.5	11
Total	24.0 ± 5.6	69.5 ± 4.1	156.7 ± 29.3	23
		Experiment 2		
Males	24.1 ± 3.3	71.7 ± 3.0	170.9 ± 21.8	14
Females	22.9 ± 3.1	67.6 ± 2.1	148.8 ± 20.1	15
Total	23.4 ± 3.2	69.6 ± 3.3	159.4 ± 23.4	29

next 18 min. They then completed a second questionnaire in the next 5 min and were again engaged in a block of simulated office tasks for another 18 min. During the remaining 14 min, subjects were allowed to relax, read books or newspapers, and converse. The procedure was repeated throughout the experimental period with different tasks presented to the subjects in a balanced order. Activities during a typical hour in any experiment lasting more than 1 h (2, 4, 6, and 8 h) are shown in Figure 1. The 1 h exposure included in the experimental design involved a high rate of temperature change (4.8 K/h). This kind of temperature transience can be caused by a sudden opening of a window or other, rather short-term, events. It is reasonable to assume that building occupants would not remain in such a condition while doing their work, which is why no performance tests were conducted during exposure to the 4.8 K/h (8.6°F/h) temperature ramp.

In addition to the sedentary work, subjects were allowed to move around the climate chamber during breaks or leave the chamber for a short period in case they needed to visit a restroom. Short intervals of a higher level of physical activity, but still at a moderate intensity, helped to simulate a typical office activity pattern. Due to the long exposure periods, subjects had access to refreshments (water and biscuits).

Clothing Insulation

Subjects wore their own clothing during all experimental sessions. Garments were selected during pre-sessions when the subjects were exposed to a constant operative temperature of 24.4°C and 21.4°C (75.9°F and 70.5°F) (50% RH, 2 h) for Experiments 1 and 2, respectively. Subjects adjusted their clothing to feel thermally neutral in both pre-sessions. At the end of each pre-session, the subjects indicated which garments they were wearing to facilitate the calculation of the respective clo values. The calculation of the clothing insulation included 0.05 clo for a light metal chair on which the subjects were seated. During the sessions with non-steady-state temperatures, subjects wore garments that were similar to those chosen during the pre-session. According to Fanger (1970), mean clothing insulation was expected to be 0.5 clo for Experiment 1 (temperature range corresponding to summer conditions) and 0.9 clo for Experiment 2 (temperature range corresponding to winter conditions).

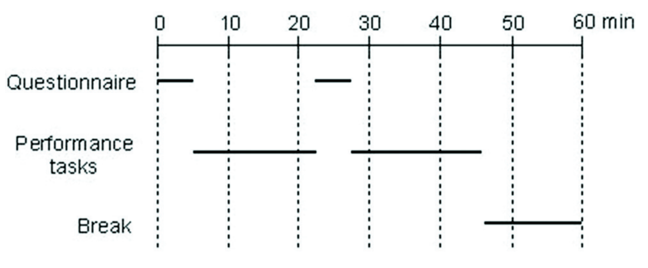


Figure 1. Activities during each hour in experiments lasting more than 1 h.

Subjective Measurements

A remote performance measurement approach was used to distribute questionnaires and performance tasks via an intranet during the experiments (Toftum et al. 2005). The questionnaire included a seven-point thermal sensation interval scale, scales to assess the acceptability of temperature and air quality, and a six-point interval scale to assess odor intensity (Figure 2). Visual analogue scale was used to assess perceptions and the intensity of selected specific and general SBS symptoms (Figure 3) (Kildesø et al. 1999). A scale to assess self-estimated performance was also included.

Performance Testing

Parallel versions were prepared for each task, so subjects performed a given version only once. All subjects performed tasks in their mother tongue (Danish). All tasks were performed on a PC, and the results were saved in a database.

Text Typing: Subjects were asked to type successive sections of text (approximately ten lines at a time) that were presented to them on the screen. The texts were taken from popular science magazines. Evaluated performance measures were: typing speed—number of characters typed per minute—and precision. The precision was determined by Levenshtein's Distance (LD). It is a measure of the similarity between two strings (shortest edit distance) (Levenshtein 1966). The edit distance is the smallest number of deletions, insertions, or substitutions required to transform the typed text into the reference text, which appeared on the screen.

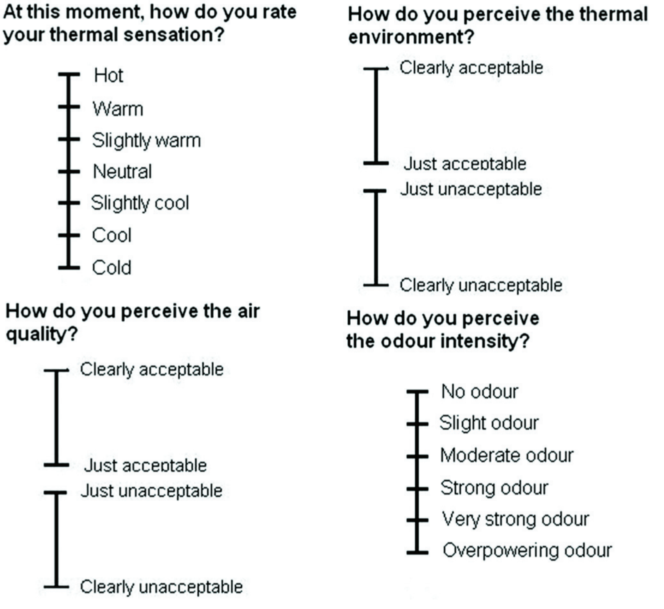


Figure 2. Scales used to assess thermal comfort and perceived air quality.

Addition: Subjects were asked to add columns of four three-digit numbers and to enter the result in a field below each column. The numbers were generated at random and contained no zeros. Eight columns of numbers appeared on the screen simultaneously. Evaluated performance measures included: addition speed—number of correct additions per minute—and addition precision. The precision was determined as the number of correct additions divided by the total number of additions done at the task block.

Reading and Comprehension: The subjects read several pages of text and were asked to assess the correctness of statements that were presented to them in the context of the text. Some statements were true and some were false. It was possible to read the text only once and the duration of reading was recorded. Evaluated performance measures were: reading speed—number of words read per minute—and precision. The precision was evaluated as a number of correct assessments divided by the total number of statements presented.

Proofreading: Subjects were asked to read and highlight words that were spelled incorrectly in sections of texts that appeared successively. The texts were taken from popular science magazines and contained deliberately inserted errors. Evaluated performance measures were: reading speed—number of words read per minute—and precision. The precision was calculated as follows: (number of correctly marked words – number of false detections)/total number of wrong words inserted.

Data Treatment

To reduce the effect of a higher and generally heterogeneous initial metabolic rate, subjects were seated in the climate chamber for 30 min before starting the session. However, it is known

Figure 3. Visual analogue scales used to assess intensity of SBS symptoms.

from earlier thermal comfort studies in climate chambers that subjects' average thermal sensation decreases steadily during the first 2 h, even during exposure to constant temperatures (Knudsen et al. 1989). To minimize the effect of this trend, an adjustment of each subject's thermal sensation votes was made, based on data obtained during exposure to a constant, operative temperature. The decrease of the metabolic rate was assumed to be approximately the same with all experimental sessions. The mean value of the last four votes of exposure to a constant temperature was considered as the steady-state thermal sensation for that condition. The difference between actual mean vote and the steady-state value was described by a logarithmic function. That function was then used to adjust the thermal sensation vote of each subject who participated in a particular experiment. In the following, only adjusted thermal sensation data will be presented.

The percentage of subjects dissatisfied with their thermal condition was determined by calculating the percentage of votes that were placed in the *negative* part of the thermal acceptability scale (from *just unacceptable* to *clearly unacceptable*, see Figure 2) for each vote.

Statistical Analysis

A commercially available statistical software package S Plus 6.0 Professional was used to analyze the data. Data with normally distributed residuals were tested with the Linear Mixed Effects model (Insightful 2001). Inspection of quantile-quantile plots (QQ-plots) together with the Kolmogorov-Smirnov goodness of fit test (Insightful 2001) were used to test whether residuals were normally distributed. The analysis also included data from subjects whose data for some treatments were missing (unbalanced data). In the case of not-normally distributed residuals, a nonparametric Friedman Rank Sum test (Insightful 2001) was applied. This analysis included only data from subjects for whom data in all experiments were available. The P-level for rejection of the null hypothesis was set to 0.05.

