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## **The relation between the thermoneutral zone and thermal comfort zone - *Determination of the thermoneutral zone and the influence on thermal behaviour***

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### **Abstract**

The thermoneutral zone (TNZ) reflects the range of ambient temperatures where no regulatory changes in metabolic heat production or evaporative heat loss occur. Indications exist that the ambient temperature range wherein a subject is feeling thermal comfortable, i.e. the thermal comfort zone (TCZ), is larger compared to the TNZ. From both the building energy-use and a health perspective this could be highly beneficial. The objective of this study is to explore the TNZ and TCZ of individual subjects, in relation to a given range of ambient temperatures. Within this study a method is developed to measure the TNZ. Subjects are exposed to two different protocols, during both protocols a drift of  $\pm 10\text{K/h}$  in ambient temperature is studied. According to the preliminary results it is possible to determine the TNZ of the subjects. Furthermore, a relation between TNZ, TCZ and the temperature preference of subjects can be observed. This approach links individual thermo-physiological properties to thermal comfort and thermal behaviour and will reveal important information for the energy use of buildings regarding user behaviour and user profiles.

Keywords: Thermo-physiology, Thermal comfort (zone), Thermoneutral zone, Thermal preference, Thermal behaviour

### **1 Introduction**

To arrive at comfortable conditions indoors energy is required generally. About one-third of the primary energy used in developed countries is currently consumed in the built environment, for a large share by heating, ventilating, air conditioning and lighting in residential, commercial and public buildings (Agency, 2007). This reveals a high importance to reduce the energy use in buildings. Therefore, predictions of the building energy consumption are necessary. However, the predicted energy use often significantly deviates from the actual energy used (Branco et al., 2004, Haas et al., 1998). This difference may be explained by the thermoregulatory behaviour of the occupants (Santin et al., 2009, Branco et al., 2004). Thermoregulatory behaviour is influenced by changes in thermal sensation and thermal comfort (Schlader et al., 2011). However, relatively little is known which (thermo)physiological parameters drive thermoregulatory behaviour, and in turn thermal comfort.

In this study it is hypothesized that the thermoneutral zone (TNZ) has an influence on thermoregulatory behaviour.

The thermoneutral zone (TNZ) is defined as the range of ambient temperatures without regulatory changes in metabolic heat production or evaporative heat loss. In a steady state

environment a person can only be within the TNZ when heat production and heat losses are in balance. Within the TNZ, resting energy expenditure (EE) is known as basal metabolic rate (BMR). Above or below the TNZ metabolic rate increases due to a change in ambient temperature (figure 1).

A recent literature study by Kingma et al. (2012) shows that the TNZ zone is affected by several factors, e.g. body composition, energy metabolism, age, gender, physical activity and clothing. Therefore, TNZ varies between different sub-populations.

Furthermore, indications exist that the ambient temperature range wherein a subject is feeling thermal comfortable, i.e. the thermal comfort zone (TCZ), is larger compared to the TNZ (van Marken Lichtenbelt and Kingma, 2013). From both health and building energy-use perspectives this could be highly beneficial (van Marken Lichtenbelt and Kingma, 2013).

Since, the TNZ and TCZ appear to be correlated to each other it is therefore hypothesized that the width and positioning of the TNZ has an influence on thermoregulatory behaviour on inter-individual level. Therefore, it is relevant to determine the TNZ of individual subjects.

Within this study a method is developed to determine the TNZ of individual subjects. Such a protocol has not yet been described before for humans.

Since the study is on-going, the first preliminary results of 6 subjects will be presented in this paper. It is expected that at the time of the conference all measurements will be completed.

