Conceptual Design of a Collective Energy-Efficient Physiologically-Controlled System for Thermal Comfort Delivery in an Office Environment

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Abstract: Despite their high energy consumption, office thermal comfort delivery mechanisms perform poorly. The recently enacted environmental protection policies, which require a significant cutback in greenhouse gas emission, can only exacerbate this situation because, given the limitations of current thermal comfort provision technologies, a reduction in energy would translate into an increased thermal discomfort in offices. Hence, this dilemma entails alternative thermal comfort delivery systems that provide higher quality thermal comfort at lower energy. This paper proposes to use physiologically-controlled thermal comfort controllers to achieve this. It also discusses advantages of this novel approach, highlights potential unobtrusive thermal comfort biomarkers, and presents the necessary steps in designing such systems. Finally, the paper briefly discusses some of our preliminary results that showcase the feasibility of such a system.

Key Words: personalized thermal comfort, energy efficient design, human-centered design, building energy-saving technologies.

1. Introduction

Despite decades of research and the resulting progress [1], thermal comfort delivery in office buildings is still marred by inefficiencies both in terms of its quality and in the amount of energy it consumes. For example, in developed countries, buildings consume 20% to 40% of the total annual energy. The bulk of this energy is solely used to maintain thermal comfort [2]. Paradoxically, despite the dedicated energy resources, thermal comfort in buildings is lacking. In a survey of buildings in the US, Canada, and Finland, Huizenga et al. [3] found that only 11% of the surveyed buildings achieved the recommended thermal comfort satisfaction rate. These results concur with the findings of the International Facility Management Association (IFMA) [4] that pinpointed a high level of complaints about thermal discomfort in buildings.

Oddly, the low performance and the high-energy consumption is not surprising. Indeed, most thermal provision systems are based on Fanger’s predicted mean vote/predicted percentage of dissatisfied (PMV/PPD) model [5] that prescribes isothermal settings to all building occupants. Although the PMV/PPD model performs well when its assumptions are met [6], some of its premises are ignored [6],[7] in practice. Even then, by design, the model cannot provide a satisfying thermal comfort to all people [7]. The model also prescribes stringent and narrow indoor air temperature ranges to provide a thermally neutral environment to all occupants. This requires a lot of energy to achieve. Surprisingly, the rationale of thermal neutrality is contested as a meretricious endeavor since, in reality, people prefer non-neutral conditions [8]–[10]. Consequently, one could argue that achieving thermal neutrality is counterproductive and energy wasteful. Due to these limitations, researchers have proposed improved thermal comfort models. For example, adaptive models [6] allow wider indoor temperature ranges; thus, require less energy. However, they are based on oversimplifications and postulations that may lead to thermal discomfort [11]. Furthermore, like the static models, they ignore personal psychophysical and psychology idiosyncrasies that affect thermal comfort perception. In a bid to accurately predict people’s thermal response to their environment, many thermophysiological models have been developed [12]. They use mathematical models to predict thermal comfort based on human body and its thermoregulation [12],[13], and can be used to predict thermal comfort in various environmental conditions [14]. Nevertheless, these models are not widely used due to their applicability limitations and a lack of independent performance validations [12].

Recent awareness campaigns for a sustainable economy have led policymakers to enact energy reduction regulations. However, technological limitations seem to thwart this effort. For example, a mandatory energy saving policy, which was introduced by the Japanese government, resulted in an increased thermal dissatisfaction and a reduction in productivity [15]. Conversely, office workers and their managers expect superior quality thermal comfort for health and productivity. Thus, delivering higher quality thermal comfort at lower energy consumption is a conundrum that requires a different engineering approach [16],[17]. Researchers have suggested using personalized thermal comfort for quality thermal comfort provision [16],[18]. Unlike centralized systems, personalized ther-
Fig. 1 An illustrative example of a typical office cubicle. There are few people in rooms A and B. Thus, cooling or warming the entire room is a waste of energy. Instead, a personalized system could be used in conjunction with the existing air conditioning to provide a targeted and personalized thermal comfort to each occupant without compromising the quality of comfort while reducing the energy consumption.

Personal comfort controllers can channel the thermal comfort to the parts of the body where it is needed the most. In their review, Vesely and Zeiler [18] underscore a 60% energy saving potential if personalized thermal comfort systems are used. What’s more, personalized systems provide higher quality thermal comfort by supplying fresh air directly to the respiratory zone. This improves one’s perception of the air quality [19],[20]. In actuality, however, personalized thermal controllers are not used. It is believed that, because current systems are manually controlled, they would be inefficient to use in real world situations [18]. This argument jibes with Peffer et al. [21]'s conclusion that most people do not know how to properly use their thermostats. Manually controlled personalized thermal comfort systems rely on the person to make the right adjustments. In practice, most people lack the necessary knowledge. To resolve this, researchers [17],[18],[22] have suggested integrating physiological parameters into the thermal comfort control loop.

This paper proposes a groundwork for a personalized thermal comfort delivery mechanism based on people’s physiological response to their surroundings, and discusses some of our preliminary results. The proposed approach makes it possible to create a physiologically-controlled personalized microclimate comfort zone around a person or a group of people in an office environment. Each occupant’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 most suitable thermal provision methods to meet everyone’s thermal comfort needs at the lowest energy. The proposed approach provides the following benefits over existing methods:

1. Heating, ventilation, and air conditioning (HVAC) systems cool or warm an entire room, including its walls and furniture, and regardless of the number of people present. This approach is energy-inefficient, especially when only a few individuals are present in a large room. For example, in rooms A and B (Fig. 1), warming or cooling the entire rooms is not economical because there are few people in the rooms. In this case, a personalized thermal comfort via a warmed chair, an under the desk foot warmer and a neck cooler could be used to reduce the energy consumption without compromising the thermal comfort. On the other hand, in room C, using a personalized thermal comfort system alone for each person may consume more energy than necessary. In this case, a combination of a centralized air conditioning unit and a personalized thermal comfort system may provide an optimum thermal comfort at the lowest energy.