RESULTS

Physical Measurements

Results of the physical measurements and mean values of clothing insulation for the experimental conditions are summarized in Table 2. The chamber ventilation system provided approximately 170 L/s (360 cfm) of fresh air (air change rate 9 h-1). That corresponded to about 28 L/s (59 cfm) per person when 6 subjects were seated in the chamber.

Thermal Sensation

Comparison of the overall mean thermal sensation during exposures to a constant temperature, 24.4°C and 21.4°C (75.9°F and 70.5°F), to data from the same temperature level reached by ramps is presented in Figure 4. The analysis showed that mean thermal sensations differed significantly only in comparison to 1.2 K/h (2.2°F/h) ramp at both temperature levels. It can also be seen from this figure that mean thermal sensation for exposure to a constant temperature was higher for higher temperature levels. The clothing adjustment during pre-sessions could be a possible cause of this difference. When exposed to 24.4°C (75.9°F), subjects chose clothing closer to what could be expected to produce a neutral thermal sensation at that temperature: 0.5 clo at 24.4°C (75.9°F), 1.2 met. On the other hand, when exposed to 21.4°C (70.5°F), subjects chose a lower value of clothing for comfort than expected: 0.7 clo at 21.4°C (70.5°F), 1.2 met. The difference in clothing resulted in a lower thermal sensation (at the level of expected thermal neutrality) during non-steady-state temperature exposures as well, despite the fact that data were adjusted for higher initial metabolic rates.

A linear relation between thermal sensation and operative temperature was observed in all studied ramps. The data obtained in Experiment 1 are depicted in Figure 5. Analysis with the Linear Mixed Effects model showed that the intercept and slope of the linear relations did not differ significantly between the 1.2 K/h (2.2°F/h), 2.4 K/h (4.3°F/h), and 4.8 K/h (8.6°F/h) ramps. With these ramps, subjects perceived the operative temperature identically, regardless of the ramp to which they were exposed. A common linear fit for the 1.2 K/h (2.2 ºF/h), 2.4 K/h (4.3 ºF/h), and 4.8 K/h (8.6°F/h) ramps is indicated by a dashed line (Figure 5). The development of thermal sensation was different in the 0.6 K/h (1.1°F/h) ramp (Figure 5—solid line). During this exposure, the thermal sensations for the same level of operative temperature were higher. This difference

(a)

(b)

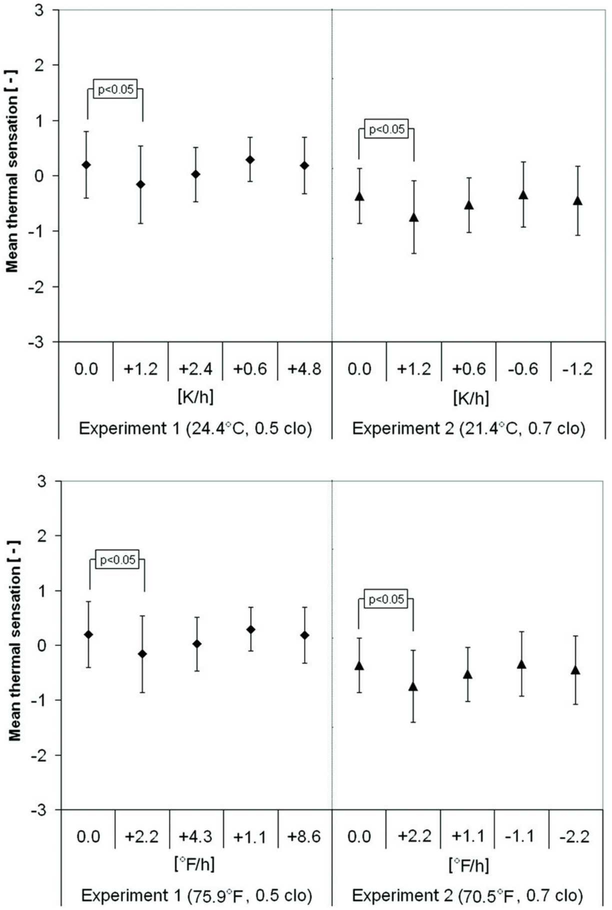
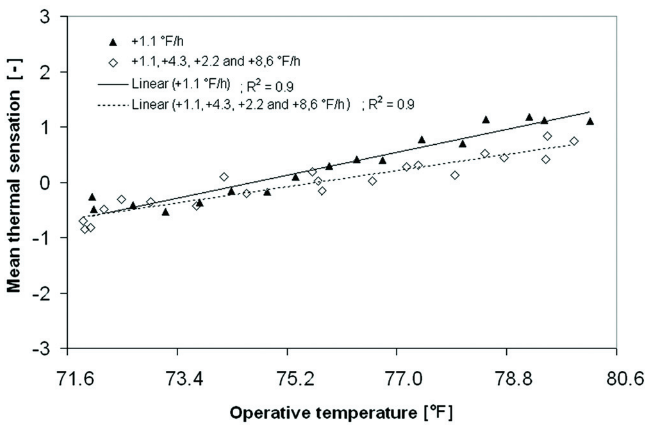


Figure 4. Comparison of mean thermal sensation at the level of thermal neutrality reached by temperature ramps to data from exposure to a constant temperature where (a) presents the data in SI units, (b) presents the data in I-P units, and the vertical bars indicate ± SD in both.

tended to be larger for higher temperatures. Subjects perceived the same temperature level to be warmer than in the case of the faster ramps. When compared with the 1.2K/h (2.2°F/h), 2.4 K/h (4.3°F/h) and 4.8 K/h (8.6°F/h) ramps, the increase in the thermal sensation during the 0.6 K/h (1.1°F/h) ramp was significantly faster ($p < 0.01$).

Figure 6 presents a linear relation between operative temperature and mean thermal sensation in Experiment 2. Analysis of the data showed no significant difference in the slope or intercept of the regression line for the 0.6 K/h (1.1°F/h) and 1.2 K/h (2.2°F/h) ramp. A common linear fit for these ramps is indicated by the dashed line. With decreasing ramps, the thermal sensation changed with

(a)



(b)

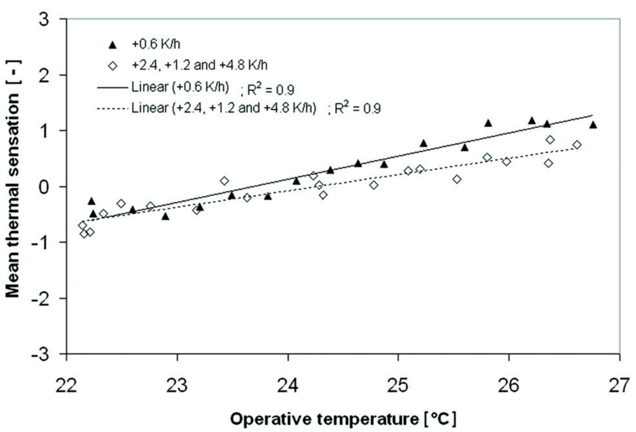


Figure 5. Mean thermal sensation votes as a function of operative temperature for Experiment 1 (22°C–26.8°C [71.6°F–80.2°F], 0.5 clo) where (a) presents the data in SI units and (b) presents the data in I-P units.

temperature significantly faster than with increasing ramps. The solid line in Figure 6 represents a linear fit for the –0.6 K/h (–1.1°F/h) ramp data. Its slope is significantly different ($p < 0.01$) from the line representing increasing ramps (0.6 K/h and 1.2 K/h). The slope of the –1.2 K/h (–2.2°F/h) ramp differed both from the slope of increasing ramps ($p < 0.05$) and the slope of the –0.6 K/h (–1.1°F/h) ramp ($p < 0.01$). Thus, the subjects appeared more sensitive to decreasing than to increasing temperature ramps and were also able to distinguish between the decreasing ramps of different rates of change of temperature.

Thermal Acceptability

The results of the analysis of the time course of thermal acceptability are summarized in Table 4. Figure 7 presents a time course of thermal acceptability during exposure to a constant operative temperature for both Experiments 1 and 2.

