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Energy efficient living - INTEWON: From measuring to modelling to managing

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ABSTRACT
In 2011, a Dutch multidisciplinary project was launched entitled "Individual-oriented information technology for energy efficient living" (INTEWON). It is a four-year study aimed at gaining more insight into the factors that determine the actual energy consumption of a household. It is a co-operation between the Maastricht University (physiology and knowledge engineering), Groningen University (human energy saving behaviour), Cauberg-Huygen engineering agency (energy calculations), and the University of Technology Eindhoven (energy technology and build environment). The purpose of the study is to obtain insight into the interaction between the individual comfort, the resulting behaviour and the techniques that enable energy efficient behaviour. It is a study in which technical, physiological and social research work together. The experiments are currently being conducted and here we report pilot data on the interaction between thermal physiology and thermal behaviour. In part I, experiments are described that are carried out in a specially designed indoor climate facilities at Maastricht University. In the laboratory the environmental conditions can be accurately prescribed whilst continuously monitoring behaviour and physiological parameters such as energy expenditure and skin temperature. In part II a novel numerical model for prediction of thermal behaviour using a Bayesian approach is described.

KEYWORDS
Thermal sensation, Physiology, Mathematical modelling, Thermal Behaviour, Thermal Comfort

INTRODUCTION

In 2011, a Dutch multidisciplinary project was launched entitled "Individual-oriented information technology for energy efficient living" (INTEWON). It is a four-year

study aimed at gaining more insight into the factors that determine the actual energy consumption of a household. It is a co-operation between the Maastricht University (physiology and knowledge engineering), Groningen University (human energy saving behaviour), Cauberg-Huygen (engineering, energy calculations), and the University of Technology Eindhoven (energy technology and build environment).
Predicting the actual energy savings in both new and existing homes is increasingly important. Mortgage lenders want the mortgage limits to be based on actual living costs, where energy costs are explicitly considered. Tenants want to agree with energy conservation plans, but desire a guarantee to achieve the savings. It is not sufficient to consider the building related energy consumption only, which is related to a (non-existent) average inhabitant with an average need for comfort. The real energy consumption is determined by the climate, the building characteristics and installation, but also and to a large extent determined by the behaviour of residents.
Therefore, this study focuses on the individual residents within a high-tech environment. It addresses questions such as: how to consolidate the installation to the user? How can you inform the user in such a way that he/she uses as little energy as possible? How do you best take into account the physiological determined needs and health of the user? The purpose of the study is to obtain insight into the interaction between the individual comfort (thermal, but also the influence of light), the resulting (thermal and energy saving) behaviour and the techniques that enable energy efficient behaviour. It is a study in which technical, physiological and social research work together.
The results of the research will enable the development of innovative monitoring and control techniques. This can lead to energy savings and realistic predictions of energy use, taking into account comfort and health of the occupants. The experiments are currently being conducted and here we report pilot data on the interaction between thermal physiology and thermal behaviour. The paper is divided into two parts. In part I, experiments are described that are carried out in a specially designed laboratory at Maastricht University. In the laboratory the environmental conditions can be accurately prescribed whilst continuously monitoring behaviour and physiological parameters such as energy expenditure and skin temperature. In part II a novel model for prediction of thermal behaviour using a Bayesian approach is described.

PART I: PHYSIOLOGY AND THERMAL BEHAVIOUR

Body temperature is regulated through both autonomic mechanisms and thermoregulatory behaviour. Thermoregulatory behaviour is driven by a combination of thermal sensation and comfort (Attia, 1984). Autonomic mechanisms include shivering, sweating, skin vasomotion and changes in energy expenditure (heat production) (Arens et al., 2006, Cabanac, 1975, Guyton and Hall, 2000). The exact relationship between thermal sensation and/or comfort and behavioural thermoregulation remains enigmatic. Therefore, this study primarily aims to link physiological parameters, such as body temperatures, skin blood flow, and energy expenditure, with thermal behaviour, thermal comfort and thermal sensation. In climate controlled respiration chambers at the department of Human Biology subjects will be exposed to transient ambient temperatures. The subjects can express their desire to change ambient temperature (protocols A and B). However, this will not be rewarded. In a separate trail the actual change in behaviour will be measured (protocol C). Furthermore, subjects will be monitored at home (protocol D). The study started recently. Here we report on the protocols A and B and related pilot experiments.

