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The User as Sensor to Reach for Optimal Individual Comfort and Reduced Energy Consumption

DEREK VISSERS¹, WIM ZEILER¹

¹Technische Universiteit Eindhoven, Eindhoven, Netherlands

ABSTRACT. The occupants are the recipients of comfort and energy. How they are cared for is becoming more important for a technical service provider and owners, because perceived comfort affects directly the productivity of the workers of an organisation. Linking more functions to the HVAC process control system creates opportunities to further expand their influence on Comfort and Energy management and monitoring. A better match between energy demand and energy need leads to an improved overall efficiency, therefore the process control of the energy infrastructure in the buildings needs to become intelligent and capable of adaptable behaviour due to changing conditions. Especially is it important to take in account the goal of the energy use: human comfort. An experiment was done to determine the relation between local conditioning of sensitive body parts and perceived comfort by the occupants. With two advanced infra red cameras the skin temperature was registered and correlated to the perceived comfort by the user. The perceived comfort was derived from the adjustment of the electrical heating panel’s controls. This approach, to include the human as a sensor in the HVAC process control loop, makes it possible to optimize energy flows in a room in relation with the individual comfort of the occupant. By only optimal conditioning of the individual workspace, the rest of the room can be held on less strict indoor thermal conditions. This climate control strategy saves up to 30% energy while it optimizes the individual perceived comfort. The experiments performed were part of the proof of principle study to see whether it is possible to use the occupant as sensor for the HVAC process control. The experiments were there only done with one test person. Future experiments must be done with more persons to look for individual difference. Also different shapes of the infra red heating elements should be tested, as well as their applications on different places. This will enable to optimize the heating effect to the hands in relation to the perceived individual comfort. Dynamic individual local comfort control, using low cost wireless sensors and infra red cameras, can improve comfort-energy management on individual level.

INTRODUCTION

There is clear need for more energy efficient buildings. Normally the attention is on energy saving technical measures like insulation or high energy efficient heating, cooling or ventilation. However, the user influence on building performances increases strongly with low energy buildings. A better match between human comfort demands and energy demands is necessary for an improved overall efficiency. Therefore, the process control of the energy infrastructure in the buildings needs to become intelligent. This means that the process control becomes capable of performing adaptable behaviour in responds to changing environmental conditions and to different needs of the occupants. Especially, it is important to take in account more precise the goal of the energy use: human comfort. Well-being, health and productivity of office workers are highly related to the indoor thermal conditions. Due to individual human differences, it is not possible to satisfy the perceived comfort of all office workers with the same indoor thermal conditions [1]. There is clear need for more individualized provided thermal comfort. Recent studies on human thermal comfort have demonstrated that the human head and extremities (hands and feet) dictate overall comfort. In ‘cooler’ conditions the hands and feet are most sensitive, while under ‘warmer’ conditions the head is the most sensitive body part [2-4]. These results led to the development of individual controlled conditionings systems with local HVAC options for direct conditioning of specific body parts [5, 6]. By conditioning these body parts with a relatively low energy input, the room temperature could be allowed to be in a relatively wide range, resulting in energy savings up to 40% [7]. The benefits of an individual controlled climatization system are only fully achieved when the user can interact with it. User problems with individual temperature control can result in energy wasting behaviour, or can even result in thermal discomfort [8, 9]. To avoid energy wasting behaviour and maintain comfort level it is almost necessary that the local HVAC set points automatically adapt to the individual needs. This requires a method to include the human body as a sensor within the control loop of these local HVAC systems.

HUMAN-IN-THE-LOOP APPROACH

The part of the occupant behaviour on which we focus our research, is the adaptive actions of the occupants in response to thermal discomfort. We look at the human
reactions to environmental stimuli, in specific the occupants’ attempts to restore their comfort. The increasing importance of user behaviour on building performances is stated by Hoes [10], who concluded that user behaviour affects building performance more in case of a highly energy efficient building. Optimizing the energy efficiency of a building makes it necessary to take the user behaviour into account. An important aspect of user behaviour is the presence of the occupants within the building. It was observed by Madahvi that workplaces of office buildings are not occupied for a large percentage of time and is responsible for unnecessary energy consumption. Furthermore being present within the building is clearly a necessary condition for occupant to be able to interact with the building; control of solar shading, window deployment, control of the lighting, use electrical appliances and control of the thermal environment. Interactions between an individual human and the buildings’ environmental systems are difficult to predict as we do not know why an individual person performs an action. We only know that a building occupant performs these actions to improve his personal comfort level. And as such it is critical for an occupant to have the ability to self-regulate his environment. The aim of this research is to determine the possibilities for taking the human in the control loop of building comfort systems in office buildings.