(a)

(b)

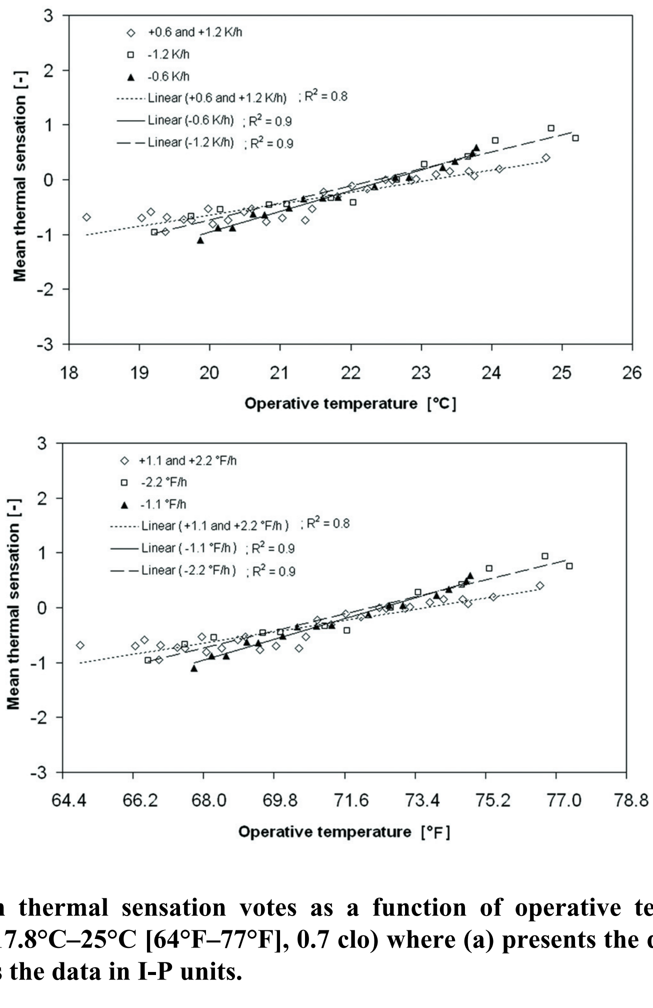


Figure 6. Mean thermal sensation votes as a function of operative temperature for Experiment 2 (17.8°C–25°C [64°F–77°F], 0.7 clo) where (a) presents the data in SI units and (b) presents the data in I-P units.

Table 4. The Data on Acceptability of Thermal Environment and Acceptability of Air Quality

Temperature Ramp	Overall Level of Acceptability of Thermal Environment		Overall Level of Acceptability of Air Quality	
	Mean(1) ± SD	p-value(2)	Mean(1) ± SD	p-value(2)
0.0 K/h	0.36 ± 0.38	< 0.05	0.26 ± 0.40	< 0.0001
2.4 K/h	0.53 ± 0.32	NS	0.42 ± 0.34	NS
1.2 K/h	0.53 ± 0.36	NS	0.36 ± 0.38	NS
0.6 K/h	0.55 ± 0.29	< 0.01	0.45 ± 0.30	< 0.0001
4.8 K/h	0.43 ± 0.41	NS	0.37 ± 0.39	NS
0.0 K/h	0.34 ± 0.33	NS	0.38 ± 0.34	< 0.01
0.6 K/h	0.43 ± 0.36	< 0.01	0.47 ± 0.33	NS
1.2 K/h	0.40 ± 0.36	< 0.0001	0.44 ± 0.32	NS
–0.6 K/h	0.37 ± 0.32	< 0.0001	0.42 ± 0.31	NS
–1.2 K/h	0.37 ± 0.35	< 0.05	0.38 ± 0.37	< 0.01

(1) Mean from all responses regardless of the vote number

(2) P-value given by Friedman Rank Sum test (Insightful 2001) for the difference in means along the exposure

(a)

(b)

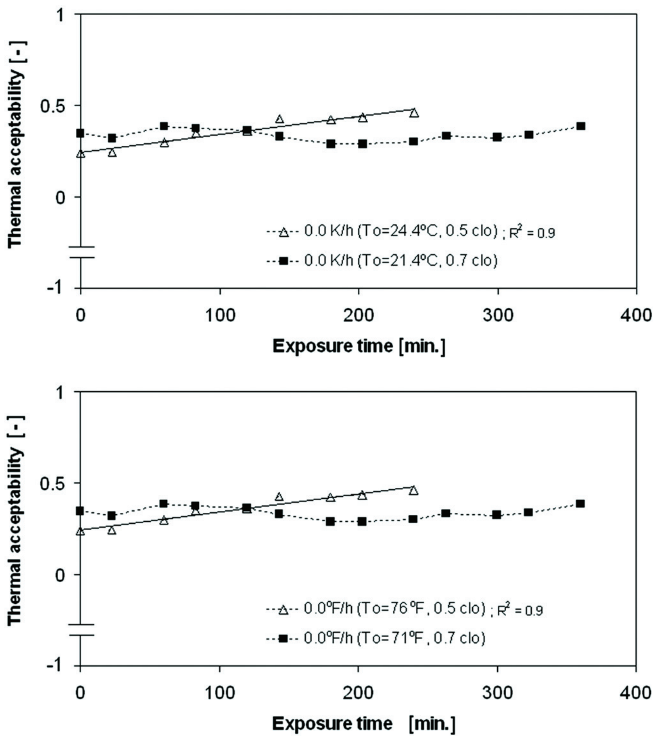


Figure 7. The time course of the thermal acceptability in Experiment 1 (24.4°C [75.9°F], 0.5 clo) and Experiment 2 (21.4°C [70.52°], 0.7 clo) where (a) presents the data in SI units and (b) presents the data in I-P units.

At 24.4°C (75.9°F), subjects perceived the thermal environment as least acceptable at the beginning of the session, then mean acceptability increased linearly with time. In contrast, thermal acceptability remained unchanged during the entire exposure to 21.4°C (70.5°F). The difference in temporal behavior of the thermal acceptability at these two temperature levels seems to be related to the subjects' clothing insulation level. At the beginning of the exposure to 24.4°C (75.9°F), higher initial metabolic rates had a stronger effect on the thermal acceptability of the subjects who were dressed to feel thermally neutral under that condition. Consequently, subjects felt warmer and perceived the environment as less acceptable. At the beginning of the exposure to 21.4°C (70.5°F), higher metabolic rates probably compensated for the fact that subjects had a lower clo value than would be expected for thermal neutrality at 21.4°C (70.5°F). This resulted in higher acceptability of that environment.

Figure 8 presents data from the increasing ramps when significant changes of thermal acceptability were observed ($p < 0.01$). The subjects' least accepted temperatures were below 20°C (68°F). Temperatures above 24°C (75.2°F) were associated with decreases of acceptability only for the 0.6 K/h (1.1°F/h) ramp. In the case of winter conditions (Experiment 2: lower temperature level, 0.7 clo), thermal acceptability continued to increase even after the operative temperature

(a)

(b)

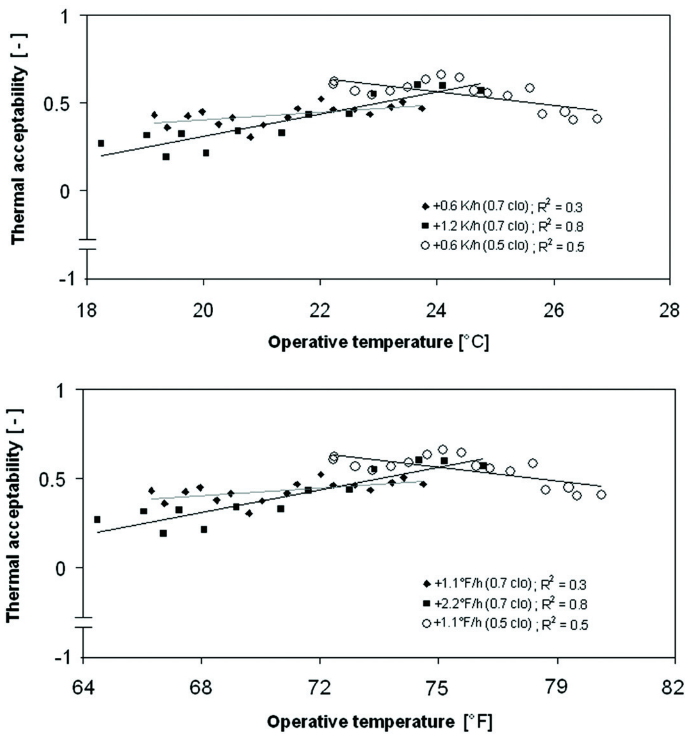


Figure 8. Mean thermal acceptability votes for increasing temperature ramps where (a) presents the data in SI units and (b) presents the data in I-P units.

crossed the neutral point. This suggests that the subjects preferred a higher than neutral temperature, probably due to a slightly lower clo value.