PART I: EXPERIMENTAL METHODS

At the laboratory, participants are randomly stratified to the sequence of three experimental settings, each performed on a separate day. Protocol A is composed of a neutral to warm transition in ambient temperature (Figure 1A). The temperature is 22°C at the start and is gradually increased by 4 K/h to 30°C. Protocol B is composed of a neutral to cold transition in ambient temperature (Figure 1B). The temperature is 22°C at the start and is gradually decreased by 4 K/h to 14°C. These two protocols are designed to register the desire to change the environment.

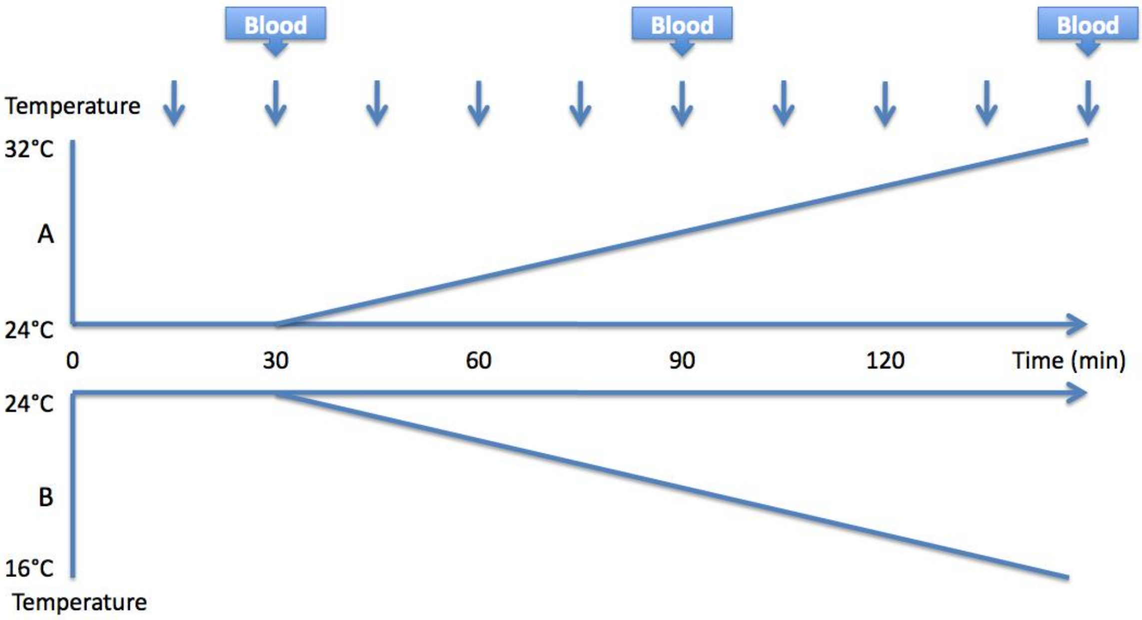

Figure 1: Timeline of the design of protocol A and B; the small arrows indicate the questionnaire that is being filled in, the rectangle shaped arrows indicate the collection of blood

During these protocols the subjects are dressed in standardized clothing (sweatpants, t-shirt and socks) and positioned on a chair behind a desk (total of 1 clo). They are asked to fill in a questionnaire for thermal sensation, thermal comfort and intended thermal behaviour every 15 minutes. Energy expenditure is measured using indirect calorimetry. Core temperature is measured using an ingestible temperature telemetry capsule. Skin temperature is measured at 16 sites, using wireless iButtons (DS1922L, Maxim, USA) (van Marken Lichtenbelt et al., 2006). Furthermore, ambient temperature and the relative humidity will be measured with these iButtons (DS1922/23, Maxim, USA) Skin perfusion is measured using laser Doppler flowmetry.

