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ORIGINAL ARTICLE

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Thermal sensation and thermophysiological responses to metabolic step-changes

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Abstract This study investigated the effect on thermal perception and thermophysiological variables of controlled metabolic excursions of various intensities and durations. Twenty-four subjects were alternately seated on a chair or exercised by walking on a treadmill at a temperature predicted to be neutral at sedentary activity. In a second experimental series, subjects alternated between rest and exercise as well as between exercise at different intensities at two temperature levels. Measurements comprised skin and oesophageal temperatures, heart rate and subjective responses. Thermal sensation started to rise or decline immediately (within 1 min) after a change of activity, which means that even moderate activity changes of short duration affect thermal perceptions of humans. After approximately 15–20 min under constant activity, subjective thermal responses approximated the steady-state response. The sensitivity of thermal sensation to changes in core temperature was higher for activity down-steps than for up-steps. A model was proposed that estimates transient thermal sensation after metabolic step-changes. Based on predictions by the model, weighting factors were suggested to estimate a representative average metabolic rate with varying activity levels, e.g. for the prediction of thermal sensation by steady-state comfort models. The activity during the most recent 5 min should be weighted 65%, during the prior 10–5 min 25% and during the prior 20–10 min 10%.

Keywords Activity · Comfort · Indoor climate · Transients

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Introduction

Standards and design guidelines for the thermal indoor environment mostly assume a steady-state activity level that is almost constant and identical for all occupants that share a uniformly conditioned zone in a building. However, activity level is a parameter that changes many times for typical office employees as they go about their daily regime of work; most prevalent are activities alternating between sedentary and slightly raised, standing activity. Short, more intense activities may occur, for example during walking on stairs. The statement is equally true of occupants in all types of indoor environments—occupational, residential, commercial, transport and recreational. It is known from steady-state models that the effect of shifting from seated to standing/walking activity on average will increase metabolic rate by approximately 0.3 metabolic units, which will ultimately amount to a change in preferred temperature of about 2.4°C according to PMV comfort theory (Olesen 2000). However, the rate at which changes in activity level affect thermal sensation are not known. Thus, activity level is probably one of the least well-described of all the parameters that affect thermal sensation and temperature preferences indoors, and metabolic transients may contribute to inter-individual differences in the perception of the thermal environment.

Only a few studies are available of human transient subjective responses to changes of metabolic rate. Gagge et al. (1969) showed that thermal and comfort sensations attained new steady-state levels circa 20–30 min after subjects were exposed to stepwise changes of metabolic rate from rest to 25%, 50% and 75% of maximum oxygen uptake at 10, 20, 30°C. However, only four male subjects participated in this study. Nielsen et al. (1979) exposed five male subjects to intermittent work-rest cycles of 5–5 min and 5–10 min at both 2 and 6 times their metabolic rate at rest. The mean thermal sensation votes of the subjects varied around neutral during the intermittent work at an ambient temperature that felt neutral during continuous work. The thermal sensation increased during the work period while the skin temperature decreased. However, the activity level applied during the work cycles was rather high (6 times basal metabolic rate) to be relevant to the levels typical of office work. Nielsen and Endrusick (1990) also showed that during alternating work–rest cycles, thermal sensation correlated well with mean body temperature and oesophageal temperature. In their study, eight subjects engaged in a twice-repeated bout of 40 min of exercise at 55% of maximum oxygen uptake that was followed by a 20 min rest. Kashimura (1985) observed five male subjects' thermal sensation during 30 min of exercise at 50% of maximum oxygen uptake. The subjects were exposed at 20, 25 and 30°C and air velocities of 0.1 or 5.0 m/s. Thermal sensation votes correlated with rectal temperature, but only slightly with mean skin temperature. Fukai (2000) let subjects walk for 20 min under a hot and humid condition (30°C, 70% rh) and then let them rest at 27°C and air humidities of 20, 30, 40, 50 or 60% rh. Subjects' thermal sensation attained the steady-state level after circa 60 min at 50% and 60% rh and sooner at lower humidities. The rather extreme environmental conditions used in their study and accumulation of sweat in the clothing are likely to have influenced the results in a way that is not typical for office buildings in many climatic regions. In a longitudinal study conducted over 2 years in an office building, Rowe (2001) collected employee reports of activities categorized as "sitting quietly", "sitting typing", "standing still", etc. Rating factors were applied to reported activities to determine a weighted average activity level for the calculation of PMV to compare with observed thermal sensations (50% for the activity during the past 10 min, 25% for the preceding 10 min, 15% for the 10 min prior to that and 10% for the 30 min prior to that). Even though the calculated PMV was slightly lower than the observed mean thermal sensation, which could be ascribed to an error in the estimation of activity, clothing insulation or both, the study underlined the importance for thermal perception of the most recent activity (10–20 min).

Many types of transient that building occupants are exposed to, such as slow temperature ramps, occur under almost quasi-steady-state conditions. The effect of such transients may be described by existing steady-state heat balance models. However, with current knowledge, the effects of metabolic transients on thermal perception and preference are not quantifiable, despite such transients being frequently initiated by the occupants' behavioural response to global and local thermal discomfort. The purpose of this study was to investigate the effect on thermal perception and thermophysiological variables of controlled metabolic excursions of various intensities and durations, imposed on subjects who alternated between sedentary activity and exercise on a treadmill as well as between different exercise intensities.

Methods

The current study comprised two stages. In the first, subjects were alternately seated on a chair or exercised by walking on a treadmill at a temperature predicted to be neutral at sedentary activity (Fanger 1970). In the second stage, subjects alternated between rest and exercise as well as between exercise at different intensities. Different subjects were used in the two stages.

