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Energy efficient living – INTEWON
Physiology and behaviour: the elastic thermal comfort zone and the need for categorization

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Abstract
This paper is a synthesis of the results from the project INTEWON and related studies. The link between the physiological thermoneutral zone (TNZ) and the thermal comfort zone (TCZ) is discussed. Secondly, we discuss the relation between thermal preference and thermal sensation and how physiological parameters, such as skin temperature can predict thermal sensation. It is shown that the identification of subject categories, based on their thermal preference, increases the predictive value of skin temperatures substantially. Finally, it is deliberated how cold acclimatization can affect the TCZ and thereby may explain differences between subjects with respect to their thermal preference.

Keywords: Thermoregulation, thermal behaviour, cold acclimatization,

1 Introduction
INTEWON, "Individual-oriented information technology for energy efficient living", is a four-year study aimed at gaining more insight into the factors that determine the actual energy consumption of a household (Kingma et al., 2012b). Although the project is distributed over multiple centres, the focus of Maastricht University laboratory is on the interaction between thermal behaviour and thermal physiology. During the Windsor conference of 2012 we presented our plans for INTEWON. Here we present the first results of the project. The just published data show how categorization of people, based on thermal preference, improves association of thermal sensation and comfort with skin temperature. Recently, we also studied the effect of cold acclimation and thermal comfort. This paper presents a synthesis and the implications of these studies on energy efficient living are discussed.

2 Physiology and behaviour
Body temperature is regulated through both autonomic mechanisms and thermoregulatory behaviour. *Physiologically* temperature regulation can be accomplished

by increasing heat loss (vasodilation, sweating), decreasing heat loss (vasoconstriction), and increasing heat production (movement, shivering, non-shivering thermogenesis). The range of ambient temperatures where no form of thermoregulation, other than blood-redistribution, is required is called the thermoneutral zone (TNZ) (van Marken Lichtenbelt et al., 2014) (figure 1). People can tolerate and even judge temperatures comfortably, even if they are outside their TNZ (Schellen et al., 2010). Therefore it seems that the thermal comfort zone (TCZ), i.e. the range of ambient temperatures where people feel comfortable, may be larger than the TNZ.