RESULTS

A pilot study was carried out to test whether the temperature transients in protocol A and B were adequate. In practise, protocol A and B were the same as describe above, however, the pilot was not carried out in the respiration chamber, but in an improvised climate chamber. Therefore the ambient conditions did not change linear over time. Energy expenditure was measured using a ventilated hood system with a mouthpiece (Omnical, IDEE, The Netherlands). For the pilot study two subjects were included.

One subject was exposed to the temperatures according to protocol A, where the temperature was increased from 22°C to 30°C (Figure 2 A1). During the trial mean skin temperature increased from 31.7°C to 33°C. Finger temperature remained stable (Figure 2 A2). There was no apparent change in energy expenditure. Thermal sensation and the desire to change the environment are in coherence, with opposite direction (Figure 2 A3 and A4). Moreover, at 90 minutes, the subject indicated that no change in ambient temperature was needed, which corresponds with the indication of being very comfortable (Figure 2 A4 and A5).

The other subject was exposed to the temperatures according to protocol B, where temperature was decreased from 22°C to 14°C (Figure 2 B1). During the trial mean skin temperature decreased from 32.5°C to 29.8°C and finger temperature decreased as well. In this protocol, energy expenditure increased from 5 to 6.5 kJ/min. Again, thermal sensation and the desire to change ambient temperature are in coherence, with opposite direction (Figure 2 B3 and B4). This is change coherent with the change in finger temperature (Figure 2 B5) and energy expenditure.