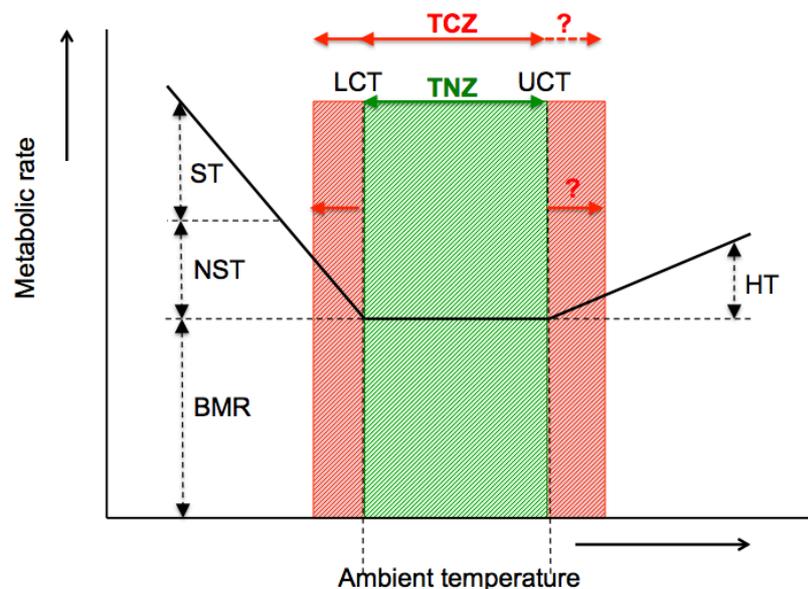


Figure 1. The thermoneutral zone (TNZ) reflects the ambient temperature range where the energy expenditure rate is at basal level (basal metabolic rate, BMR) and there are no thermoregulatory changes in metabolic rate (non-shivering thermogenesis, NST; shivering thermogenesis, ST; or heat-related thermogenesis, HT) or sweating. Below the lower critical temperature (LCT) metabolic heat production increases and above the upper critical temperature (UCT) sweating occurs due to a respectively decrease or increase in ambient temperature. The relation as depicted is mainly derived from animal studies. For the cold side data is available from human studies. For the warm side little is known until now, and the relation is complex due to an interaction of sweating and increase in metabolic rate.

The thermal comfort zone (TCZ) represents the range of ambient temperatures wherein a subject is feeling thermal comfortable (adapted from (van Marken Lichtenbelt and Kingma, 2013)).

## 2 Methods

In order to determine individual TNZs a climate room set-up with experimental subjects is used. The measurements are conducted in the respiration chambers of the Maastricht University. In total 16 healthy female subjects will visit the laboratory on two occasions for two different protocols. Subjects were taking oral contraceptives and were not measured during their menstruation period to standardize hormonal effects on thermoregulation. The subject characteristics are summarized in Table 1.

The volunteers were given detailed information regarding the purpose and the methods used in the study, before written informed consent was obtained. The protocol was approved by the ethics committee of Maastricht University Medical Centre+ and performed according to the Declaration of Helsinki.

Table 1. Subject characteristics

Age (year)	26.1 ± 4.17
Height (cm)	171.7 ± 0.06
Mass (kg)	63.7 ± 6.39
BMI (kg/m <sup>2</sup> )	21.6 ± 1.35
Bodyfat% (%)	25.7 ± 4.95

Values are presented as mean ± SD (n=6)

### 2.1 Study protocol

Subjects will be exposed on two different days to two different protocols, 1 and 2, consisting of an increasing and decreasing temperature drift ( $\pm 10\text{K/h}$ ) (Figure 2). Each protocol starts with a baseline measurement at a thermoneutral level ( $30^\circ\text{C}$ ) for one hour. During protocol 1 the temperature will increase in 1h from a thermoneutral temperature ( $30^\circ\text{C}$ ) to a warm ambient temperature ( $40^\circ\text{C}$ ). During protocol 2 the temperature will decrease in 1,5h from a thermoneutral temperature ( $30^\circ\text{C}$ ) to a mild cold ( $15^\circ\text{C}$ ) ambient temperature. Each subject completed the experimental protocols in balanced order. Two protocols are necessary because the cold and warm side of the TNZ need to be measured separately.