According to thermoreception of the human body, the ideal sensing point is located in the human brain (hypothalamus). It is however unrealistic to sense this part of the human body. It is possible to measure the physiological responses to temperature variations of human skin. These responses reflect the energy balance between the human body and the environmental conditions. The hands are probably the most sensitive body parts for human thermoregulatory system [12]. In addition, the finger skin temperature and finger-forearm temperature gradient are highly sensitive indicators of body thermal state in the cool region [11]. The main idea is that the level of heating can automatically be adapted to the changed skin temperatures of these body parts, which are out of the comfortable range, before the user decides to take any control action due to perceived discomfort. Infrared thermography is applied to measure transient skin temperatures of face and hands. In this way we performed a non-contact measurement, with no hinder for office worker. This means that cool whole-body sensations can probably be recognized by a transition of the finger skin temperature out of the comfortable range. To prove the hypothesis that hand and facial skin temperature can be used as (feed-forward) control indicators experiments were done with a personalized radiant heating system in a slightly cold office environment, see Fig. 1.

**FIRST EXPERIMENT**

An experimental workplace set-up with two individual controlled electrical radiant panels was built in the Building Physics and Systems laboratory of the University of Technology in Eindhoven. The design is based on earlier research done by Filippini [5]. A simplified sketch of the microclimate set-up is shown in Fig. 2.
The objective of the measurements was to determine the correlation between the skin temperature variations of the face and hands, the local ambient conditions, and the radiant heating panel temperatures for a typical winter situation. The radiant panel temperatures are characterized by the control action of the user. One human subject (male) has participated several times in this research. The subject had the ability to influence his local climate by ‘easy understandable’ control options. The only intervention in the individual thermal climate was the use of individually controlled infra red heating panels. The panels were placed vertically in front of the office desk and therefore not optimized to heating the hands. Future experiments must be done with more test persons to look for individual difference. Also different shapes and locations of the infra red heating panels should be tested to optimize the heating effect to the hands in relation to the overall perceived individual comfort.

RESULTS FIRST EXPERIMENT: USER CONTROLLED THERMAL COMFORT

First experiments showed that the finger skin temperature is the most promising indicator to predict whole-body thermal sensations under slightly cool room conditions. These results are consistent to the findings of Wang [11] and Humphreys [13]. Facial skin temperature variations show however less correlation with the environmental control actions of the human subject. The goal of the user-controlled experiments (n=5 sessions) was to detect a feed forward transition out of the comfort zone, at time $t_x$, before the user took any control action at time $t_y$. First results show that this transition is quite difficult to detect. Standard fluctuations of 2 °C in finger skin temperature make it difficult to recognize a clear trend out of the neutral zone. Additionally, in some of the user-controlled experiments a decreasing trend in finger temperature is shown before the user had taken any control action (Fig. 3). While in other sessions the decreasing trend was recognized too late (Fig. 4), which means that subject already had taken a control action to compensate for his cool sensations. More experiments are needed to accept or reject the hypotheses.
which can transfer the radiation more concentrated to the specific body parts.

THE 2nd EXPERIMENT
To test the hypothesis that finger skin temperature can be used as control parameter for personalized heating a new experiment was performed. An improved heating system was applied which radiates the heat more concentrated to the hands. This heating system consists of two incandescent reflector heating lamps (Philips R125 IR250) focusing each on one hand. About 90% of the energy is transmitted as infrared radiation. At maximum temperature the heating lamps emit mostly in the IR-A and IR-B wavelengths. The sensitivity of the human skin is not equal for all wavelengths. As mentioned before consists the skin of different layers such as the epidermis and the dermis. All these layers have different light-absorbing characteristics.

The human skin is more sensitive to visible (0.3–0.7μm) and middle infrared (1.7–2.3μm) wavelengths then to near-infrared (0.8–1.35μm) [2]. This difference results from the wavelengths’ variable depth of penetration into the skin, relative to where the thermoreceptors are located. It can be seen that infrared radiation in the IR-B and IR-C ranges is absorbed in the top layers of the skin. Due to the low thickness of these layers a relatively strong heating effect can be achieved. The IR-A wavelengths have a greater penetration power. This means that the heat is dissipated in a larger skin volume. An electrical dimmer was used to vary the radiant heating intensity of the lamps. The heating system was controlled by using subject’s finger skin temperature (obtained by IR thermography) as control parameter. The control scheme is shown in Fig. 5 and the set-up of the experiment in Fig. 6.

During all cases, the basic room air temperature was set to 19.8°C, which is below the thermo neutral zone of the subject. The finger skin temperature was presumed to decrease.

When finger skin temperature reaches a predefined lower limit, local heating will be applied to subject’s hands. The IR heater will be switched off when skin temperature reaches the upper limit. Skin temperature is then allowed to drop, and can be used as control indicator again. The turn-on and turn-off temperatures differ significantly, to ensure that the influence on thermal sensations is large enough. The difference between the turn-on and turn-off temperature defines a certain bandwidth.

A thermal acclimatization time of 20 minutes was applied to ensure that the subject’s upper-extremity skin temperature was in the neutral zone (31-36°C) at the start of the session. The total duration of the experiment was 3.5h, see Fig. 8. The subjects wore office clothing resulting in a clo-value of 0.82, as in the first general proof of principle experiment. The face and hands of the test person were uncovered.