Figure 9 shows mean thermal acceptability data for decreasing temperature ramps. Analysis showed that mean thermal acceptability changed significantly both during the –0.6 K/h (1.1°F/h) ramp ($p < 0.0001$) and –1.2 K/h (–2.2°F/h) ramp ($p < 0.05$), but no clear linear trend was observed. Subjects' acceptability of the environment was higher when temperatures decreased toward the neutral point. However, as the temperature continued to fall, so did the acceptability.

Percentage of Subjects Dissatisfied with the Thermal Conditions

Figures 10 and 11 show the percentage of subjects dissatisfied with the thermal environment (calculated from the thermal acceptability data) as a function of mean thermal sensation in both SI (Figure 10) and I-P (Figure 11) units. The curve indicating PPD (Fanger 1970) was included in the figures for purposes of comparison. As may be seen from Figures 10a and 11a, responses recorded for the ±1.2 K/h (±2.2°F/h) ramps follow the PPD curve quite closely. Actually, predictions of the PPD model could be used to judge the occupants' thermal sensation satisfactorily. Considering the 4.8 K/h (8.6°F/h) ramp, Figures 10b and 11b shows that as the temperature (and consequently the thermal sensation) increased, the percentage of dissatisfied participants

(a)

(b)

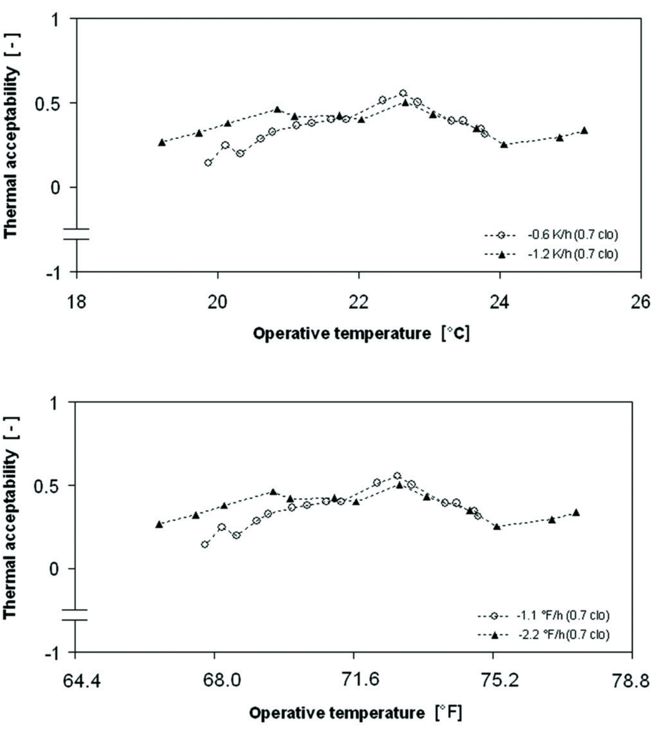


Figure 9. Mean thermal acceptability votes for decreasing temperature ramps where (a) presents the data in SI units and (b) presents the data in I-P units.

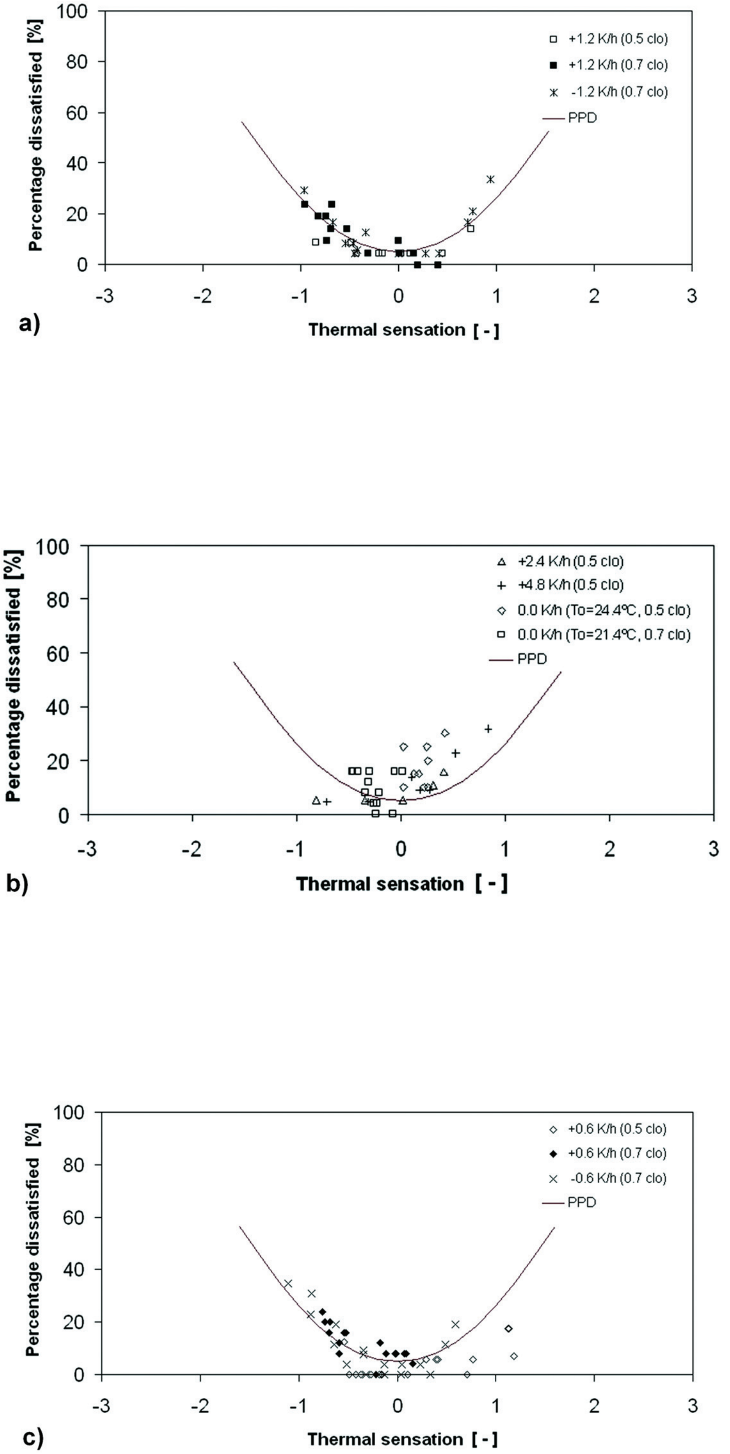


Figure 10. Percentage of subjects dissatisfied with thermal environment in SI units.