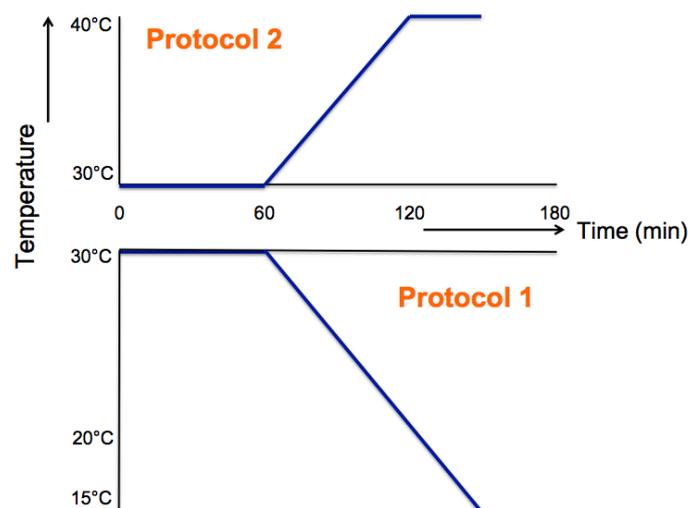


Figure 2. Measurement protocol 1 (increasing temperature drift,  $+10\text{K/h}$ ) and 2 (decreasing temperature drift,  $-10\text{K/h}$ )

## 2.2 Measurements

During the measurements subjects are semi-nude in supine position. Energy expenditure is measured through indirect calorimetry. Skin temperatures are measured at 26 body sites (Schellen et al., 2012) using wireless sensors (accuracy  $\pm 0.125^{\circ}\text{C}$ ) which were attached to skin using semi-permeable adhesive tape. Mean skin temperature is calculated based on the 14 point weighing proposed by EN-ISO 9886 (2004). Core temperature is measured using a telemetric pill (accuracy  $\pm 0.1^{\circ}\text{C}$ ), ingested one hour previous to the start of the experiment. Skin blood flow is measured at 4 body sites (hand, underarm, abdomen and toe) using laser Doppler flowmetry.

Air temperature and relative humidity were measured according to NEN-EN-ISO 7726 (2001) at 0.1, 0.6, 1.1 and 1.7 m height next to the subject.

## 2.3 Questionnaires

Thermal behaviour, sensation and comfort are measured on a 6-minute interval using the TherMU questionnaire. The questionnaire includes, among others, 7-point interval scales to assess global and local thermal sensation, questions regarding the acceptability of the thermal environment, and Visual Analogue Scales (VAS) to assess the importance to change and rate of sweating and shivering (EN-ISO, 2005) (Kildeso et al., 1999). The questionnaires were presented in Dutch to the subjects through an Internet browser. A commercially available statistical software package (PASW Statistics 21.0, SPSS Inc., Chicago, USA) is used to analyse the data.

## 3 Results

### 3.1 Physiological responses

In table 1 the averaged mean, distal and proximal skin temperatures and core temperature are represented. Skin temperatures are significantly different between the protocols (t-test,  $P < 0.001$ ).

Table 1: Mean, distal, and proximal skin temperatures and core temperature during both protocols including baseline period

Variable	Protocol 1	Protocol 2
Mean skin temperature [ $^{\circ}\text{C}$ ]	32.7 $\pm$ 2.0	34.5 $\pm$ 0.9*
Distal skin temperature [ $^{\circ}\text{C}$ ]	30.4 $\pm$ 2.7	33.1 $\pm$ 1.4*
Proximal skin temperature [ $^{\circ}\text{C}$ ]	33.5 $\pm$ 2.0	35.1 $\pm$ 0.9*
Core temperature [ $^{\circ}\text{C}$ ]	37.7 $\pm$ 1.0	37.2 $\pm$ 1.1

Values are presented as mean  $\pm$  SD, n=6, \* significant ( $P < 0.001$ ) different from protocol 1

### 3.2 Determination of the thermoneutral zone (TNZ)

The thermoneutral zone is defined as the range of ambient temperatures without regulatory changes in metabolic heat production or evaporative heat loss, i.e. the range in ambient temperatures where energy expenditure is at a constant level.