![Figure 6. Experimental setting to measure the effect of individual controlled additional radiative heating.](image)

A thermal acclimatization time of 20 minutes was applied to ensure that the subject’s upper-extremity skin temperature was in the neutral zone (31-36°C) at the start of the session. The total duration of the experiment was 3.5h, see Fig. 8. The subjects wore office clothing resulting in a clo-value of 0.82, as in the first general proof of principle experiment. The face and hands of the test person were uncovered.

![Figure 7. Experimental setting 2 with test person](image)

Real-time measurements of the upper-extremity skin temperature were performed using an infrared camera (FLIR ThermaCAM S65-HS) with a thermal sensitivity of 0.08°C at 30°C, a spatial resolution of 320x240 pixels, and a spectral range of 7.5-13 μm. ThermaCAM researcher has been used as data processing tool.

![Figure 8. Time schedule of the experiments.](image)
An MxN skin surface area has been selected at the 3th finger of the occupant’s left hand for measurement of the finger skin temperature. An example is presented in Fig.9, where skin temperatures are shown in a histogram along with the normal density spread. The mean local skin temperature (μ) has been used as control variable for the personalized heating system.

![Infrared measurement skin temperature](image)

**Figure 9.** Real-time control signal (μ) obtained from IR measurement of upper-extremity skin temperature.

Fig. 10 shows the results of the session in which finger skin temperature is again controlled in a small bandwidth. However in this session the influence of transitions out of the small bandwidth were examined on thermal sensation and preferences. The upper-extremity skin temperature is controlled in a small bandwidth (Fig. 10). In upper part, the primary vertical axis shows the moving average fingertip skin temperature measured by IR thermography. The secondary vertical axis shows if the hand-heating system was activated (1) or deactivated (0). The total power during activation was 95W. In middle part of Fig. 10, the overall thermal sensation (WB-TS) and local thermal sensation of the hands (TS-hands) are shown on the 7-point ASHRAE thermal sensation scale. In lower part of Fig. 10, the user preferences for a warmer, neither warmer nor cooler, or a cooler environment are presented. The mean environmental conditions and corresponding standard deviation (SD) are also included. To assess the thermal environment (without personal heating), the PMV is calculated according to the model of Fanger [14]. In addition, the mean skin temperature is included for comparison of the different cases.

When skin temperature fluctuated in the narrow band of 29-31.5°C, the thermal sensations remained about neutral (TS=0) and no additional heat was preferred. Immediately after the 1st transition out of the small bandwidth (t=55min), the local sensation dropped below neutral and extra heating was preferred. Remarkable is that the preference for extra warmth disappeared after a while (t=70min), when the skin temperatures were not yet in the small comfort bandwidth. Also after the 2nd transition the local sensation votes dropped below neutral and a warmer environment was preferred. From this it can be concluded that environmental control actions are needed when the finger skin temperature gets below the small comfort bandwidth. There for the local heating system has to respond before the lower limit of the comfort bandwidth is reached.

![Upper-extremity skin temperature controlled in a small comfort temperature bandwidth with two transitions out of the bandwidth. Fingertip skin temperatures (moving average) versus heating level, Whole-body and local thermal sensation, and heating preferences.](image)

**Figure 10.** Upper-extremity skin temperature controlled in a small comfort temperature bandwidth with two transitions out of the bandwidth. Fingertip skin temperatures (moving average) versus heating level, Whole-body and local thermal sensation, and heating preferences.
REDUCED ENERGY CONSUMPTION

The potential energy saving results from the fact that less energy is needed to condition the individual workplace instead of the entire room. To be able to calculate the possible reduction in energy demands the third floor of an existing office building was chosen. This was done because we had detailed enough information about that situation necessary to perform accurate calculations. In the reference case the room air temperature is controlled at 22.0°C by a central HVAC system and no personalized conditioning was applied. The energy saving potential is calculated for different ambient room temperatures. The minimum recommended basic air temperature is 19.5°C which gives a potential energy consumption reduction of 17%, see Fig.11.

![Figure 11. Potential reduced energy consumption](image)

DISCUSSION AND CONCLUSIONS

As the building occupant is the recipient of comfort and energy. How they are taken care for is becoming more important. Starting with the most important goal, providing comfort to the occupants, a new in depth approach to integrate perceived comfort of the occupants into the process loop of the HVAC systems was developed. We looked for critical comfort performance indicators. According to our experiments the finger skin temperature is the most promising critical comfort indicator to include in the-human-in-the-loop HVAC process control strategy. The finger temperature is highly sensitive for slightly cool office conditions. The change in the finger temperature correlates with the whole-body thermal sensations. To prove the hypothesis that the finger skin temperature can be used as a comfort control indicator for personalized heating, experiments were performed. Finger temperatures of a subject were held within a comfortable range of skin temperatures, while whole-body sensations and local sensation were surveyed. At this stage the experiments performed were only a proof of the principle; the effect of the changes in thermal indoor conditions was intensively tested on only one person. By taking the human in the control loop of building systems it becomes possible to apply a bottom-up approach process control strategy with the human as leading factor in the built environment. As indicated by calculations based on a real reference case the potential energy reduction is around 17%.

To achieve this potential reduction of energy demand, the building occupants need to be measured and monitored intensively. The technological development of low cost sensors should make that possible as well as affordable.

REFERENCES