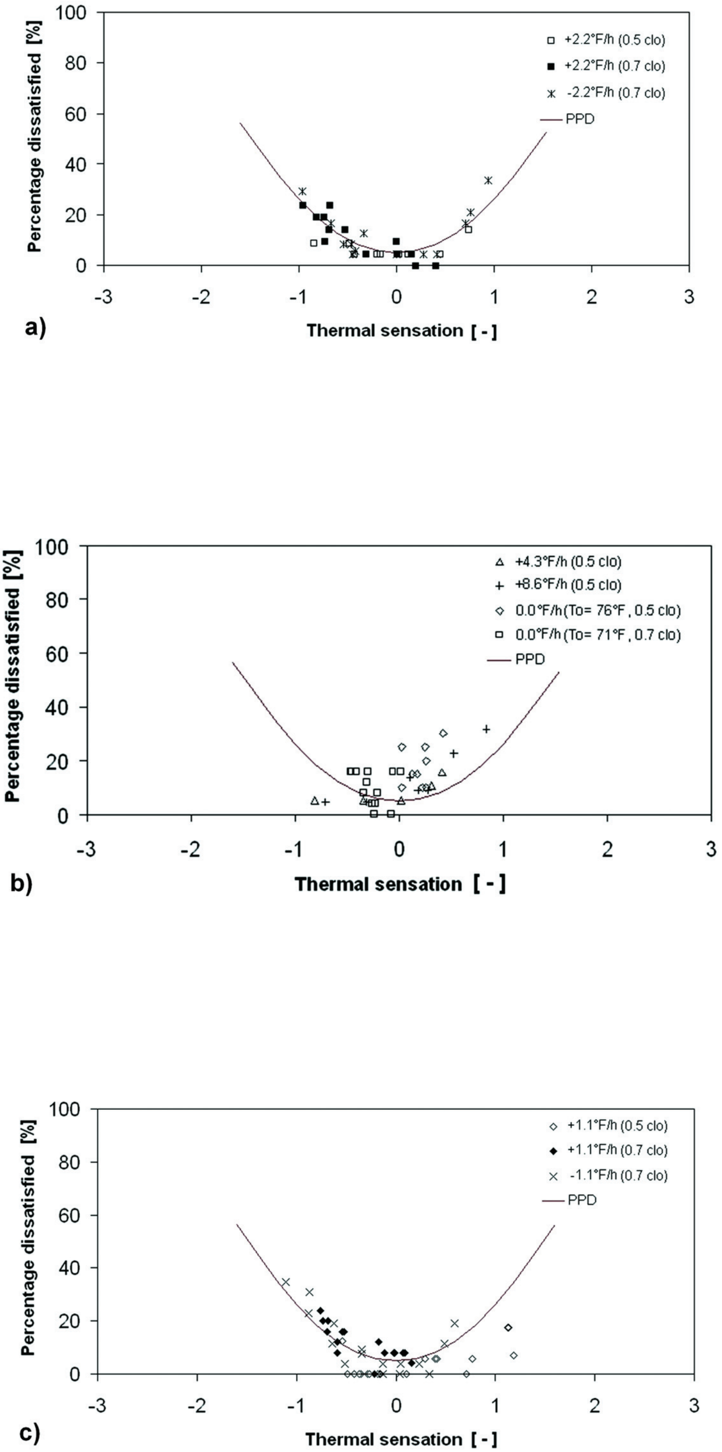


Figure 11. Percentage of subjects dissatisfied with thermal environment in I-P units.

increased faster than predicted by the PPD model. Responses recorded for the ±0.6 K/h (±1.1°F/h) ramps (Figures 10c [SI] and 11c [I-P]) closely follow the PPD model within the thermal sensation range from slightly cold to neutral. In the range from neutral to slightly warm, the percentage of dissatisfied participants was lower than predicted by the PPD model with 0.6 K/h (1.1°F/h) in the summer temperature range.

In summarizing the data presented in Figures 10 (SI) and 11 (I-P), it is noted that subjects' dissatisfaction deviates from the PPD model estimates for very steep or very moderate temperature ramps. In the first case, dissatisfaction can be expected to intensify more rapidly, whereas in the second it seems to lag behind the predicted values. The latter observation should, however, be limited to the thermal sensation range from neutral to slightly warm.

Perceived Air Quality

Results of the analysis into whether the mean acceptability of air quality votes changed significantly with time within each condition are summarized in Table 4.)During the exposure to a constant temperature, subjects needed approximately 120–150 min to adapt their olfactory senses to the pollution level in the climate chamber (Figure 12a and 12b). The moderate increase of the mean acceptability votes indicated that subjects' adaptation seemed to be more pronounced at the

(a)

(b)

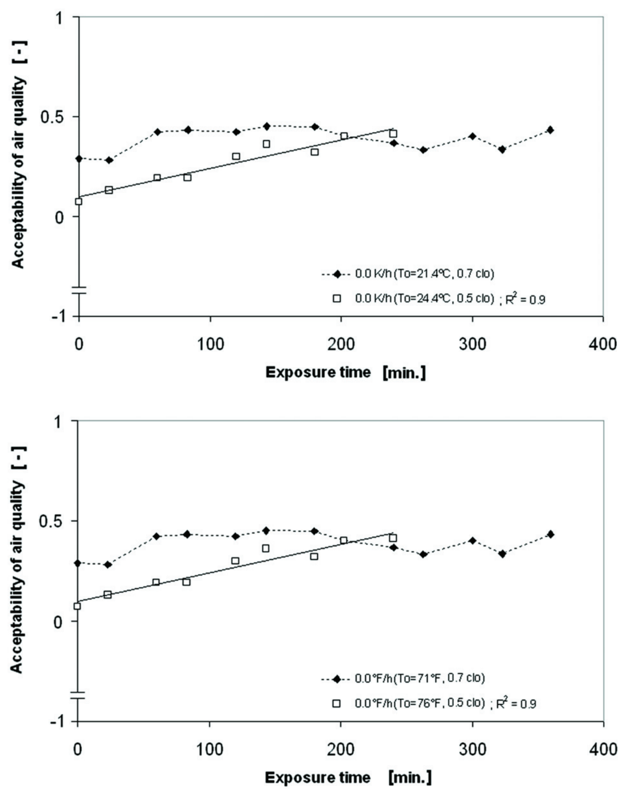
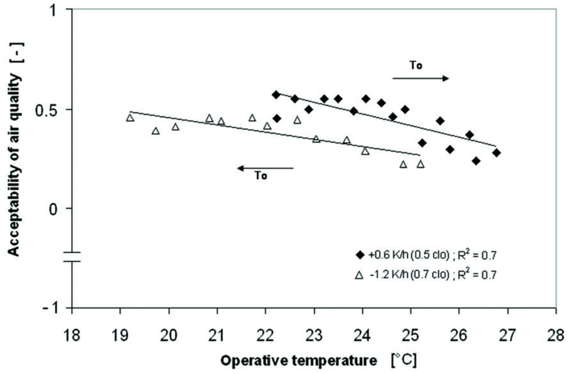


Figure 12. The time course of the acceptability of air quality in Experiment 1 (24.4°C [75.9°F], 0.5 clo) and Experiment 2 (21.4°C [70.52°F], 0.7 clo) where (a) presents the data in SI units and (b) presents the data in I-P units.

(a)



(b)

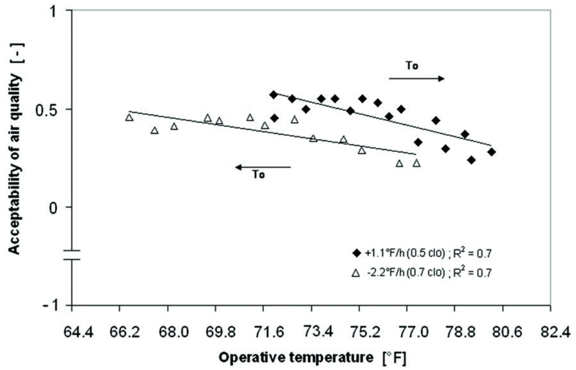


Figure 13. Acceptability of air quality as a function of operative temperature where (a) presents the data in SI units and (b) presents the data in I-P units.

higher temperature levels. Figure 12 shows that acceptability of the air quality improved linearly with exposure time in that case. Adaptation was less pronounced, but nevertheless significant ($p < 0.01$), at lower temperature levels. During exposure to temperature ramps, the acceptability of the air quality depended linearly on the operative temperature. This relationship was statistically significant for the 0.6 K/h (1.1°F/h) ramp ($p < 0.0001$) in Experiment 1 and for the –1.2 K/h (2.2°F/h) ramp ($p < 0.001$) in Experiment 2 (Figure 13). The results seem to be consistent with those obtained by Fang et al. (1998), who showed linear dependency between acceptability of air quality and the enthalpy of the air.

No significant changes in the odor intensity were observed. Subjects perceived the environment as corresponding to a *little bit less than slight odor* category on the scale (Figure 2).