Effects on overall thermal sensation of metabolic transients are most likely related to body core temperature and deep body thermoreceptors, and, as such, attenuated and slowed down by the body's thermal inertia. Saltin and Hermansen (1966) showed that core temperature was related to the relative work load of an individual and not to the absolute work performed. Thus, in the current experiments, exercise intensity was controlled according to the relative work load of each subject, aiming at 20%, 40%, and 60% of the maximum possible work load of each subject.

In a series of pre-experiments, the relation between heart rate and treadmill walking speed was determined for each subject. In addition, the maximal power output was determined according to a procedure suggested by Andersen (1995), the aim being to relate treadmill speed with relative work load. In the present study, relative work load (RW) was determined as the ratio of the heart rate recorded at each exercise intensity to the maximal heart rate. The heart rate of a subject resting on a chair corresponded to 0% work load while 100% corresponded to a subject exercising at their own maximal intensity. For each subject, the metabolic rate was approximated with the measured heart rate as input to a linear interpolation between the heart rate at sedentary activity, at which M was assumed constant at 58.2 W/m^2, and the heart rate recorded at the maximum work load at each subject's maximum oxygen consumption (Andersen 1995).

Stage 1 experiments

In each experimental session, subjects were randomly assigned to three exercise bouts used to study decay of metabolic heat and one bout for the study of accumulation of heat. The duration of the accumulation phase was held constant at 30 min and it was always the final bout of exercise performed during a session. Figure 1a shows the schedule of an experimental session. All exercise took place on a treadmill. Between bouts of exercise, subjects performed sedentary work (reading, writing).

Twenty-four subjects (12 female and 12 male) participated as volunteers. They were mostly university students and were paid for their participation. Table 1 shows anthropometric data for the subjects. It was intended that each subject should participate in three experimental

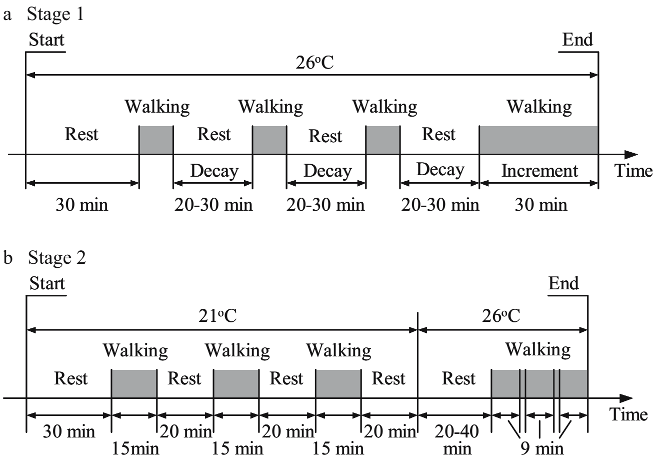


Fig. 1 Schedule of the experiments in each phase

sessions, but subjective responses were recorded from only 22 of the subjects for all experimental conditions.

During the experiments, subjects wore a standard uniform consisting of a thin, long-sleeve cotton shirt, trousers and their own underwear. The clothing insulation of this ensemble was around 0.7 clo, including chair insulation, as measured by a seated thermal manikin.

All experiments were carried out in climate chamber #3 at the International Centre for Indoor Environment and Energy, Technical University of Denmark (Kjerulf–Jensen et al. 1975). In the chamber, mean radiant temperature was equal to air temperature and the air velocity was low (<0.1 m/s). All experiments in this stage were conducted at a temperature of 26°C. The relative humidity was not controlled, and varied in the range between 15% and 50% between experimental sessions. There was only negligible variation of rh within sessions.

Each experiment commenced with subjects getting dressed in the uniforms and attaching the heart rate sensor to their chest before entering the chamber. During the first 30 min of an experiment, subjects adapted to the environment at sedentary activity before starting the first bout of walking activity. During the rest periods, subjects answered questions regarding thermal sensation on a 9-point scale (ASHRAE 7-pt scale with very hot and very cold added as end points), thermal comfort, thermal acceptability, and temperature preference every minute during the first 6 min after the metabolic step-change and every 3rd minute during the remaining period. Fig. 2 shows the questionnaire. During the walking period of the accumulation phase, subjects answered only one question regarding their thermal sensation.

Skin temperature was measured on 12 subjects at nine points (forehead, chest, back, anterior thigh, posterior thigh, shin, calf, upper arm, hand). Local skin temperature was measured with thermistors (Astra Meditec), which were attached to the skin with vapour permeable surgical tape. The thermistors had an accuracy of ±0.1°C. Mean skin temperature $\left(\overline{T_{sk}}\right)$ was calculated as an area-weighted average of measurements using the following formula, modified from Nishi et al. (1975).

$$\begin{aligned}\overline{T_{sk}} = & 0.07 * T_{head} + 0.175 * T_{chest} + 0.175 * T_{back} \\ & + 0.14 * T_{upper\ arm} + 0.05 * T_{hand} + 0.095 \\ & * T_{anterior\ thigh} + 0.095 * T_{posterior\ thigh} + 0.10 \\ & * T_{shin} + 0.10 * T_{calf}\end{aligned} \quad (1)$$

Oesophageal temperature was measured on six subjects with a copper-constantan thermocouple with silicone tube (Ellab), which had an accuracy of ±0.1°C. Subjects inserted the sensor to a depth corresponding to one quarter of their height.

Stage 2 experiments

Stage 2 experiments were designed to investigate whether the rate of change of thermal sensation was affected by ambient temperature. Also, the experiments were performed to investigate human response to metabolic step-changes between different exercise intensities as well as between rest and exercise.

Twenty-four subjects (12 female and 12 male) participated as volunteers. Table 2 shows their anthropometric data. Each subject participated in only one experimental

Table 1 Subjects' age, height, weight, target and observed relative work load and approximated metabolic rate in the stage 1 experiments (mean±s.d.)

