THERMAL SENSATION AND COMFORT WITH TRANSIENT METABOLIC RATES

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ABSTRACT
This study investigated the effect on thermal perceptions and preferences of controlled metabolic excursions of various intensities (20%, 40%, 60% relative work load) and durations (3-30 min) imposed on subjects that alternated between sedentary activity and exercise on a treadmill. The thermal environment was held constant at a temperature corresponding to PMV=0 at sedentary activity. Even low activity changes of short duration (1 min at 20% relative work load) affected thermal perceptions. However, after circa 15 min of constant activity, subjective thermal responses approximated the steady-state response, after both up-steps and down-steps of activity.

INDEX TERMS
Thermal sensation, Thermal comfort, Metabolic rate, Transients

INTRODUCTION
Activity level is a parameter that changes many times for a typical office employee as they go about their daily regime of work. The statement is equally true of occupants in all types of indoor environments - occupational, residential, commercial, transport and recreational. Yet, activity level is probably one of the least well-described parameters of all the parameters that affect thermal sensation, comfort and temperature preferences indoors. It is affected by large interindividual differences in fitness and body mass, and it contributes to interindividual differences in the perception of the thermal environment. We know 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 met units, which will ultimately amount to a change in preferred temperature of about 2.4°C (Olesen 2000). What we do not know is the delay or the rate at which changes in activity level affect thermal sensation and comfort. This study investigated the effect on thermal perceptions and preferences of controlled metabolic excursions of various intensities and durations imposed on subjects that alternated between sedentary activity and exercise on a treadmill, while the thermal environment was held constant at a temperature corresponding to neutral at sedentary activity.

METHODS
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.

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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 work load.

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 workload. In the present study, relative work load was determined by the heart rate recorded at each exercise intensity. The heart rate of a subject resting on a chair corresponded to 0% relative work load while the 100% relative work load was that of a subject exercising at maximal intensity.

In each of the three experimental sessions subjects participated in, they were randomly assigned to three exercise bouts used to study decay of metabolic heat (table 1) 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. Figure 1 shows the schedule of each experiment. All exercise took place on a treadmill. Between bouts of exercise, subjects performed sedentary work (reading, writing).

Table 1. Relative work loads and exercise durations applied for the study of decay of metabolic heat.

<table>
<thead>
<tr>
<th>Relative work load (%)</th>
<th>Duration of exercise prior to decay (min)</th>
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<tbody>
<tr>
<td>10</td>
<td>20</td>
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<tr>
<td>20</td>
<td>30</td>
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<td>5</td>
<td>10</td>
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<td>10</td>
<td>15</td>
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<tr>
<td>3.3</td>
<td>6.6</td>
</tr>
<tr>
<td>6.6</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure 1. Schedule of the experiments.

Twentyfour subjects (12 female and 12 male) participated as volunteers. They were mostly university students with an average age of 24.3 years, and were paid for their participation. Each subject was supposed to participate in three experimental sessions, but subjective responses were recorded from only 22 of the subjects. During the experiments, subjects wore a standard experimental uniform consisting of a thin cotton shirt and trousers and their own underwear. The clothing insulation of this ensemble was around 0.6 clo, including chair insulation, as determined by a thermal manikin.
All experiments were carried out in a climate chamber at the Technical University of Denmark. In the chamber, mean radiant temperature was equal to air temperature and the air velocity was low (< 0.2 m/s). All experiments were conducted at a temperature of 26°C, which corresponds to PMV = 0 at sedentary activity and a clothing insulation of 0.6 clo. The relative humidity varied in the range between 15 % and 50%.

An 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 and the accumulation walking period, subjects answered questions regarding thermal sensation on a 9-point scale (ASHRAE 7-pt scale with very hot and very cold), thermal comfort, thermal acceptability and temperature preference every minute during the first six minutes after the metabolic step-change and every third minute during the remaining period.

RESULTS
Table 2 shows the average values of subjects’ height, weight, target and observed relative work load and metabolic rate (M). 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/m², and the heart rate recorded at the maximum work load (Andersen 1995).

<table>
<thead>
<tr>
<th>Sex</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>Target relative work load (%)</th>
<th>Observed Relative work load (%)</th>
<th>Approximated metabolic rate (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Females</td>
<td>169.3 ± 4.5</td>
<td>61.5 ± 12.4</td>
<td>0</td>
<td>-1 ± 6</td>
<td>55 ± 25</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>20</td>
<td>17 ± 6</td>
<td>130 ± 35</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>40</td>
<td>31 ± 13</td>
<td>185 ± 55</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>60</td>
<td>60 ± 15</td>
<td>305 ± 75</td>
</tr>
<tr>
<td>Males</td>
<td>181.9 ± 4.9</td>
<td>75.0 ± 6.9</td>
<td>0</td>
<td>1 ± 7</td>
<td>65 ± 35</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>20</td>
<td>14 ± 4</td>
<td>135 ± 25</td>
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<td></td>
<td></td>
<td></td>
<td>40</td>
<td>39 ± 13</td>
<td>265 ± 85</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>60</td>
<td>59 ± 13</td>
<td>365 ± 95</td>
</tr>
<tr>
<td>Females and males</td>
<td>175.6 ± 7.9</td>
<td>68.3 ± 12.0</td>
<td>0</td>
<td>0 ± 6</td>
<td>60 ± 30</td>
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<tr>
<td></td>
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<td></td>
<td>20</td>
<td>16 ± 6</td>
<td>130 ± 30</td>
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<td></td>
<td>40</td>
<td>34 ± 13</td>
<td>215 ± 75</td>
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<td></td>
<td></td>
<td>60</td>
<td>59 ± 14</td>
<td>335 ± 90</td>
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</tbody>
</table>