Intensity of SBS Symptoms

Table 5 summarizes the results of the analysis of data regarding the intensity of SBS symptoms for all tested conditions. Increasing temperature ramps increased the intensity of headache, deteriorated concentration ability, and decreased self-evaluated performance. Examples of the

Table 5. Development of the Intensity of SBS Symptoms During Exposure to Operative Temperature Ramps and Constant Temperature

Temperature Ramp, K/h	Nose	Mouth	Skin	Eye	Smart Eyes	Gritty Eyes	Headache	Well Feeling	Fatigue	Concentration Ability	Self-Evaluated Performance
	Dryness										
Experiment 1											
0.0	NS	NS	NS	NS	NS	NS	↓	NS	NS	NS	NS
0.6	NS	NS	NS	NS	NS	NS	↓	↓	↓	↓	↓
1.2	NS	|	NS	|	↓	NS	↓	↓*	NS	↓	↓
2.4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
4.8	NS	NS	NS	NS	NS	NS	↓	↓	NS	↓	↓*
Experiment 2											
0.0	|*	NS	NS	NS	NS	|*	NS	|	|*	NS	↓
0.6	NS	NS	NS	NS	NS	NS	↓	↓	NS	↓	↓
1.2	↓	NS	NS	NS	NS	NS	|*	NS	|	↓	↓
–0.6	NS	↑	NS	NS	NS	NS	|	↓	|	↓	↓
–1.2	NS	↑	↑*	NS	NS	NS	NS	NS	↑*	↑	↑*

Legend: A vertical line (|) indicates that there was a significant change of the symptom along the condition, but no consistent trend of mean values was observed. An upward-facing arrow (↑) indicates that symptom became significantly less severe along the condition. A downward-facing arrow (↓) indicates that symptom became significantly more severe along the condition. NS means that no significant change of symptom was observed. An asterisk (*) indicates that statistical analysis showed either a low level of significance ($0.05 > p > 0.01$) or the result was very close to significance level ($0.1 > p > 0.05$).

(a)

(b)

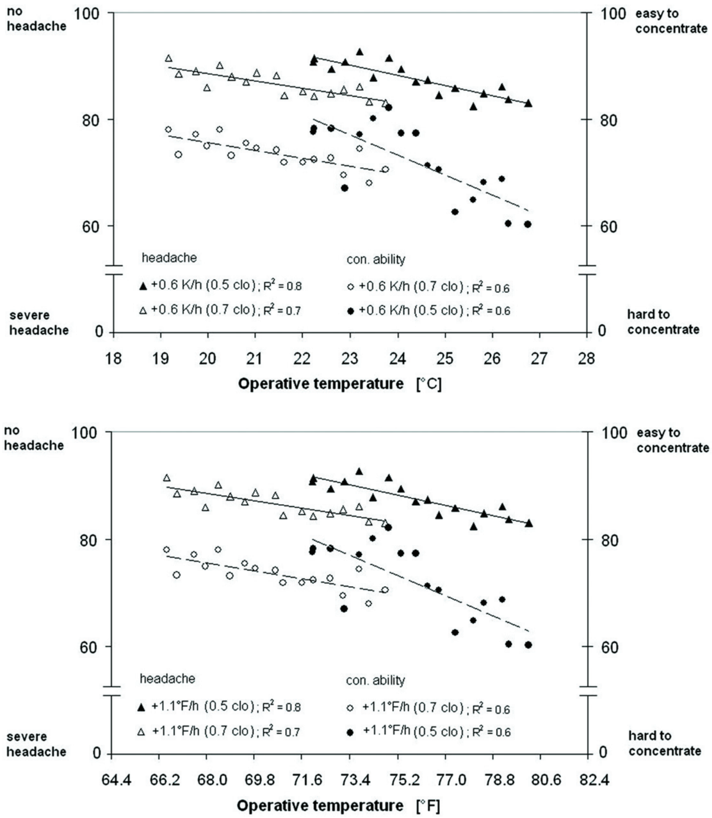


Figure 14. Development of intensity of headaches and ability to concentrate for the 0.6 K/h (1.1°F/h) temperature ramp in Experiment 1 (0.5 clo) and Experiment 2 (0.7 clo) where (a) presents the data in SI units and (b) presents the data in I-P units.

evolution in the intensity of headaches and ability to concentrate for the +0.6 K/h (+1.1°F/h) ramps, are depicted in Figure 14. On the other hand, the –1.2 K/h (–2.2°F/h) ramp had a positive effect on concentration ability, self-evaluated performance, and decreased fatigue. It also decreased mouth and skin dryness. The results clearly show that general symptoms were more affected than specific symptoms related to local irritation of mucous membranes (e.g., nose, eyes, mouth).

Office Work Performance

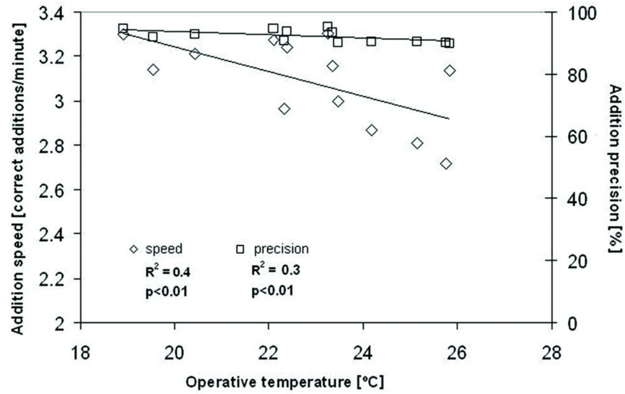
Mean values of the performance speed and precision for any particular type of task were calculated for every task block in each of the studied conditions. There was only one task block per task type in the 2.4 K/h (4.3°F/h) ramp condition. Because of this, it was not possible to analyze the change of the performance metrics in a particular task along the ramp. It was therefore decided to exclude the performance data from the 2.4K/h (4.3°F/h) ramp from further analysis. Table 6 summarizes an analysis conducted to determine whether the mean

Table 6. Summary of the Observed Effects of Studied Conditions on Subjects' Performance

<table>
<tr><th>Performance Metrics</th><th colspan="8">Task Speed</th><th colspan="8">Task Precision</th></tr>
<tr><td>Temperature Ramp</td><td colspan="2">0.0 K/h</td><td colspan="2">0.6 K/h</td><td colspan="2">1.2 K/h</td><td>–0.6 K/h</td><td>–1.2 K/h</td><td colspan="2">0.0 K/h</td><td colspan="2">0.6 K/h</td><td colspan="2">1.2 K/h</td><td>–0.6 K/h</td><td>–1.2 K/h</td></tr>
<tr><td>Experiment</td><td>E1</td><td>E2</td><td>E1</td><td>E2</td><td>E1</td><td>E2</td><td>E2</td><td>E2</td><td>E1</td><td>E2</td><td>E1</td><td>E2</td><td>E1</td><td>E2</td><td>E2</td><td>E2</td></tr>
<tr><td>Addition</td><td>NS</td><td>NS</td><td>NS</td><td>NS</td><td>↑*</td><td>NS</td><td>NS</td><td>NS</td><td>NS</td><td>NS</td><td>NS</td><td>NS</td><td>NS</td><td>NS</td><td>NS</td><td>NS</td></tr>
<tr><td>Proof-Reading</td><td>↑</td><td>↑</td><td>↑*</td><td>↑</td><td>NS</td><td>↑*</td><td>NS</td><td>NS</td><td>NS</td><td>NS</td><td>NS</td><td>|*</td><td>↑</td><td>↓</td><td>|</td><td>NS</td></tr>
<tr><td>Reading and Comprehension</td><td>↑</td><td>|</td><td>NS</td><td>↓</td><td>↑</td><td>↑*</td><td>↑</td><td>↑</td><td>NS</td><td>↓</td><td>|*</td><td>↑</td><td>NS</td><td>NS</td><td>↑</td><td>↑</td></tr>
<tr><td>Text Typing</td><td>↑</td><td>↑</td><td>|*</td><td>NS</td><td>NS</td><td>↑*</td><td>NS</td><td>↑*</td><td>NS</td><td>NS</td><td>NS</td><td>NS</td><td>NS</td><td>NS</td><td>NS</td><td>NS</td></tr>
</table>

Legend: E1 represents Experiment 1, while E2 represents Experiment 2. A vertical line (|) indicates a significant change in performance metrics during the exposure, but no consistent trend of mean values was observed. An upward-facing arrow (↑) indicates an increase of task speed or precision during the exposure. A downward-facing arrow (↓) indicates a decrease of task speed or precision during the exposure. NS means that no significant change was observed. An asterisk (*) indicates that statistical analysis showed a low level of significance ($0.05 > p > 0.01$).