Sex	Age (years)	Height (cm)	Weight (kg)	Target relative work load (%)	Observed relative work load (%)	Approximate metabolic rate (W/m^2)
Females	23.5±2.3	169.3±4.5	61.5±12.4	20	17±5	130±30
				40	32±13	190±55
				60	59±13	300±70
Males	25.0±4.4	181.9±4.9	75.0±6.9	20	14±5	130±30
				40	40±13	270±85
				60	59±12	370±90
Females and males	24.3±2.3	175.6±7.9	68.3±12.0	20	16±5	130±30
				40	35±13	220±75
				60	59±12	335±85

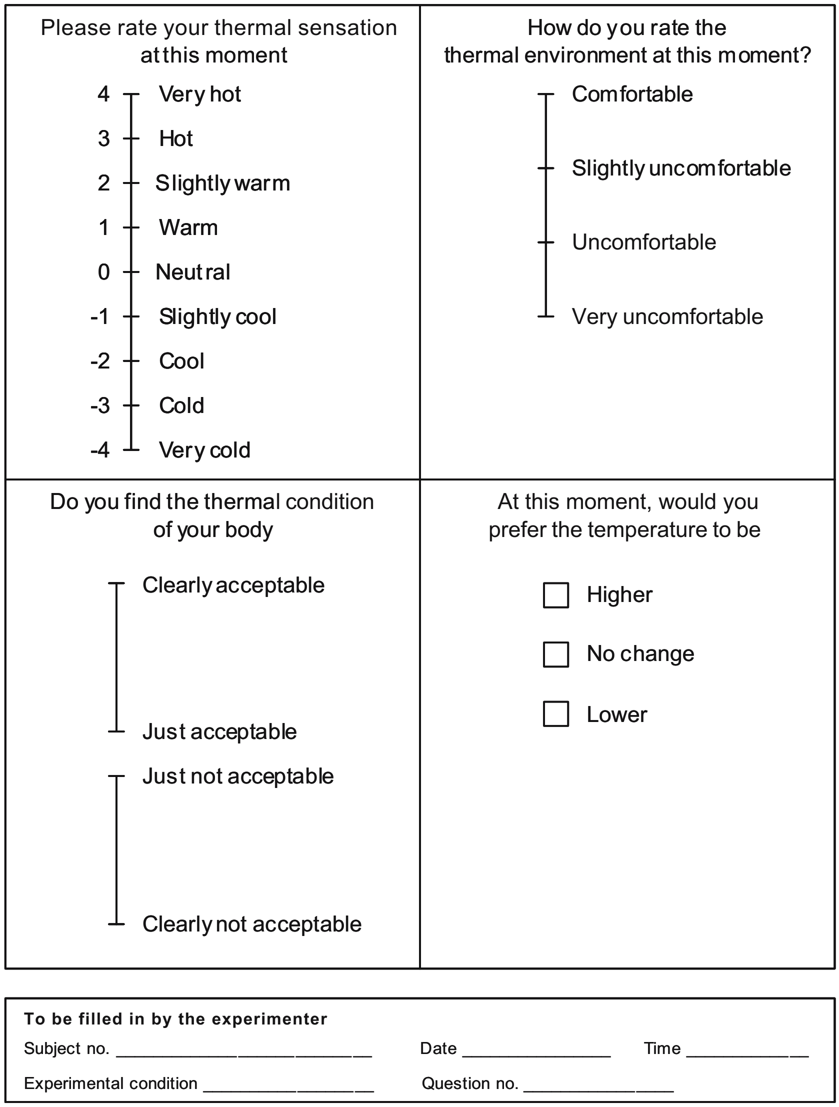


Fig. 2 Thermal comfort questionnaire applied in the study

session. The experimental uniform was the same as in the stage 1 experiments.

In a random, but balanced, order subjects were assigned to three exercise bouts to study accumulation and decay of metabolic heat at a temperature of 21°C. The exercise intensities were 20%, 40% and 60% RW, and the exercise durations were 15 min. After these exercise bouts, subjects entered an adjacent climate chamber, held at 26°C, and were assigned to three successive exercise intensities, which were increased from 20% to 60% and back to 20% RW. The exercise at each intensity had a duration of 9 min and the treadmill speed was changed within 1 min between

Table 2 Subjects' average age, height, weight, target and observed relative work load and approximated metabolic rate in the stage 2 experiments (mean±s.d.)

Sex	Age (years)	Height (cm)	Weight (kg)	Target relative work load (%)	Observed relative work load (%)	Approximated metabolic rate (W/m^2)
Females	25.1±3.7	166.3±5.1	58.3±5.7	20	19±4	140±20
				40	34±4	205±30
				60	50±7	280±50
Males	22.6±2.3	176.6±7.5	70.2±8.2	20	18±4	145±35
				40	33±7	220±55
				60	52±10	315±80
Females and males	23.8±3.3	171.5±8.2	64.2±9.2	20	19±4	145±25
				40	33±6	215±45
				60	51±9	300±70

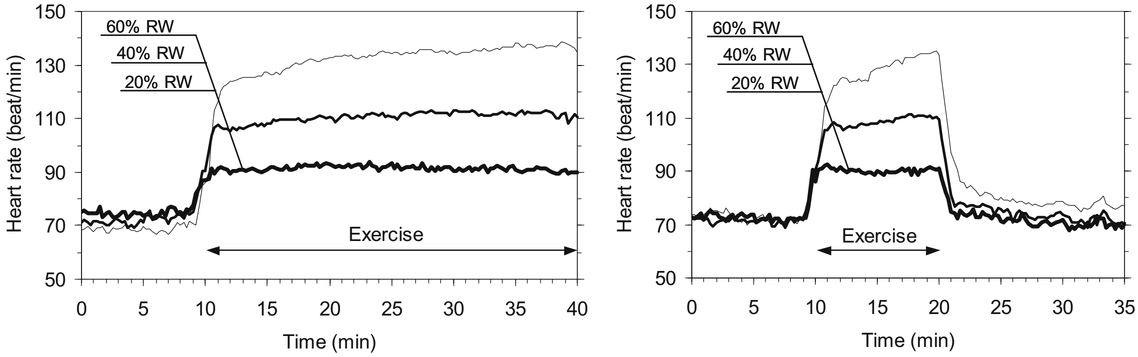


Fig. 3 Examples of observed heart rates. *Left*: during 30 min of exercise in stage 1 experiments. *Right*: during and after 10 min of exercise in stage 1 experiments

each 9-min period at constant intensity. As shown in Fig. 1b, this part of an experimental session was conducted at a temperature of 26°C. Between bouts of exercise, subjects performed sedentary work (reading, writing).

