An efficient thermal comfort delivery in workplaces

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***Abstract*—Prevailing mechanisms that deliver thermal comfort in workplaces are energy-hungry and yet provide a sub-optimal thermal comfort. Indeed, they are based on flawed premises and purposely ignore decisive precursors to thermal comfort. This research proposes to estimate a person's thermal comfort level from the fluctuations in his physiological signals and to use appropriate constrained optimization algorithms to provide an optimum and personalized thermal comfort using the least possible energy. The preliminary findings strongly suggest the feasibility and practicality of such an approach.**

***Index Terms*—personalized thermal comfort, humanized computing, smart building**

I. INTRODUCTION

Despite almost a century of research on thermal comfort, its provision is based on fundamentally flawed assumptions, achieves a lackluster performance and requires an excessive energy to operate [1, 2]. Indeed, thermal comfort is defined as "the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation" [3] —Thus, it is a personal psychological sensation and varies from a person to another. On the contrary, prevailing thermal comfort provision mechanisms are based on heat and energy transfer principles and prescribe stringent and narrow indoor air temperature ranges in order to provide a neutral environment (i.e, an environment in which people do not wish to be warmer or cooler) to all occupants. Nevertheless, there is credible evidence that people prefer non-neutral thermal conditions [4]. To further exacerbate the situation, it is believed that thermal neutrality is partially responsible for building-induced illnesses that are commonly known as sick building syndrome (SBS) [5]. Ergo, achieving thermal neutrality is only meretricious, energy wasteful and—to some extent—deleterious. Further, existing thermal comfort provision methods preclude many precursors to thermal comfort such as office occupants' personal psychophysics, their genders, their thermal adaptation, their physiological makeup, and their age differences. This results in an inadequate thermal comfort distribution.

Recently, there are worldwide policies to curtail agents of anthropogenic climate change that impose, inter-alia, strict reductions in energy use in buildings. These regulations, given the limitations of current thermal comfort provision technologies, can only aggravate the level of thermal discomfort in workplaces. Hence, as already asserted by many prominent researchers [1, 4–7], there is a need for a paradigm shift in the way thermal comfort is provided.

II. PROPOSED SOLUTION

This research proposes to provide thermal comfort based on a person's physiological response to his surrounding thermal environment. In fact, humans maintain their body core temperature via a thermal regulation process that is mostly controlled by the brain's hypothalamus, which serves as the "thermostat" of the body (Fig. 1). In a nutshell, the hypothalamus receives sensory inputs from thermo-receptors and initiate appropriate processes to keep constant the body's core temperature. For instance, when it is hot, the hypothalamus activates heat dissipating and body cooling mechanisms such as sweating and vasodilation. Conversely, when it is cold, the hypothalamus activates thermogenesis mechanism (e.g., shivering in skeletal muscle and heat generation in brown adipose tissues) and other mechanisms to reduce heat dissipation (e.g., cutaneous vasoconstriction and piloerection) [8]. The activity of thermoregulation can be indirectly monitored by e.g. the heart rate variability (HRV). There is indeed evidence that the very-low-frequency (VLF) band of the HRV power spectra mirrors thermoregulatory vasomotor control activities [9]. Furthermore, since thermoregulation affects eccrine sweat glands [8], we surmise that there might be a possibility to detect when people feel hot via e.g., their electrodermal activity (EDA).

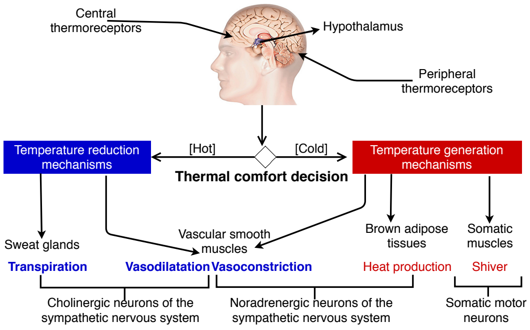

Fig. 1. A simplified human thermoregulation —the hypothalamus checks the body's core temperature and starts necessary thermogenesis or heat dissipating processes to maintain the body's core temperature.