(a)



(b)

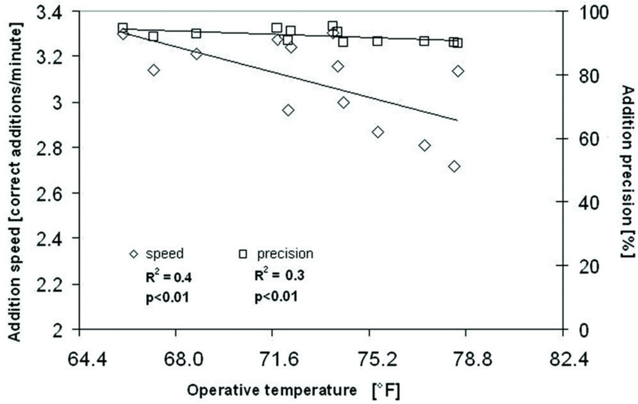
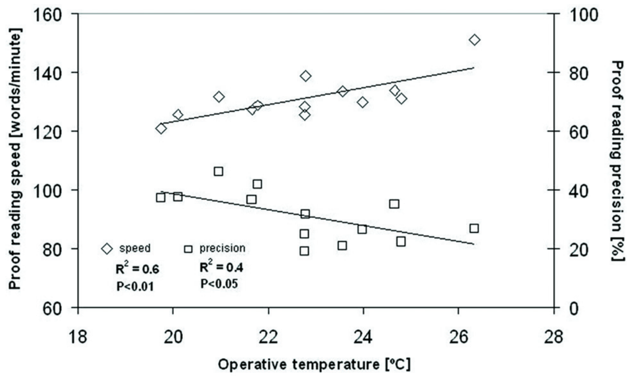


Figure 15. Addition speed and precision as a function of increasing operative temperature where (a) presents the data in SI units and (b) presents the data in I-P units.

task speed or mean task precision changed during any exposure. The speed in every task except for addition increased during exposure to a constant operative temperature of 24.4°C (75.9°F). Thereafter, precision remained unchanged in all tasks. When exposed to a constant operative temperature of 21.4°C (70.5°F), the speeds of both proofreading and text typing increased significantly ($p < 0.001$) during the exposure. Precision decreased only in the case of reading and comprehension.

As can be seen from Table 6, the analysis did not show any consistent positive or negative effects of the temperature ramps on either the speed or the performance. Addition and text typing seem to be least affected both in terms of speed and precision. Proofreading speed was influenced either positively or remained unchanged. Proofreading precision was significantly compromised only in the case of the 1.2 K/h (2.2°F/h) ramp at lower temperature levels (Experiment 2). Reading and comprehension speed decreased significantly ($p < 0.001$) only in the case of the 0.6 K/h (1.1°F/h) ramp at lower temperature levels (Experiment 2). Decreasing temperature ramps had a significant positive effect on reading speed and precision in the reading and comprehension task.

(a)



(b)

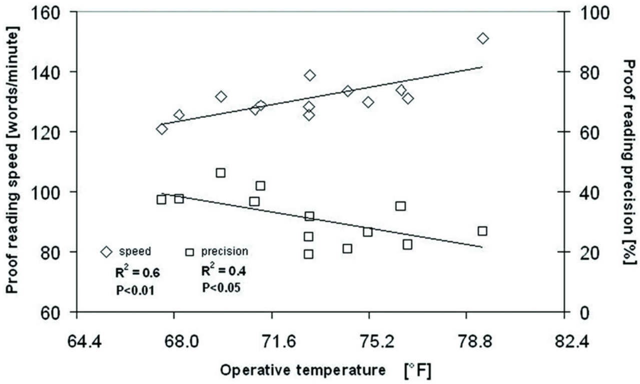


Figure 16. Proofreading speed and precision as a function of increasing operative temperature where (a) presents the data in SI units and (b) presents the data in I-P units.

No consistent effect of changing temperature on office work performance was observed within experimental conditions, and thus, performance outcomes of each type of task were pooled and analyzed, irrespective of the temperature ramp applied. However, the data from increasing and decreasing ramps were analyzed separately.

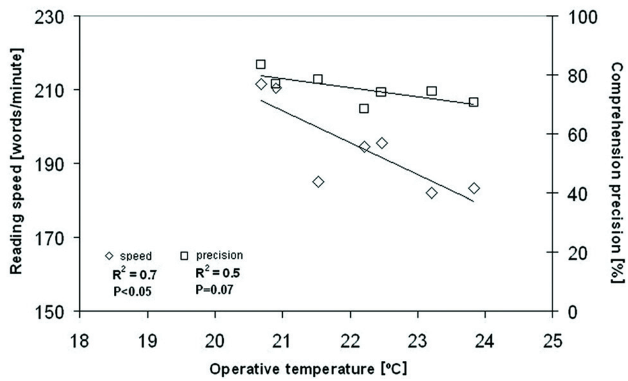
Figure 15 and Figure 16 show results of the analysis involving increasing temperature ramps. A significant linear relationship was observed between the operative temperature and addition (both speed and precision) as well as proofreading (both speed and precision). Whereas, rising temperatures had a negative effect on addition speed, they had a positive effect on the speed of proofreading. With rising temperatures, subjects read more quickly, but they detected slightly fewer mistakes in the text at the same time (Figure 16). Decreasing temperature ramps positively influenced both reading speed and the precision of the reading and comprehension task (Figure 17).

DISCUSSION

Intensity of SBS Symptoms

No significant effect of temperature ramps was observed for SBS symptoms related to local irritation of mucous membranes, while general symptoms such as intensity of headaches, general

(a)



(b)

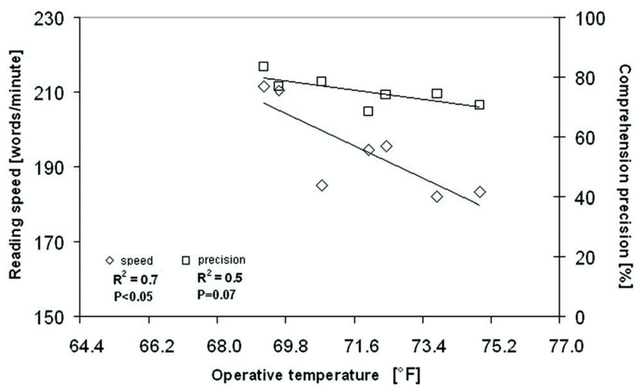


Figure 17. Reading speed and comprehension precision as a function of decreasing operative temperature where (a) presents the data in SI units and (b) presents the data in I-P units.

well-being, and concentration ability were significantly affected by most of the temperature ramps. The intensity of these general symptoms increased about 2%–3%/K. This seems to be in agreement with a previous study by Fang et al. (2004) in which an increase of the temperature also increased the intensity of these symptoms. However, it should be noted that in the present study the general slope of the symptoms' increase is much lower than shown previously; about 2%–3% in intensity per 1°C (1.8°F) increase in temperature as compared with a 12% increase in intensity of SBS symptoms per 1°C (1.8°F) temperature increase above about 22.5°C (72.5°F), as estimated by Seppänen and Fisk (2005). Moreover, a general level of the symptoms' intensities was rather low in the present study. The observed increase in the intensity of general symptoms could be caused not only by increasing temperatures but also by the duration of the exposures (this could not be tested statistically as time and temperature were interrelated in the experimental design). It is not possible to determine whether people had more headaches because of the fact that the temperature increased at 0.6 K/h (1.1°F/h) or due to the fact that they were sitting in the climate chamber for 8 h. The fact is that for a summer condition (0.5 clo), with the 0.6 K/h (1.1°F/h) ramp lasting 8 h, all general symptoms became significantly more severe with time, while there was no significant change with the 2.4 K/h (4.3°F/h) ramp lasting 2 h under the same condition. This suggests that it was possibly the combination of exposure duration and increasing temperature that affected the intensity of SBS symptoms.