Two adjacent and interconnecting chambers (#5 and #6) accommodated the experiments (Toftum et al. 2004). The temperature of chamber #5 was 21°C, and that of chamber #6 was 26°C. The relative humidity of chamber #5 varied in the range between 20% and 60%, and that of chamber #6 varied in the range between 15% and 45%.

Each experiment commenced with subjects getting dressed in the uniforms and attaching the heart rate sensor to their chest before entering chamber #5. During the first 30 min, subjects adapted to the environment at sedentary activity before starting the first bout of walking activity. After three walking periods and three rest periods, subjects were asked to enter chamber #6. Subjects then started the successive exercise series after 20–40 min of adaptation to the environment at sedentary activity.

Results

Figure 3 shows examples of heart rates as observed during the stage 1 experiments. Heart rates mostly changed within 1 or 2 min after both up-steps and down-steps of activity and remained stable after this period, unless at 60% RW. Tables 1 and 2 show the target and observed RW and approximated metabolic rate (M) in stage 1 and 2, respectively. As shown in Table 2 and 3, metabolic rates from 130–145 W/m^2, 190–220 W/m^2 and 280–370 W/m^2 corresponding to 20%, 40% and 60% RW were estimated. The 20% RW corresponded to seated or standing light work, whereas the metabolic rates at 40% and 60% RW corresponded to heavy work and were thus not typical for office activities. These workloads were included to extend the scope and the general applicability of the study.

Table 3 Fitted values of the factor k in Eq. (2) as well as the observed mean thermal sensation at time t=0 [TS (t=0)]

Stage	Activity prior to step-change	Activity after step-change	Air temp. (°C)	TS (0)	k
1	Sedentary	20%–30 min	26	0.22	0.17
1	Sedentary	40%–30 min	26	0.25	0.11
1	Sedentary	60%–30 min	26	0.27	0.18
1	20%–10 min	Sedentary	26	1.12	0.36
1	20%–20 min	Sedentary	26	1.35	0.22
1	20%–30 min	Sedentary	26	1.52	0.24
1	40%–5 min	Sedentary	26	1.34	0.19
1	40%–10 min	Sedentary	26	2.00	0.26
1	40%–15 min	Sedentary	26	2.40	0.19
1	60%–3.3 min	Sedentary	26	1.54	0.19
1	60%–6.6 min	Sedentary	26	2.23	0.19
1	60%–10 min	Sedentary	26	2.73	0.20
2	Sedentary	20%–15 min	21	–0.35	0.30
2	Sedentary	40%–15 min	21	–0.60	0.31
2	Sedentary	60%–15 min	21	–0.45	0.22
2	20%–15 min	Sedentary	21	0.44	0.27
2	40%–15 min	Sedentary	21	1.38	0.28
2	60%–15 min	Sedentary	21	2.22	0.20
2	20%–9 min	60%–9 min	26	1.17	0.19
2	60%–9 min	20%–9 min	26	2.55	0.18

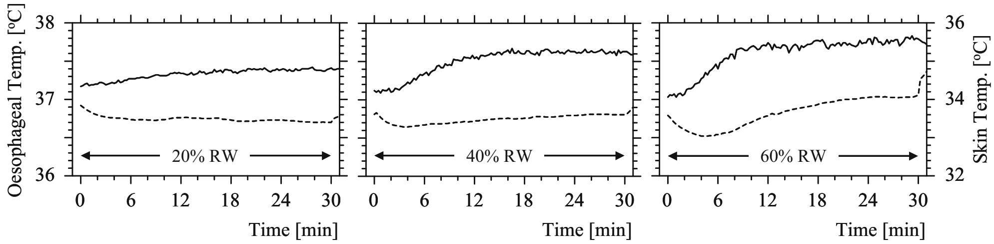


Fig. 4 Oesophageal and mean skin temperature during the accumulation phases of stage 1 experiments. *Solid lines* oesophageal temperature (n=6), *dotted lines* mean skin temperature (n=12)

Stage 1 experiments

Figure 4 shows the average oesophageal temperature (n=6) and average skin temperature (n=12). Approximately 2 min after onset of exercise oesophageal temperature started to climb and rose exponentially to a new steady-state level within circa 15 min, irrespective of the RW. Due to increased convection in the clothing as a result of the walking movements (pumping effect), mean skin temperature initially decreased and remained stable at a lower level than during sedentary activity, except at 60% RW where mean skin temperature rose steadily throughout the 30-min exercise period.

Similarly, Fig. 5 shows oesophageal and skin temperatures during the decay phase when subjects returned to sedentary activity after exercise at 20% RW for 10, 20 and 30 min; 40% RW for 5, 10 and 15 min; and 60% RW for 3.3, 6.6 and 10 min. The figure also indicates the oesophageal and mean skin temperatures prior to the exercise leading up to the decay phase. From the beginning of the decay phase, the oesophageal temperature tended to decrease exponentially before stabilizing at a new level within 5 min. Immediately after returning to sedentary activity, mean skin temperature started to increase as a result of reduced convection in the clothing and stabilized at a new steady-state level within 5 min.