In Figure 3 the results of two typical subjects are represented. In this figure energy expenditure is related to the ambient temperature at 0.6m (subject position) and a distinction

is made for both protocols. The dotted lines represent the critical limits with respect to the TNZ. The TNZ for subject 3 the TNZ ranges from 28.0-32.1°C, and subject 5 from 22-32.4°C.

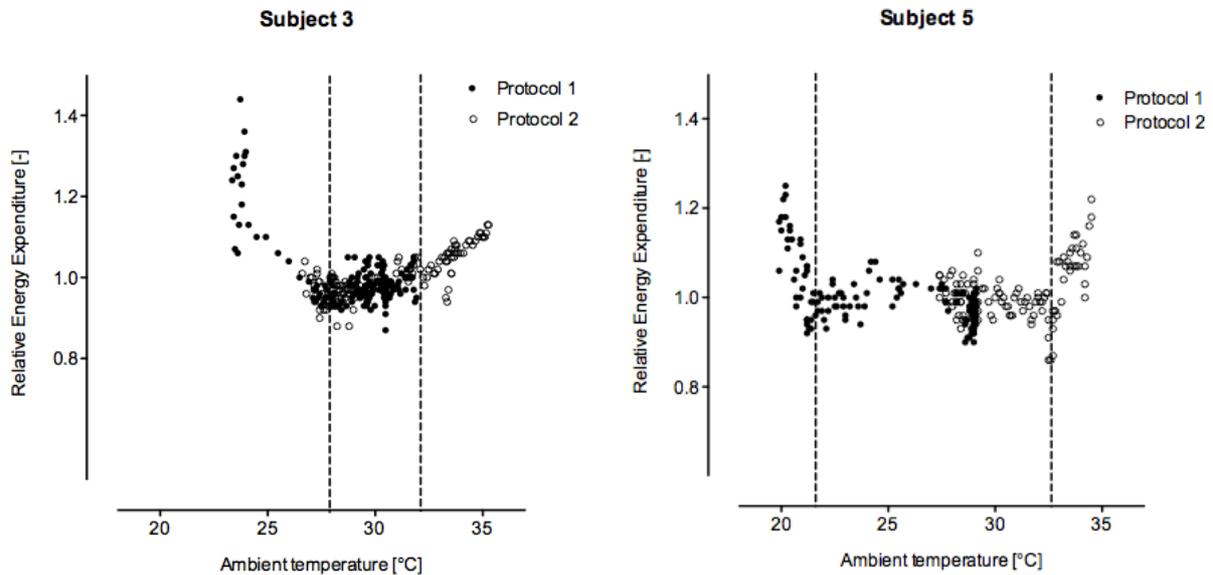


Figure 3. Normalized energy expenditure vs. ambient temperature for two typical subjects. The black dotted lines represent the upper and lower critical temperatures of the TNZ.

### 3.3 Thermoneutral zone (TNZ) vs. thermal comfort zone (TCZ)

In figure 4 the thermal comfort zone (TCZ) is represented in relation to the TNZ for two typical subjects. For subject 3 no clear lower critical temperature can be distinguished, the upper critical temperature equals 35.0°C. For subject 5 the TCZ ranges between 24.4-35.1°C