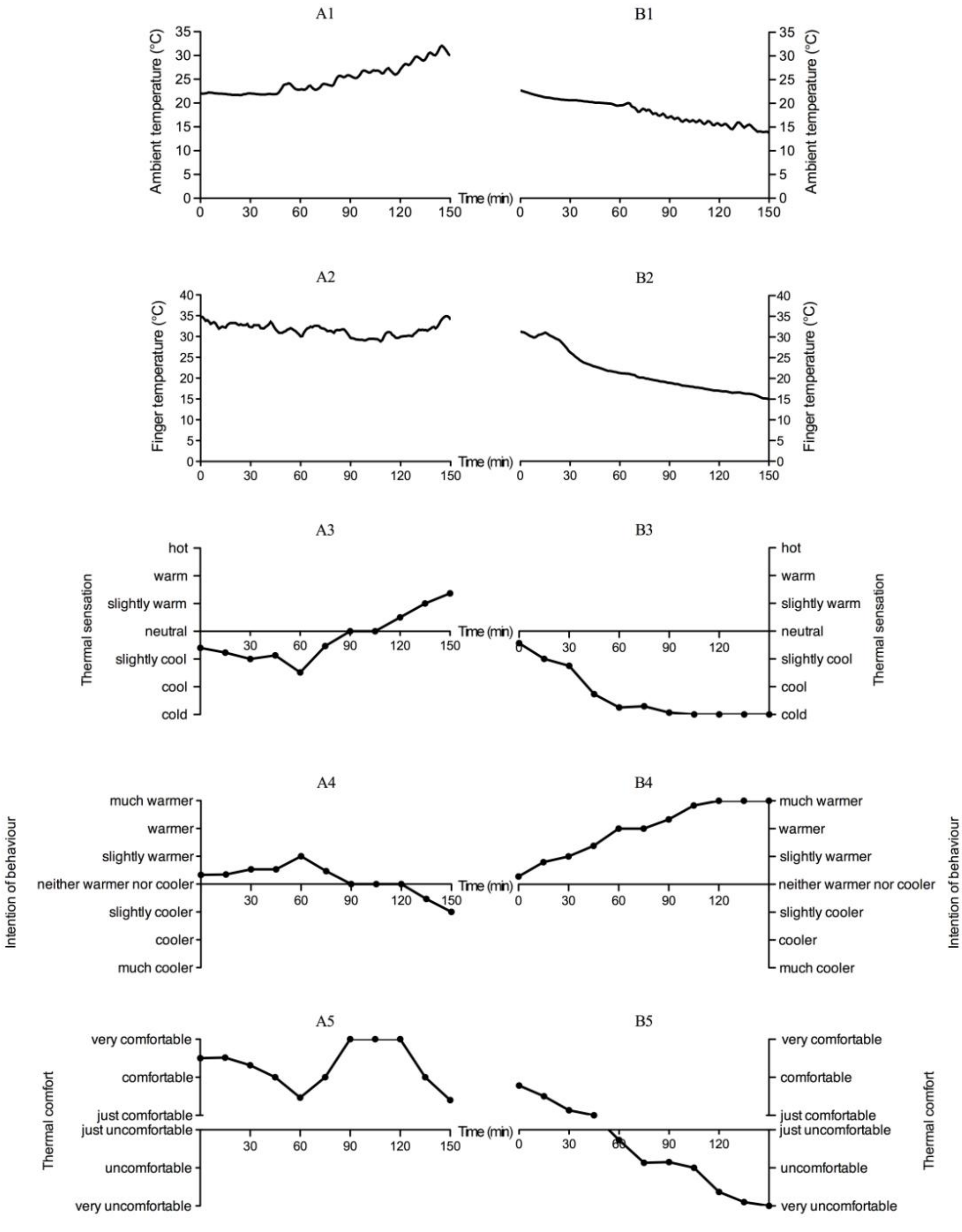

Figure 2: Change of different parameters during the pilot study. At the left the graphs of protocol A and at the right the graphs of protocol B. The first one indicating ambient temperature (℃), second finger temperature (℃), third thermal sensation, fourth desired change in environment and fifth thermal comfort.

DISCUSSION

The pilot study shows that thermal sensation is related to ambient temperature, finger temperature and skin temperature. Furthermore, there is a trend for an inverse relation between ambient temperature and the intention of behaviour. These findings are most obvious when ambient temperature decreased.

The design of the two protocols is considered adequate, although the ambient temperature at the start (22°C) seems too low, i.e. at baseline both participants reported thermal sensation below neutral (Figure 2 A3 and B3). Therefore, the start temperature of the experiments is increased to 24°C.

The results of the experiments will provide insight in the relation between thermal sensation and the physiology and health of residents. Moreover the obtained data will serve as input for a model for the prediction of thermal behaviour as described in Part II.

PART II: MODELLING THERMAL BEHAVIOUR

One of the branches of the INTEWON project is dedicated to modelling thermal behaviour. Here, the use of a probabilistic model is explored to estimate when a person will undertake action to modify its thermal environment. The novelty of the model is that it works from the perspective of the residents, in contrast to more traditional approaches that model thermal behaviour from the perspective of the environment. This novel approach potentially allows for optimal resource management in the built environment. Therefore the model could be of high benefit in new buildings.

MODEL DESCRIPTION

The model discretizes the states a person can be in; the person is either "Idle" or in "Action" (see Figure 3). Between time periods a person can switch states with a given probability. The focus of this study is on the transition probability from "Idle" to "Action". In simplest form, the probability being in state "Action" is equal to the amount of transitions observed from "Idle" to "Action" divided by the total amount of periods observed. In the example of Figure 3 this probability equals 33%. However, using information available of the individual residents could help to more accurately estimate the transition probabilities. In other words, it may be possible to estimate the probability of undertaking action given knowledge of the residents' conditions. For the physiological condition skin temperature of the finger is used. Finger temperature is considered as a proxy of the thermal state of the body; when finger skin temperature is low, the body tries to preserve heat, vice versa; when finger temperature is high the body tries to lose heat (Kingma et al., 2011). In Figure 3 an example of this process is shown. For instance, 1/7th of the observations finger skin temperature was 32°C, moreover, during all these observations the state of the resident was "Idle". Hence the probability of being in "Action" given a finger temperature of 32°C is negligible. Likewise, in case finger skin temperature was 30°C the probability of being in state "Action" is 50%, which is considerably higher than the *a priori* probability of 33%.
The hypothesis is that the transition probability is a function of the physiological condition of the person. The null hypothesis is that the transition probability is uniform over the physiological conditions. With this information the conditional probability for the transition from "Idle" to "Action" given a specific skin temperature is derived.