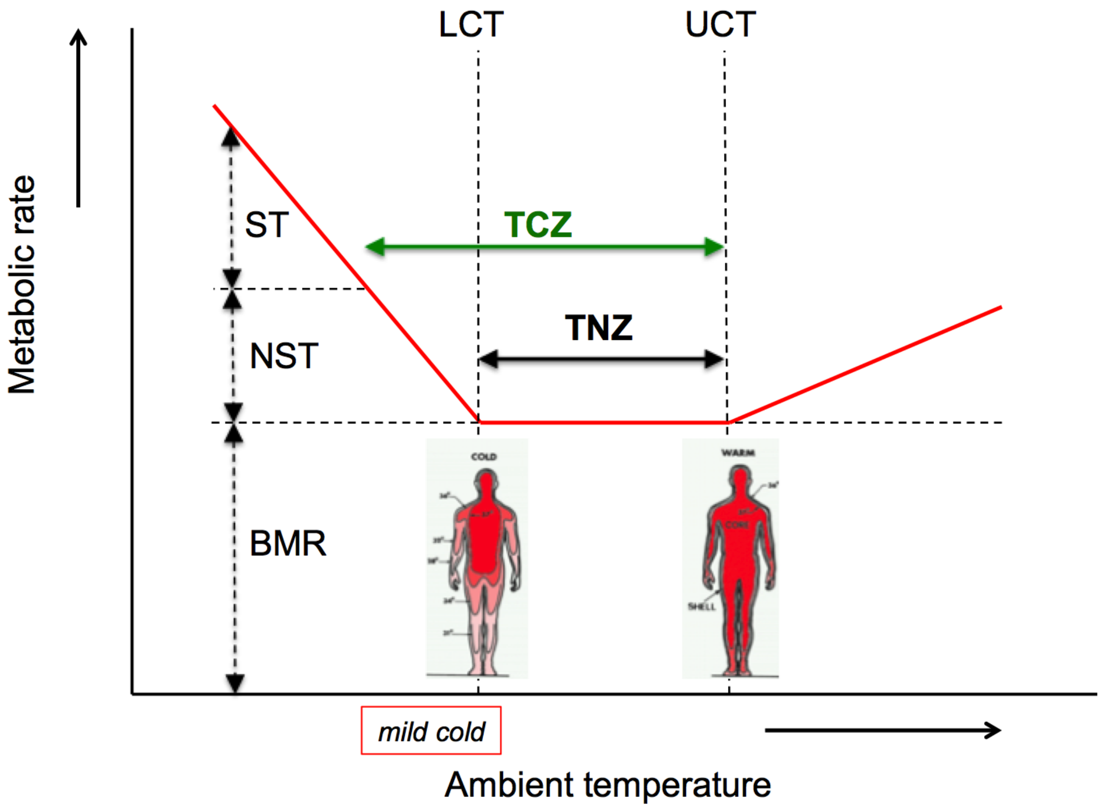


Figure 1. Thermoneutral zone and thermal comfort zone (after (van Marken Lichtenbelt et al., 2014)) The thermoneutral zone (TNZ) is the ambient temperature range at which the energy expenditure is at basal level (basal metabolic rate, BMR) and the heat dissipation of the body is achieved by changes in peripheral perfusion. Below the lower critical temperature (LCT) nonshivering thermogenesis (NST) and eventually shivering (ST) takes places. Above the upper critical temperature (UCT) also increases in energy expenditure occur partly due to increase in heart rate. An important question is how the thermal comfort zone (TCZ) is related to the TNZ. The expected thermal comfort zone (TCZ) after acclimation is depicted. For clarity the sweat response in not indicated.

It is generally accepted that thermoregulatory *behaviour* is driven by a combination of thermal sensation and comfort (Schlader et al., 2009) (Gagge et al., 1967). Relations between thermal sensation and comfort and body temperature have also been described before. However, to our knowledge, no scientific report identifies the direct relation between thermoregulatory behaviour and body temperature. Nevertheless, in context of INTEWON we recently identified that thermal preference is highly correlated to thermal sensation (Figure 2) (Christel M.C. Jacquot et al., in press). Thermal preference is assumed a key factor for actual thermal behaviour and is used as a proxy for thermal behaviour. On top of that, the point at which participants indicate that a change in ambient temperature is required is bound within a narrow box of thermal preference (i.e. slightly warmer to slightly cooler) and thermal sensation (i.e. slightly cool to slightly warm) (Figure 2).