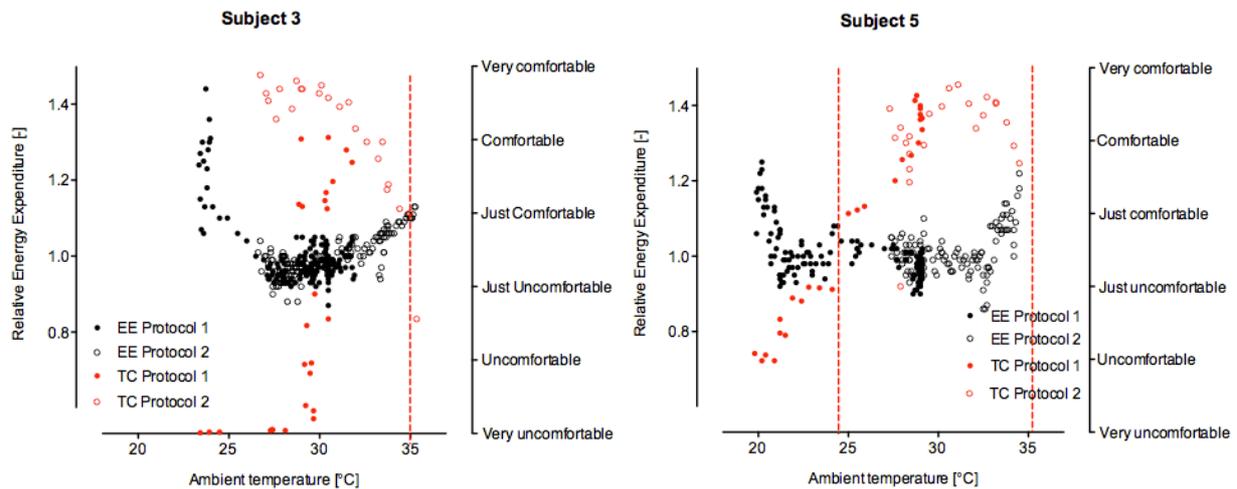


Figure 4. Normalized energy expenditure vs. ambient temperature vs. thermal comfort for two typical subjects. The red dotted lines depict the upper and lower critical temperatures of the TNZ. The black dots represent the energy expenditure data and the red dots represent the thermal comfort data.

### 3.4 TNZ in relation to thermal behaviour

The hypothesis of this study is that the TNZ of individual subjects can be used to explain thermal behaviour. In a recently published study we have shown that thermal behaviour can be explained by thermal preference and thermal sensation of the subjects, indicated by among others the strong correlation between preference and sensation (Jacquot et al., 2014). The current study again shows that these two parameters are strongly correlated (Figure 5).

Therefore, thermal sensation is regarded as an important parameter to predict thermal behaviour. To test the assumption that the TNZ is linked to thermal behaviour, the data of the TNZ and thermal sensation for the two same typical subjects (3 and 5) are analysed (Figure 6). For subject 3 the results show a relation between the warm side of the TNZ and thermal sensation, i.e. beyond the upper critical TNZ temperature (black dotted line) the thermal sensation exceeds the upper thermal sensation boundary (blue dotted line) according to the EN-ISO 7730 (2005) standard. However, for subject 5 no clear relation between TNZ and thermal sensation can be observed.

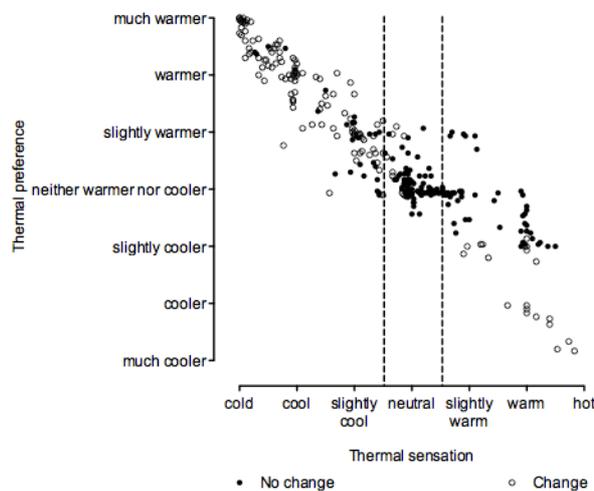


Figure 5. Thermal preference vs. thermal sensation. The open dots represented the data where the subject actually wanted to change their thermal environment (intention to change)