As shown in Figs. 6 and 7, the average thermal sensation started to rise or decline immediately (within 1 min) after subjects commenced at or finished exercise, respectively. During the first 5 min of the exercise or rest periods, in particular, thermal sensation rose or fell most rapidly, whereas after approximately 15 min a new steady-state was reached.

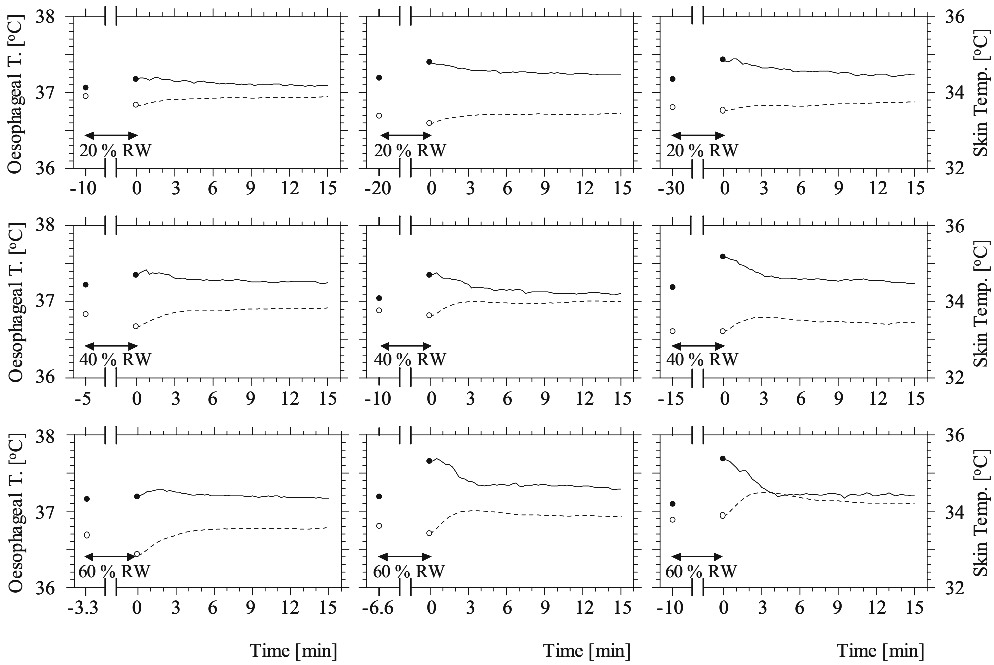


Fig. 5 Oesophageal and mean skin temperature during the decay phases of the stage 1 experiments. *Solid lines* oesophageal temperature (n=6), *dotted lines* mean skin temperature (n=12)

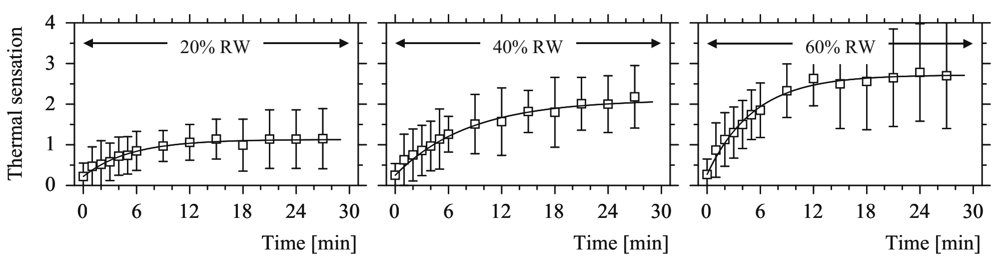


Fig. 6 Average thermal sensation after an up-step of exercise in stage 1 (n=22). *Error bars* show SD, *solid lines* regression lines

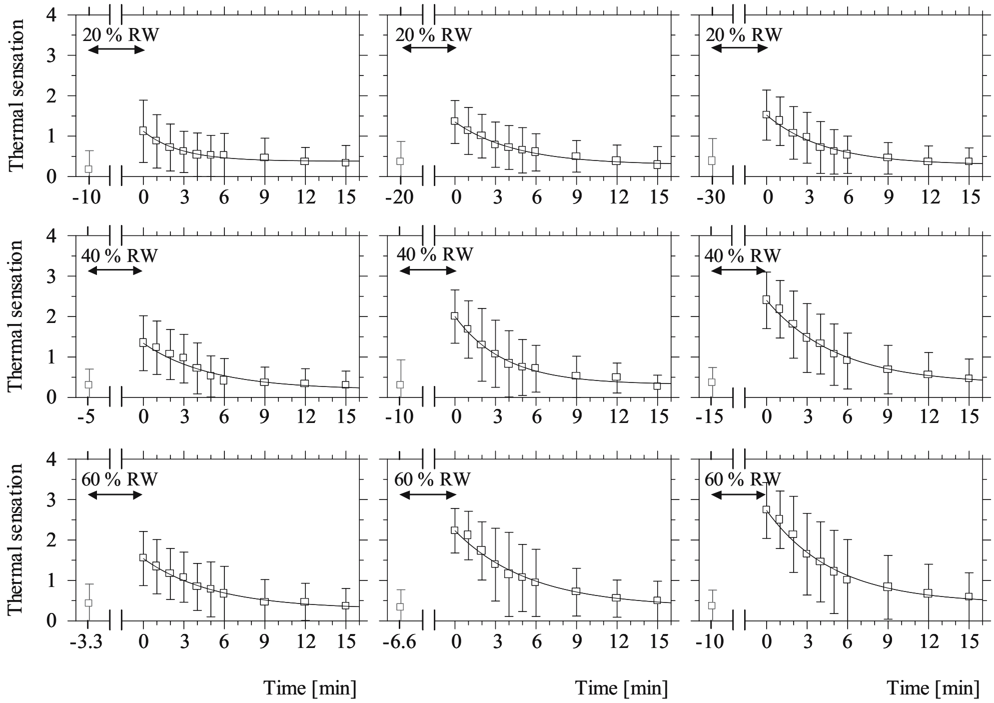


Fig. 7 Average thermal sensation after a down-step of exercise in stage 1 (n=22). *Error bars* show SD, *solid lines* regression lines

Thermal sensation correlated well with oesophageal temperature, both during exercise (r=0.91) and after exercise when subjects again were seated (r=0.82). However, thermal sensation correlated only little with mean skin temperature, both during exercise (r=0.24) and after exercise (r=0.06).