The relationship observed between the acceptability of the air quality and operative temperatures (or more precisely the enthalpy of the air) suggests that in the case of insufficient ventilation, a temperature increase could cause further degradation of perceived air quality, even when occupants were adapted to the actual air quality level. Poor air quality may, in the final analysis, result in increased intensity of SBS symptoms and in decreased overall comfort and productivity of the occupants. Moreover, exposure to temperature ramps lasting longer than 4 h may contribute to an aggravation of general symptoms due to fatigue.

Thermal Comfort

Subjects who were dressed in summer clothing (approx. 0.5 clo) immediately perceived operative temperature ramps of 1.2 K/h (2.2°F/h), 2.4 K/h (4.3°F/h), and 4.8 K/h (8.6°F/h) in the temperature range of 22°C–26.8°C (71.6°F–80.2°F). The perception of the thermal environment was the same regardless of the ramp to which they were exposed. A temperature ramp 0.6 K/h (1.1°F/h) was recognized with about a 3 h delay. Afterward, the same operative temperature was perceived as warmer than in the case of steeper ramps. However, a higher thermal sensation was not accompanied by higher dissatisfaction with the environment. During exposure to the 0.6 K/h (1.1°F/h) ramp at lower temperatures and higher clothing insulation (19°C–23.8°C [66.2°F–74.8°F], 0.7 clo), subjects did not perceive a given operative temperature differently from the 1.2 K/h (2.2°F/h) ramp. This result suggests that it may not be the temperature ramp itself, but rather a combination of temperature level above 24.4°C (75.9°F) and duration of the exposure that influenced the thermal sensation of the subjects. Although the design of the experiment did not allow separation of the combined effect of rising temperature and time, the fact that subjects spent 8 h in the climate chamber could result in fatigue, which consequently may have influenced thermal sensation. The results of the present study do not seem to be in conflict with findings of previous studies (Berglund and Gonzalez 1978a). Subjects could not distinguish slow temperature increases of 0.6 K/h (1.1°F/h) for the first 3–4 h of exposure. However, as exposure continued, a linear relation between thermal sensation and temperature was observed. A higher level of clothing insulation seemed to extend the delay period for very moderate ramps (0.6 K/h). It also introduced the delay into steeper ramps (1.2 K/h), whereas delay was not observed in the case of light clothing.

A comparison of the percentage dissatisfied with the thermal environment obtained in the present study with predictions by the PMV/PPD model did not show consistently that the acceptability range specified by current standards could be extrapolated when subjects were exposed to temperature ramps (ASHRAE 2004; ISO 2005). During exposure to the 4.8 K/h (8.6°F/h) ramp, the percentage of dissatisfied increased faster than predicted by the model. On the other hand, subjects accepted the slightly warm environment during the 0.6 K/h (1.1K/h) ramp more readily than the model would predict. The data from the ±1.2 K/h, 2.4 K/h, and –0.6 K/h (±2.2°F/h, 4.3°F/h, and 8.6°F/h) ramps followed the relationship given by the PMV/PPD model quite well. A rather high percentage of dissatisfied subjects during the exposure to a constant temperature of 24.4°C (75.9°F) cannot be fully explained. It is possible that as thermal acceptability data were not adjusted for higher initial metabolic rate, and thus higher dissatisfaction at the beginning of the ramp, this influenced the mean values given in Figure 10b (Figure 11b is in I-P units).

ASHRAE Standard 55 (ASHRAE 2004) specifies maximum rates of temperature change recommended during different periods of time (Table 1). The steepest temperature ramp specified in the standard is 1.1 K/0.25 h (2°F/0.25 h) (~ 4.4 K/h), which corresponds fairly well with the steepest ramp tested in the present study (4.8 K/h [8.6°F/h]). The results suggest that a ramp with such a slope would negatively affect occupants of a building, although only for exposures longer than 0.25 h. Even if a particular temperature level was perceived the same way as in the case of flatter ramps (in terms of thermal sensation), subjects' dissatisfaction with the condition was higher than allowed by the standard. This indicates that subjects indeed disliked this rate of temperature change but not necessarily the temperature level. This ramp also significantly increased headaches and decreased well-being and concentration ability. Although only a positive ramp of this slope was tested, it is reasonable to assume that the ramp at equal value but opposite direction would have had similar negative effects.

For 1, 2, and 4 h of exposure, Table 1 recommends maximum temperature increases of 2.2°C, 2.8°C, and 3.3°C (2.2 K/h, 1.4 K/h, and 0.8 K/h [4°F/h, 2.5°F/h, and 1.4°F/h]). Regarding these slopes, the study showed that thermal sensation can be predicted by PMV/PPD and, at the same time, the definition of the comfort zone according to current standards (ASHRAE 2004, ISO 2005) seems to be appropriate. Nevertheless, these standards do not deal with exposures lasting more than 4 h. Because of that, an additional recommendation would be that the operative temperature should not exceed 25.5°C (77.9°F) (for 1.2 met and 0.5–0.6 clo) during long duration exposures.

Office Work Performance

Analysis of the subjects' performance among conditions did not show any consistent effect of temperature ramps on speed or accuracy of the simulated tasks. Further analysis was focused on the relationship between the temperature level and performance regardless of the slope of the applied ramp. A significant linear relationship was found for the speed and precision of addition and proofreading. Table 7 shows a general overview of the development of the mean task speed. Increasing temperature ramps negatively influenced subjects' speed in tasks representing repetitive mental work—addition and text typing. Addition speed remained unchanged during exposure to a constant temperature, while it generally decreased during positive ramps. The same was observed for addition precision. Text typing speed increased during the exposure to constant temperatures, whereas it remained unchanged during ramps. Reading speed in the proof-reading task seemed to be unaffected by increasing temperatures, while the ability of the subjects to find mistakes in the given text decreased with rising temperatures. Reading and comprehension were the most complex tasks used in this study. Subjects had to read the text first and then answer the questions. This required not only concentration and vigilance, but also tested their memory and ability to apply rule-based logical thinking. The complexity of the task might have been the reason for obtaining rather inconsistent results, even in the case of exposure to a constant operative temperature. Nevertheless, when temperatures were decreasing, subjects read faster and also answered more questions correctly.

Table 7. Overview of the Observed Trends of the Mean Task Speed

	Constant Temperature		Increasing Ramps	Decreasing Ramps
	24.4°C (75.9°F)	21.4°C (70.5°F)		
Addition	NS	NS	↓ [↓]	NS
Proofreading	↑	↑	↑ [↓]	NS
Reading and Comprehension	↑	NS [↓]	NS	↑ [↑]
Text Typing	↑	↑	NS	NS

Legend: An upward-facing arrow (↑) indicates an increase of the mean task speed during the exposure. A downward-facing arrow (↓) indicates a decrease of the mean task speed during exposure. An arrow in square brackets, [↑] or [↓], indicates the significant trend in the mean task precision, if any. NS means that no significant trend in the mean task speed was observed.

CONCLUSION

- A relationship between mean thermal sensation and the percentage of thermally dissatisfied subjects was in fairly good agreement with predictions by the PMV/PPD model.
- Increasing the operative temperature had a slight but significantly negative effect on general SBS symptoms, such as intensity of headaches, well-being, or fatigue. Similar results were observed for self-evaluated concentration ability and performance.
- No significantly consistent effect of individual temperature ramps on office work performance was found.
- No general effect (negative or positive) on specific symptoms related to local irritation of mucous membranes (nose, eyes, mouth) was observed.
- Adaptation to indoor air quality occurred after approximately 2 h during exposure to a steady temperature. A linear relationship between acceptability of air quality and temperature (enthalpy) was observed in temperature ramps.
- A linear relationship between mean thermal sensation and operative temperature was observed in all temperature ramps studied. Very moderate ramps (±0.6 K/h (±1.1°F/h)) were sensed by sedentary subjects with 3–4 h delay (depending on the level of clothing).
- Increasing operative temperature appeared to negatively affect the speed of addition and text typing, regardless of the slope of the ramp, when compared to a constant temperature condition.

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