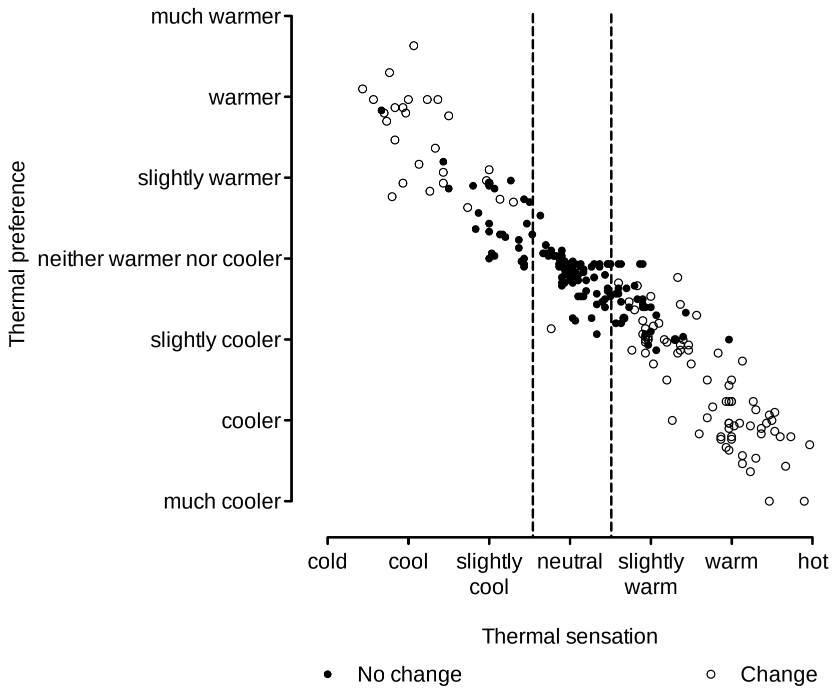


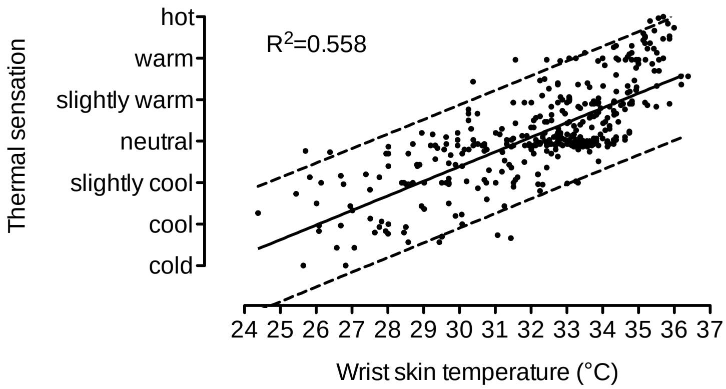
Figure 2. Correlation between thermal sensation and thermal preference with the requested change as an indicator of actual behaviour (open symbols: change, closed symbols: do not change, dotted lines: boundaries of the PMV-model for an acceptable thermal environment for general comfort)(after (Christel M.C. Jacquot et al., in press)).

3 Categorization

In the study by Jacquot et al. we have identified, based on the individual neutral thermal sensation range, three of the potential four different categories of persons regarding thermal preference:

- Broad range preference
- Narrow temperature range
- Cool preference
- Warm preference

By using these categories the correlation between skin temperature measurements and reported thermal sensation is significantly improved (Figure 3).



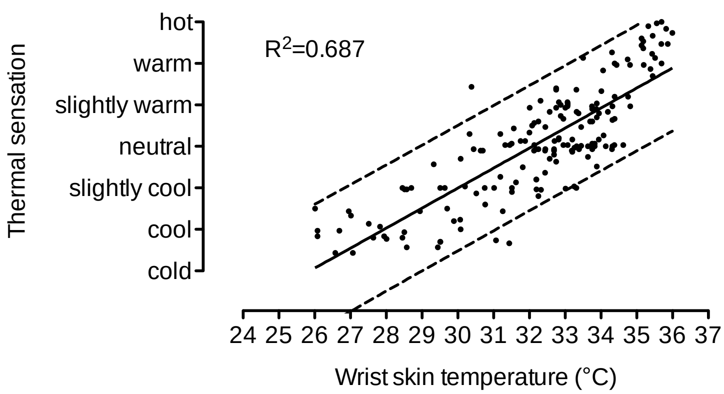


Figure 3. Correlations between wrist skin temperature and thermal sensation with the regression line and the prediction intervals ($P<0.001$) for all the subjects together (A); and for a subgroup categorized as broad range preference subjects (B).Note that despite a reduced number of data point the regression coefficient is higher due to restriction to one category (from (Christel M.C. Jacquot et al., in press))

The results also show that skin temperatures were significantly related to the intention of thermoregulatory behaviour. The latter was obtained by adding a separate question to the standard comfort and sensation scales. Importantly, the results indicate that categorization of the subjects in at least two classes (narrow ambient temperature range preference, broad ambient temperature range preference) improves these correlations substantially. For reliable and accurate predictions of thermoregulatory behaviour in the built environment such a categorization seems to be crucial.