Figure 8 shows examples of corresponding values of rates of change of oesophageal and skin temperature as well as thermal sensation. Only figures for 40% RW at activity up-steps and after exercise at 40% for 10 min at downs-steps are shown here. For other exercise intensities and durations, similar patterns were observed, although

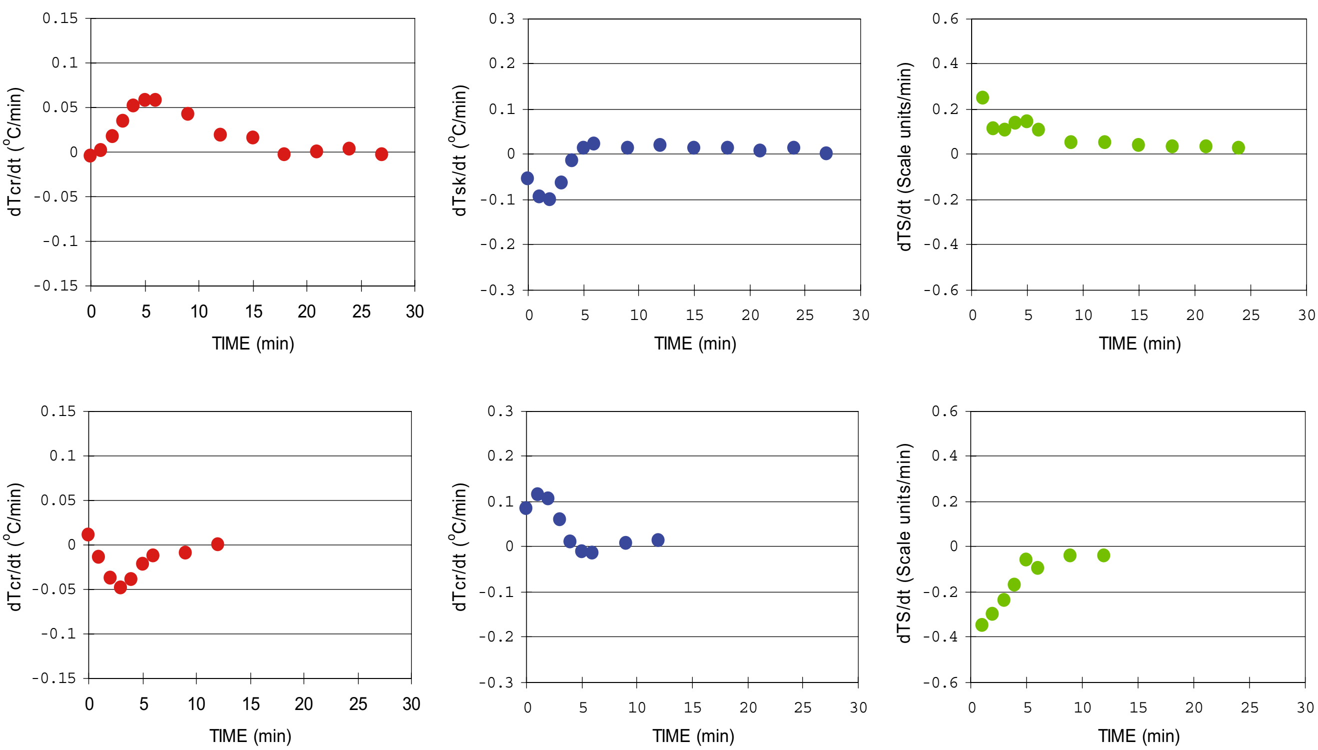


Fig. 8 Rate of change of oesophageal temperature (dTcr/dt), skin temperature (dTsk/dt) and mean thermal sensation (dTS/dt). *Upper figures*: activity up-step with exercise at RW=40%. *Lower figures*: activity down-step after exercise at RW=40% for 10 min

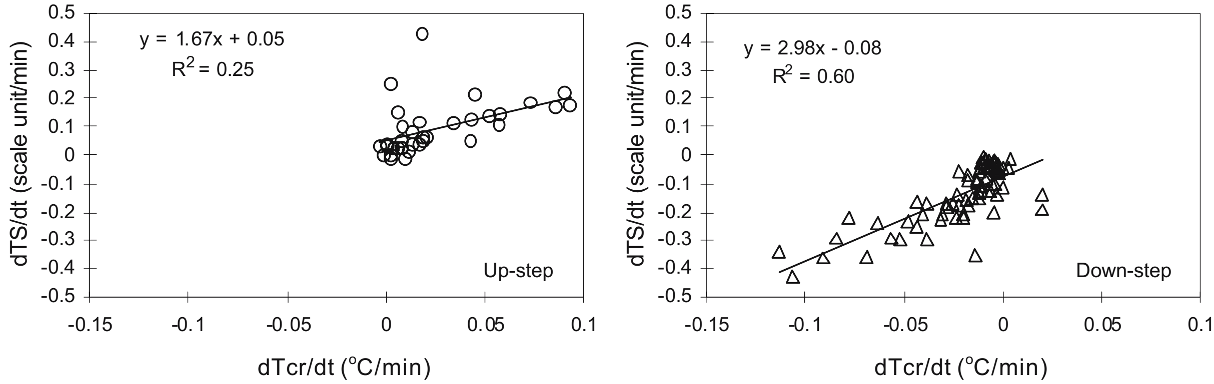
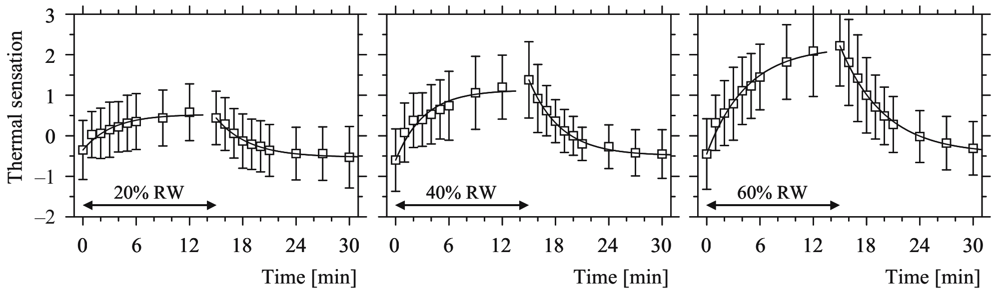