Considering that thermal comfort is, by definition, a psychological sensation, and depends on the human thermoregulation, and given that thermoregulation activities induce detectable physiological changes, we hypothesize that thermal comfort state could be more accurately estimated based on the variation in the person's physiological signal (e.g., HRV and EDA). The detected thermal comfort state could thereafter be used to fully automate indoor air conditioning (Fig. 2). Our method presents three advantages. First, the provided thermal comfort would reflect the person's actual thermal comfort expectations. Second, it could be possible to significantly reduce the required thermal comfort provision energy by letting the indoor temperature drift away from thermal neutrality and adjust it only if people are about to feel thermally uncomfortable. Third, unlike existing systems that cool or warm an entire room, including its walls and furniture, and regardless of the number of people present, our approach takes into consideration that,

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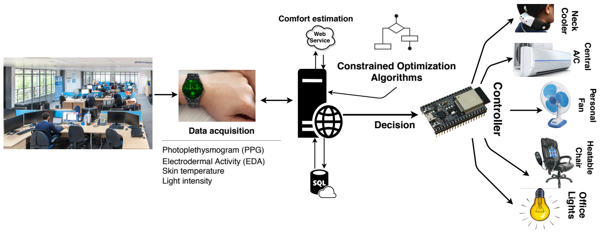

Fig. 2. Efficient thermal comfort provision in a workplace—A person's thermal comfort is estimated from his physiological signal. Thereafter, constrained optimization algorithms are used to activate suitable actuators to deliver an optimum and personalized thermal comfort using the least possible energy.

in uniform indoor environments, only a few body parts such as the head, the wrist, fingers, and feet are responsible for most of the thermal discomfort [10], to utilize a combination of centralized air conditioning and personalized thermal comfort provision systems in order to channel the thermal comfort to these parts of the body that are mostly responsible for the thermal discomfort. Therefore, our approach may result in a higher quality thermal comfort and would require less energy.

III. RESEARCH METHODOLOGY

Experiments will be conducted in seven different thermal chambers whose thermal settings correspond to a cold, a cool, a slightly cool, a neutral, a slightly warm, a warm and a hot sensation on the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) thermal sensation scale (Table I). In each experiment, physiological signals (ECG, photoplethysmography (PPG), EDA, and skin temperature) will be recorded simultaneously on human subjects. The recorded physiological signals will be used to train classification machine learning models that will be used to predict the thermal comfort. The provision of thermal comfort will be achieved by creating a microclimate comfort zone around a person or a group of people in which each individual's thermal comfort is estimated from a variation in his physiological signals due to his body's response to the surrounding thermal environment. After that, appropriate utility functions can be used to select the suitable thermal comfort provision methods to meet everyone's thermal comfort needs at the lowest energy (Fig. 2).

TABLE I
PROPOSED EXPERIMENT SETTINGS †

	cold	cool	slightly cool	neutral	slighly warm	warm	hot
air temperature (°C)	15	18	21	25	27	29	32
air speed (m/s)	0.1	0.1	0.1	0.1	0.1	0.1	0.1
humidity (%)	40	40	50	50	50	80	80
clothing level	0.57	0.57	0.57	0.57	0.57	0.57	0.57
PMV	-3.24	-2.28	-1.25	0.01	0.64	1.58	2.62

† The clothing are trouser, short sleeve, shirt, socks, shoes, underwear (SSU)

IV. COMPLETED WORK

Our preliminary published results [11] confirm our hypothesis. In summary, we observed that HRV is distinctively different depending on the thermal environment (Fig. 3) and that it is possible to reliably (with an accuracy greater than 90%) predict each subject's thermal state. We also developed a system that predicts, in real-time, the thermal comfort of a person based on a PPG signal recorded on his wrist [12] and showed that although both thermal comfort and work stress affect HRV, their effect on a person's HRV is perhaps non-overlapping and that the two can be distinguished with a 99% accuracy [13].

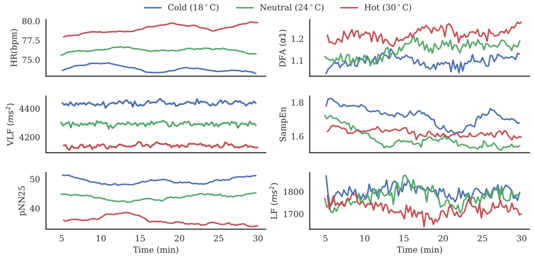

Fig. 3. Heart rate variability (HRV) indices distinctively change depending on the thermal environment.

V. CONCLUSION AND FUTURE WORK

Existing thermal comfort provision mechanisms are energy-intensive and yet provide an inadequate quality of thermal comfort. This research proposes to estimate people's thermal comfort based on changes in their physiological signals. The estimated comfort could thereafter be used to provide a personalized thermal comfort and to optimize the required energy. Our preliminary results indicate that thermal comfort states (cold, neutral and hot) can be reliability predicted from a person's HRV and that, although both thermal comfort and work stress affect HRV, their effect on a person's HRV is perhaps non-overlapping and that the two can be reliably distinguished.

Our future research will focus on refining our prediction models by collecting new physiological data in thermal chambers and to build a proof of concept system that will be used to validate, contrast and compare the merits our approach with existing thermal comfort provision methods.

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