4 Thermal acclimation

A possible explanation for the existence of categories can be individual differences in temperature acclimatization. Recently we performed a 10 day cold acclimation study on the effect on energy metabolism and thermal comfort and sensation (van der Lans et al., 2013). After such relatively short period, the capacity for non-shivering thermogenesis (figure 1) increased significantly together with an increase in brown fat activity. Brown fat is a tissue that when activated produces body heat without shivering (van Marken Lichtenbelt et al., 2009). It is markedly different from white fat. It is mainly located in the neck region and along the spines. Instead of fat storage active brown fat consumes fat and then produces heat that can be used to maintain body temperature (non-shivering thermogenesis). Several studies indicate that is also plays a role in glucose metabolism. Therefore brown fat and NST may be beneficial for treatment and/or prevention of the metabolic syndrome (obesity/type 2 diabetes). Drifting temperatures inside buildings, therefore are not only energy efficient, but potentially also healthy (van Marken Lichtenbelt and Kingma, 2013). Interestingly, the experiments also revealed that cold acclimation in parallel with the increase in NST significantly increased comfort ratings (figure 4).

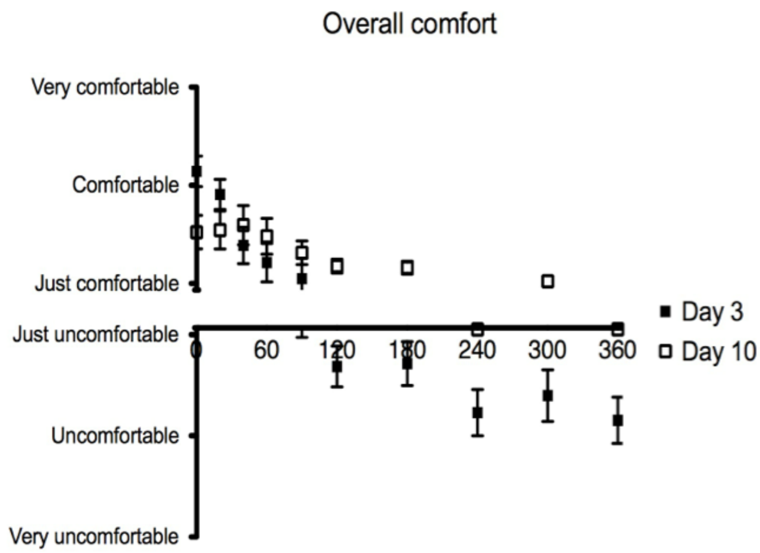


Figure 4. Graphical reflection of VAS scales; a higher sensation and thermal comfort and lower self-reported shivering were reported on day 10, as compared to day 3.
The incremental area under the curve decreased with 57%, 72% and 61% for sensation, thermal comfort and self-reported shivering respectively (p-values; <0.05, <0.01 and <0.01 respectively). This was tested with a paired samples t test. Values are expressed as means with SEM. Closed squares represent the 3rd day of acclimation (1st time 6 hours cold exposure), open squares represent the 10th day.(from (van der Lans et al., 2013)).

5 Discussion

The results indicate that the thermal comfort zone (TCZ) can vary and may increase relatively to the TNZ. In other words, the ambient temperature range wherein a subject is feeling thermally comfortable is larger compared to the TNZ. The magnitude of cold acclimation may determine the comfort category. How heat acclimation links to the TCZ is currently under investigation. In future research it is important to determine the boundaries of both TNZ and TCZ for the different categories, i.e. narrow range preference, broad range preference, cool preference and warm preference. Using categories can be helpful to make more realistic predictions of the energy use of buildings. Apart from the level of acclimation, it would be interesting to examine the existence of these categories in different groups of humans. It is likely that obese subjects

have a TNZ that is shifted to cooler ambient temperatures, while elderly are expected to have a relatively small TNZ (Kingma et al., 2012a). It is likely that an indoor climate with fluctuations in temperature (seasonal, but also daily or local) may positively affect peoples TNZ through mild acclimatization, thereby increasing comfort and health.
In conclusion, insight on thermal acclimatization and the use of categories based thermal preference may lead to better predictions of energy use and realistic calculations of energy consumption in the built environment.

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