Fig. 9 Rate of change of thermal sensation (mean of all subjects) as a function of the rate of change of oesophageal temperature (mean of six subjects)

Fig. 10 Average thermal sensation with metabolic step-changes at 21°C of stage 2 experiments. *Error bars* show SD, *solid lines* regression lines



peak values increased with increased intensity and duration. Also, at 60% RW, a sign shift was observed in the rate of change of skin temperature due to an undershoot at onset of exercise and overshoot after cessation of exercise. Oesophageal temperature and thermal sensation generally stabilized faster at a new steady-state lever after a down-step of activity than after an up-step.

For all stage 1 experimental exposures combined, Fig. 9 shows the rate of change of thermal sensation as a function of the rate of change of oesophageal temperature, separately for up-step and down-step of activity. Fig. 9 also shows the result of a simple linear regression between the two variables and the corresponding regression equations. The slope of the regression line with down-steps was 2.98 as opposed to 1.67 for up-steps, which indicates that even though the level of the core temperature varied between the applied RWs, was the thermal sensation more sensitive to changes in core temperature with down-steps of activity than with up-steps.

Stage 2 experiments

Figure 10 shows that exercise at a temperature of 21°C yielded a similar increase of thermal sensation as at 26°C, approximately 1 scale unit at 20% RW, 2 scale units at 40% RW, and 2.5 scale units at 60% RW, although the thermal sensations at onset of exercise was lower than at 26°C. Also, the rates of change of thermal sensation were comparable to those observed at 26°C.

Figure 11 shows the average thermal sensation when the exercise intensity was changed consecutively from 20% RW to 60% RW and back to 20% RW. The rate of change of thermal sensation after the step-changes was comparable to the rates observed when subjects shifted between sedentary activity and walking on the treadmill, and it is thus assumed that the activity level prior to and after an activity change does not affect the course of the thermal sensation after the change.

No significant differences between female and male subjects' thermal sensation were observed, although they obtained different metabolic rates at the same RW.

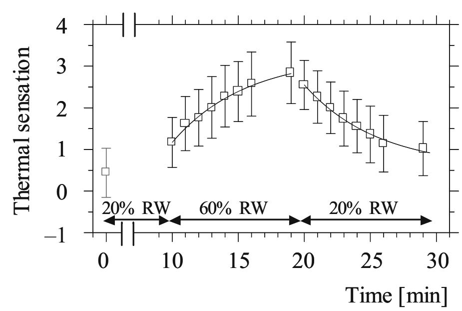


Fig. 11 Average thermal sensation with metabolic rate changed from 20% RW (9 min) to 60% RW (9 min) and back to 20% RW (9 min). *Error bars* show SD, *solid lines* regression lines

Discussion

An increase of thermal sensation was observed immediately after subjects increased their activity from sedentary to walking on the treadmill. During the first minute, the average thermal sensation rose 0.3 scale units when activity was increased from sedentary to 20% RW. In buildings, in practice, this corresponds to walking at a slow pace or standing, light work. In laboratory settings, between subject-variability of preferred temperature of 1.15°C, corresponding to ΔPMV of 0.3, has been observed with resting subjects dressed in 0.6 clo (Fanger and Langkilde 1975). Thus, even minor activity changes of short duration that inevitably occur in buildings may affect thermal sensation by an amount that corresponds to the inter-individual variability.

Under transient conditions both accumulation and decay of thermal sensation approximated exponential curves, as shown in Figs. 6, 7, 10 and 11. Based on the experimental results an empirical model has been fitted to the transient mean thermal sensation as a function of time:

$$\begin{aligned}\overline{TS}(t) &= \overline{TS}(t=\infty)\\ &\quad - \left\{\overline{TS}(t=\infty) - \overline{TS}(t=0)\right\} \cdot e^{-k \cdot t}\end{aligned} \tag{2}$$

in which $\overline{TS}(t)$ is the mean thermal sensation at time t, $\overline{TS}(t=0)$ the mean thermal sensation when the metabolic step-change occurred, $\overline{TS}(t=\infty)$ the steady-state mean thermal sensation after the step-change, t the time elapsed after the metabolic step-change (min), and k an empirically fitted parameter.