As evident in Table 2, it was difficult to precisely control the relative work load at the target level, most noticeably at the 40% level.

Average thermal sensations observed during the decay phase are presented in Figure 2 for the nine combinations of exercise intensity and duration. At each level of relative work load, subjects' average thermal sensation was clearly higher than before the onset of exercise. Within each relative work load, a longer exercise duration resulted in a warmer thermal sensation at the end of the exercise period. The average thermal sensations observed just after exercise at the high relative work loads were higher than after lower relative work loads,
Despite a shorter duration of the exercise, for all tested exercise durations and intensities, average post-exercise thermal sensation approximated the pre-exercise level after circa 15 min of sedentary activity.

![Graphs showing thermal sensation decay](image)

**Figure 2.** Average thermal sensation during the decay phase. (Y-axis: -4: very cold, -3: cold, -2: cool, -1: slightly cool, 0: neutral, 1: slightly warm, 2: warm, 3: hot, 4: very hot).

Figure 3 shows that after 1 min of exercise, average thermal sensation already was higher than before the beginning of the exercise, even at 20% relative work load. At all exercise intensities thermal sensation observed during the accumulation phase was nearly stable after circa 15 min of exercise. Figure 4 compares average thermal sensation with predictions made with the PMV model, which is based on steady-state responses recorded after three hours of exposure at constant activity (Fanger 1970). For relative work loads up to 40%, PMV predicts well the thermal sensation observed after 15 min. Yet, at 40% and 60%, which is just outside and well outside the recommended range for use of PMV (46 W/m² < M < 232 W/m², PMV < ± 2), observed thermal sensations were lower than PMV. Both accumulation and decay of thermal sensation approximated exponential curves. No substantial differences between female and male subjects’ thermal sensation were observed, although female and male subjects obtained different metabolic rates at the same relative work loads.

Comfort perception deteriorated slightly during exercise, but was restored to the pre-exercise level after approximately 15 min of sedentary activity (Figure 4). In addition, exercise at 20% relative work load caused a substantial fraction of the subjects to prefer a lower temperature. Temperature preference seemed to be nearly stable after 7-9 min of sedentary activity. A pre-exercise thermal sensation of neutral was aimed at, but on average subjects' thermal sensation vote during rest was 0.2-0.3, which may explain the high fraction of subjects preferring lower temperature during sedentary activity.
DISCUSSION
Within one minute of an increase from sedentary activity to 20% relative work load, average thermal sensation increased approximately 0.3 scale units. In buildings in practice, this exercise intensity corresponds to walking at a slow pace or standing and performing light work such as filing. 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 take place in buildings affect thermal sensation by an amount that corresponds to the interindividual variability.

This finding is particularly important for field studies of occupant perceptions in buildings. Often in these studies, the average metabolic rate of the past hour is estimated on the basis of a questionnaire identifying the percentage of time the person was sedentary, standing, or walking, which is used as input to a prediction of thermal sensation that eventually may be
compared with observed values. When predicting thermal sensation, a detailed description of
the activity during the past 15 min may improve precision. This same point is equally
applicable to thermal comfort standards such as CEN ISO 7730 (1994) and ASHRAE 55

Steady-state models for the prediction of thermal sensation seem to be applicable after
approximately 15 min of constant activity. However, the current results showed some
deviation between predictions and observations particularly at the highest work load, which
was the result of using PMV to predict thermal sensation outside the validity range. During
the experiments, the humidity control of the climate chamber was not working properly and as
a consequence, air humidity was not constant between some experiments. Humidity variations
in the range from around 15% rh to 50% rh, as observed during the present experiments,
correspond to a variation of steady-state PMV of around 0.3.

CONCLUSIONS
Even low activity changes of short duration affect thermal perceptions and preferences of
humans. However, after circa 15 min of constant activity, subjective thermal responses
approximate the steady-state response, after both up-steps and down-steps of activity.

ACKNOWLEDGEMENTS
This study was supported by the Danish Technical Research Council (STVF) as part of the
research programme of the International Centre for Indoor Environment and Energy
established at the Technical University of Denmark for the period 1998-2007. The authors
wish to thank Dr Bodil Nielsen, University of Copenhagen, for her valuable advice on the
assessment of metabolic transients.

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