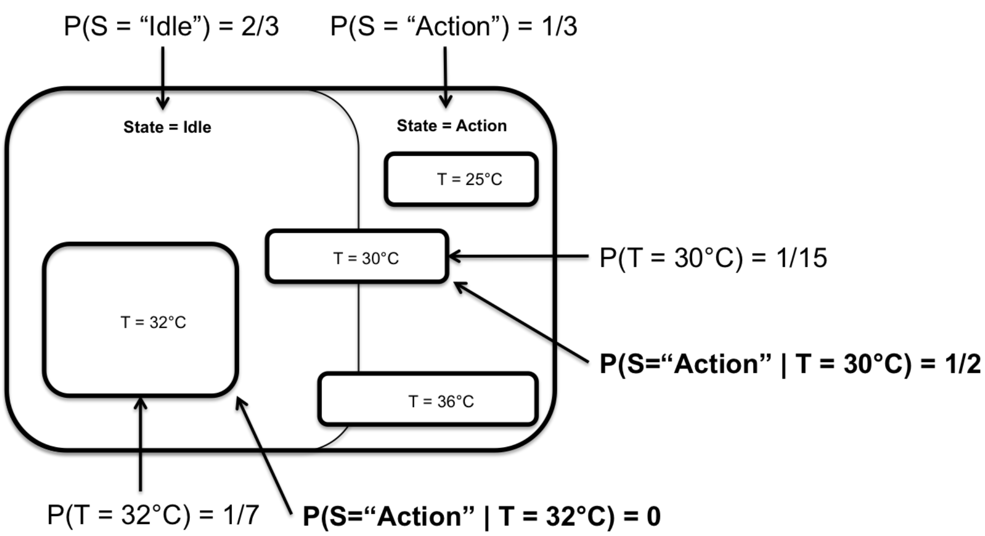

Figure 3: Schematic view of the model. A person can be an "Idle" state or in an "action" state. The surface area of the state indicates the relative distribution between states for a given individual. In this example 67% of the observations the individual was "Idle" and 33% of the observations the individual was in state "Action". The temperature blocks indicate the relative probability of occurrence. In this example for T=32°C this probability is 14%. The probability of being in state "Action" given a finger skin temperature of 32°C is equal to 0%.

The model requires *input* on the finger temperature (T_t), in degree Celsius; the model *output* is the probability that the user will undertake action given the specific finger skin temperature:

$$P(S_t = \text{"action"} \mid T = T_t) \quad (1)$$

The transition probability is estimated by using Bayes theorem (Bernardo and Smith, 2000):

$$P(S_t = \text{"action"} \mid T = T_t) = P(S_t = \text{"action"})\ P(T = T_t \mid S_t = \text{"action"}) / P(T = T_t) \quad (2)$$

Here $P(S_t = \text{"action"})$ is the *a priori* probability that a person will undertake action, $P(T = T_t \mid S_t = \text{"action"})$ is the conditional probability that a specific skin temperature is observed given that a person will undertake action and $P(T = T_t)$ is the *a priori* probability that a specific skin temperature is observed. The factors at the right hand side of Equation 2 are calculated as:

$$P(S_t = \text{"action"}) = \#(S = \text{"action"}) / (\#(S = \text{"action"}) + (\#(S = \text{"idle"})) \quad (3)$$

$$P(T = T_t) = \#(T = T_t) / (\#(T = T_t) + (\#(T \neq T_t)) \quad (4)$$

$$P(T = T_t \mid S_t = \text{"action"}) = \#(T = T_t \mid S_t = \text{"action"}) / (\#(T = T_t \mid S_t = \text{"action"}) + \#(T \neq T_t \mid S_t = \text{"action"})) \quad (5)$$

Here # stands for the count of observations.