With Eq. (2) transient thermal sensation can be predicted from the steady-state thermal sensation prior to the metabolic step-change and the steady-state thermal sensation after the step-change. For each experimental condition, k was determined by non-linear regression analysis. Table 3 shows that k varied in the range 0.11 to 0.18 with up-steps of activity in the stage 1 experiments and with down-steps in the range 0.19 to 0.36, independently of the RW, which indicates faster response to activity down-steps than to up-steps. The k-values determined in the stage 2 experiments seemed also to be independent of the RW, but the values, at least for the activity up-steps, were higher than in stage 1. The value of k for up-steps of activity seemed to be affected by the ambient temperature, and seemed smaller at higher temperature than at lower temperature. However, with down-steps of activity k was not related with the ambient temperature. Eq. (2) shows that the transient thermal sensation can be predicted from the thermal sensation obtained when the activity step-change occurred and the steady-state thermal sensation after the step-change. For example, when k is set at a constant value of 0.23, which is the mean value of k for down-steps in the stage 1 experiments, Eq. (2) implies that the thermal sensation has changed 50 % after 3–4 min, and 90 % after 10–11 min. Eq. (2) and the k-values shown in Table 3 apply under the conditions that prevailed during the current experiments, i.e. no noteworthy sweating was observed and temperatures were moderate. A higher sweat rate caused for example by high activity or high temperature may leave the clothing moist or wet, which would most likely affect thermal sensation responses. Other factors that may affect responses may include an initial core temperature that deviates significantly from the one aimed at in the current study, e.g. corresponding to a neutral thermal sensation, or temperatures beyond the comfort range. However, the current study focuses on office buildings, where activity levels are moderate and temperatures most often in or near the comfort range. For such environments and types of work, Eq. (2) and the tabulated k-values may be used to predict transient thermal sensation with metabolic step-changes.

Although not as apparent from the results of the stage 2 as the stage 1 experiments, the current results indicate that thermal sensation was more sensitive to and changed faster with down-steps of activity than with up-steps. This corresponds well with de Dear et al. (1993) who observed that humans were generally more sensitive to warm–to–cold temperature step-changes than they were to cold–to–warm step-changes of equal magnitude. In the study of de Dear et al. (1993), the response to the environmental transient was mediated by the cutaneous thermoreceptors, whereas in the current study changes in internal temperature were registered by core thermoreceptors rather than peripheral. As shown in Fig. 8, the core temperature did seem to stabilize faster (dTcr/dt=0) after a down-step of activity (5–10 min) than after an up-step (10–20 min) and Fig. 9 shows that the sensitivity of thermal sensation to changes in core temperature differed considerably between activity up-steps and down-steps. The mechanisms that govern dissipation of heat from the deeper tissue thus seem faster than the generation and successive accumulation of metabolic heat in the body.

With all types of metabolic step-change used in this study, thermal sensation immediately started to rise or decline within 1 min after the change occurred, and almost attained a new steady-state level after approximately 15–20 min. This result is broadly consistent with the findings of Gagge et al. (1969), who showed that thermal sensation reached steady-state after circa 20–30 min. Also, when the metabolic change was between different exercise intensities, thermal sensations followed this same pattern. The activity levels applied in the current study resulted only in modest sweating, and subjects' clothing was slightly wet only after exercise at 60% RW for 30 min. The humid clothing in this case may have affected their expressed thermal sensation immediately after cessation of exercise, until excess moisture had evaporated. This may explain why thermal sensation changed more rapidly than in the experiments conducted by Fukai (2000), who observed steady-state thermal sensations after nearly 60 min under some experimental conditions. However, based on the current experiments it is not possible to state if the response time to metabolic transients of occupants who feel cool/cold or warm/hot prior to the activity step-change may be different from the one that was observed.

During field studies of occupants' thermal perceptions in buildings, an average metabolic rate of the past hour has often been estimated on the basis of a questionnaire identifying the fractions of time, occupants were sedentary, standing or walking. The average metabolic rate was then used as input to the prediction of thermal sensation. Realizing that this method could lead to significant errors in the analysis of thermal responses, newer practice has been to divide the past hour prior to completing the questionnaire into 10-, 20- or 30-min intervals and let occupants specify their activity during each interval (e.g. Rowe 2001). A time weighted average could then be used to predict thermal sensation. After both up-steps and down-steps of activity, thermal sensation reached a new steady level after approximately 15–20 min of constant activity and the current results thus indicate that knowledge of the activity is required only for this period leading up to the completion of a thermal comfort questionnaire. Eq. (2) and an average (of all experiments) *k*-value of 0.22 (Table 3) suggest a weighting of 65% for the activity during the most recent 5 min, 25% for the prior 10 to 5 min, and 10% for the prior 20 to 10 min. This weighting focuses exclusively on the past 20 min during which the specification of occupants' activities will be more precise and probably easier for the occupant to summarize. However, in instances with only minor variation in activity, as is typical in office buildings, the two sets of weighting factors will yield nearly similar average activity levels.

An indirect method for the determination of the relative work load and the metabolic rate was used in this study as no equipment was available for the measurement of oxygen consumption. ISO 8996 proposes that in a case of dynamic work using major muscle groups and with only a small amount of static muscular load and with absence of thermal strain and mental loads, the metabolic rate may be estimated by the heart rate and that a linear relationship exists between heart rate and metabolic rate. When these criteria are fulfilled, the accuracy of the method is within ±10%. Furthermore, a predictive yet reliable and reproductive method (standard deviation circa 10% of the observed value) for the determination of maximum oxygen consumption based on maximal power output was used rather than direct measurement on each subject (Andersen 1995). These things considered, we assume that the relative work load and the metabolic rate were valid and estimated with acceptable accuracy, although the applied method was not optimal.

Conclusions

Under the applied experimental conditions, thermal sensation started to rise or decline immediately after a change of activity. After approximately 15–20 min under constant activity, subjective thermal responses approximated the steady-state response.The sensitivity of thermal sensation to changes in core temperature was higher for activity down-steps than for up-steps.

For both up-steps and down-steps the rate of change of thermal sensation followed an exponential relation. A model was proposed that estimates transient thermal sensation with metabolic step-changes. Input to the model is the time elapsed after the metabolic step-change, the steady-state thermal sensation prior to the metabolic step-change and the steady-state thermal sensation after the step-change. Based on predictions by the model, weighting factors were suggested to estimate a representative average metabolic rate with varying activity levels, e.g. to be used in the prediction of thermal sensation by steady-state comfort models. The activity during the most recent 5 min should be weighted 65%, during the prior 10–5 min 25% and during the prior 20–10 min 10%.

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