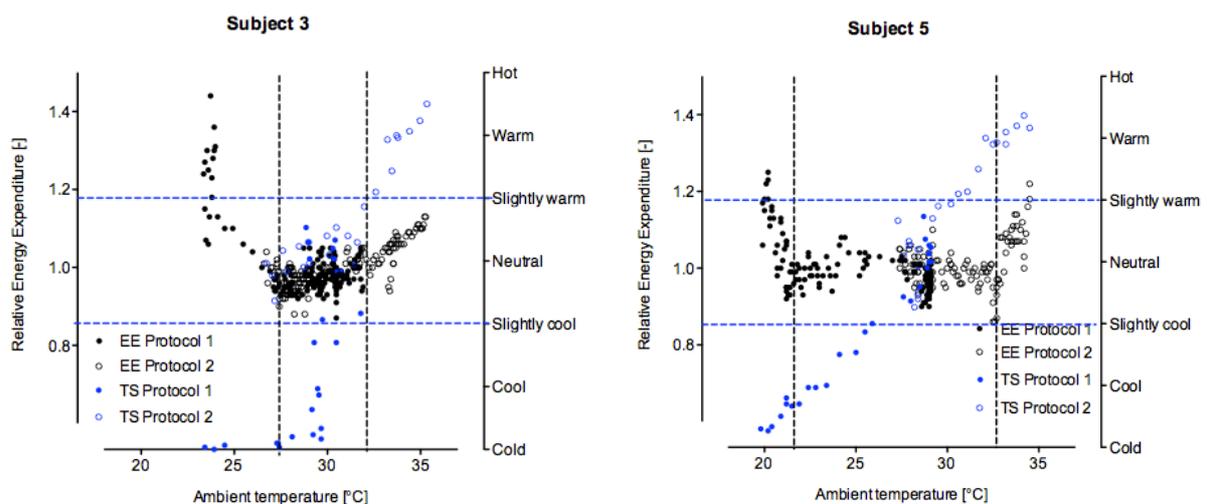


Figure 6. Normalized energy expenditure vs. ambient temperature vs. thermal sensation for two typical subjects. The blue dotted lines depict the thermal comfort boundaries from the EN-ISO 7730 standard (2005). The black dotted lines represent the upper and lower critical temperatures of the TNZ. The blue dots depict thermal sensation data assessed on the 7-point thermal sensation scale and the black dots represent the normalized energy expenditure data.

## 4 Discussion

Within this study the objective is to determine the thermoneutral zone (TNZ) and the thermal comfort zone (TCZ) of individual subjects. The hypothesis is that thermoregulatory behaviour of individuals can be explained according to their TNZ and TCZ. In order to be able to make realistic building energy predictions it is indispensable to include the thermal behaviour of occupants (Branco et al., 2004, Haas et al., 1998).

Within this paper preliminary results (6 out of 16 subjects) are presented. Subjects were exposed to two different protocols; an increasing (+10K/H) and a decreasing (-10K/h) temperature drift.

Although subjects are similar from a morphological point of view (Table 1), the first results indicate that there exist significant differences in thermal comfort, sensation, and behaviour in relation to the ambient temperature (Figure 3,4, and 6). Two typical subjects were selected for a detailed analysis. For subject 3 a relatively small (28.0-32.1°C) TNZ can be determined, where for subject 5 a relatively large (22.0-32.4°C) TNZ can be observed. With respect to the TCZ it is difficult to define the lower critical temperature for subject 3. This subject voted both comfort and discomfort at within a small range of ambient temperatures in the TNZ. For subject 5 the TCZ ranges from 24.4-35.1°C. For both subjects the TCZ is larger compared to the TNZ on the warm side of the TNZ. For the cold side of the TNZ the TCZ is smaller. However, in a previous study of our research group it is shown that after a short cold acclimation period of ten days, the TCZ can be significantly enlarged (van der Lans et al., 2013). From both health and building energy perspectives these results can be highly beneficial (van Marken Lichtenbelt et al., 2014). Furthermore, the results presented here support the hypothesis that the TCZ can be larger than the TNZ.

Another objective of this study was to develop a method to determine the TNZ of individual subjects, as this was not yet available for humans. All current TNZ data is obtained from animal studies. In the first pilot studies we tested slower temperature drifts ( $\pm 5$  K/h). However, the results showed no significant increases in energy expenditure during the drifts. Therefore it was decided to increase the temperature slopes. According to the results presented here, the developed protocols provide information on the TNZ. However, future analysis should further elaborate on this, especially on the effects of hysteresis.

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