RESULTS

Data of a pilot study (n=11) in which subjects could actually change the indoor temperature, was used to estimate the transition probabilities. During the pilot study subjects were dressed in a t-shirt and shorts and could choose to sit in either a cool room (Tair = 14°C) or in a warm room (Tair =35°C). Skin temperature was measured in 10-minute intervals using iButtons. The estimated transition probabilities are shown in Figure 4. ANOVA testing revealed that both distributions significantly differ from the uniform distribution ($p<0.001$ for change to cold environment and $p<0.010$ for change to warm environment). For comparison, the estimated *a priori* probability to "Change to cold environment" was $P(S_t$ = "Change to cold")=0.14 and the *a priori* probability to "Change to warm environment" was $P(S_t$ = "Change to warm")=0.11.

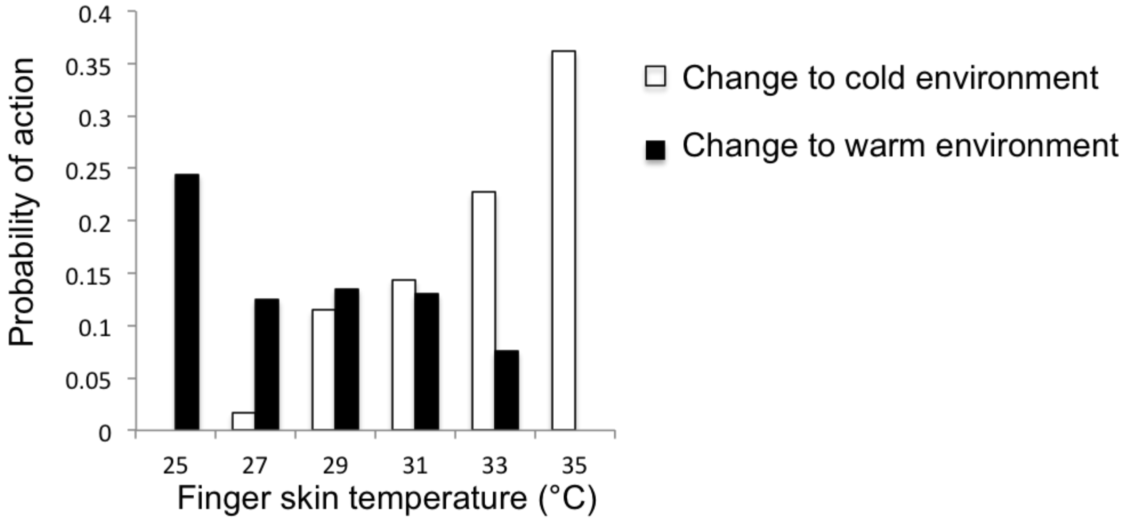

Figure 4: Estimated transition probabilities to be in state "Action" over a range of finger skin temperature.

DISCUSSION

The model developed in this study used information from the physiological state of the body (i.e. finger skin temperature) to estimate whether a person would perform action to change its ambient environment. In the near future, data from the experiments described in part I, will be used to validate individually attuned models. Apart from physiological input, future studies could also incorporate other variables that provide information on the inhabitant (e.g. time of day or season). Overall, the power of the presented model is that it is a tool to learn the behavioural characteristics of individual residents. This tool is useful in predicting when and where resources should be allocated to ensure residents well being and comfort.

GENERAL CONCLUSION

This paper describes the firsts steps of a multidisciplinary project on realizing energy efficient living. Although the experiments are still being performed, results from pilot data already show promising results on the usability of physiological parameters to predict individual thermal behaviour. In turn, this will help to understand the thermal needs of residents. The next step will be on the development of strategies for management of thermal and energy saving behaviour such that the thermal needs are satisfied in an energy efficient manner.

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