2. HVAC systems cool or warm a whole body of the person. This scheme does not necessarily provide the optimum thermal comfort. 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 [23]–[25]. Thus, spending more energy on these parts of the body may prove useful than trying to provide thermal comfort to the entire body. Hence, this approach may provide better thermal comfort and reduce the energy consumption.

3. There is a trend of over-cooling in summers and warming in winters [26],[27]. For example, in its survey, the U.S. General Services Administration reported that 40% of the surveyed buildings were colder than the recommended air temperature, resulting in an estimated annual waste of 18.7 million kWh [27]. The proposed system would be automatically controlled based on people’s physiological response to the environment and would potentially improve thermal comfort prediction accuracy and avert the overcooling and over-warming.

4. As suggested by Kaczmarczyk et al. [19], this approach may also reduce thermal monotony and comfort-related illness such as the sick building syndrome (SBS) that plague users in static and homogeneous thermal environments.
2. Proposed System

2.1 Potential Thermal Comfort Biomarkers

Human thermal comfort is a "condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation" [28]. Thus, it is a personal feeling, and its perception varies from one person to another [8],[10]. However, like other physiological processes, the perception of thermal comfort is regulated by the nervous system [29].

Humans homoiothermally maintain their body core temperature via complex thermal regulation processes that are under the command of the brain’s hypothalamus (Fig. 2). The hypothalamus itself receives thermal sensory input from thermal sensor receptors. These receptors transmit thermal sensation signal to sensory neurons in the dorsal root ganglia, which, in return, relay the received information to thermal sensory neurons located in the dorsal horn [30]. In hot environments, for example, the hypothalamus initiates different physiological processes (sweating, vasodilation, etc.) to increase heat dissipation; thus, cooling down the body. On the contrary, in cold environments, the body’s heat is conserved by reducing sweat production, vasoconstriction, and piloerection. Moreover, body heat can be produced via, e.g., shivering [30],[31]. These thermogenesis and cold-defensive mechanisms emanate from the skin’s thermoreceptors and are mediated by an identical pathways from the preoptic area of the hypothalamus [32]. In hot or cold environments, the conscious perception of temperature and unconscious mechanism to protect the body against extreme temperature fluctuation are synchronized by different neural pathways [30],[33]. Since thermal regulation is controlled by the nervous system, thermal comfort could be explicitly monitored by measuring the variation of the brain activities using, e.g., an electroencephalogram. This strategy, however, would be too quixotic to use in real world settings. Instead, the comfort could be implicitly monitored by recording the byproduct of the thermal regulation by way of other biosignals that are controlled by the nervous system. Furthermore, since the body’s heat is transferred via blood flow [34], heart rate variability (HRV) has been proposed as a good indicator of thermal comfort [29],[35]–[39]. In this study, we hypothesize that thermal comfort could be better predicted and provided using physiological signals. Alberdi et al. [40] give an overview of such physiological signals and highlight common features that are used to analyze them. In this paper, only unobtrusively measurable physiological signals are considered.

2.1.1 Electrocardiogram

The electrocardiogram (ECG) is a record of the electrical signal of the heart. It allows monitoring the time fluctuations of heart beats, i.e., HRV (Fig. 3). Various methods are used to extract HRV indices. These include statistical methods, spectral analysis, long and short-range correlation, complexity analysis, entropy and regularity analysis, nonlinear dynamic analysis, fractal and chaotic analysis, and many other approaches summarized in [41],[42].
2.1.2 Electrodermal activity

The Electrodermal Activity (EDA) measures the skin conductance variability due to sweat glands. The sympathetic nervous system (SNS) controls the secretion of skin sweat; thus, the EDA is believed a reliable measure of the autonomic sympathetic nervous system [43]. Like the ECG, the EDA signal can be unobtrusively recorded by electrodes [44]. Well-known EDA indices include the mean amplitude, the root mean square (RMS), and the standard deviation values.

2.1.3 Blood pressure

The blood pressure (BP) is a measure of the pressure of blood on the wall of the blood vessels. It is unobtrusively recorded using a stethoscope. The SNS control the BP at rest and in response to external environmental stimuli [45]. Common BP indices are the mean, the standard deviation, the peaks, and the systolic and diastolic blood pressure values.

2.1.4 Blood volume pulse

The blood volume pulse (BVP) measures the variation in the blood volume in vessels. It is clinically used as a non-invasive method to assess the cardiovascular systems. It can also be used to monitor hypertension and human sexual arousal [46]. The BVP can be recorded unobtrusively by photoplethysmography sensors [47].

2.1.5 Skin temperature

The skin temperature (ST) is an important and a proven indicator of thermal comfort [25],[48],[49]. It is one of the six metrics included in the PMV/PDD model. The mean, maximum, minimum, and the standard deviation values are some of the indices that have been used to study ST variation.

2.1.6 Respiration signal

The central and peripheral nervous systems play a significant role in controlling both the volitional and involuntary respiration [50]. Accurate respiration signal can be measured using a pneumotachograph. This approach is, however, intrusive. Alternatively, the respiration signal can be recorded using other non-invasive methods [51]. It can also be estimated from an ECG signal [52]. To analyze the respiration signal, researchers have used the mean respiration rate, the standard deviation, the root mean square, the spectral energy, the respiratory central frequency, the respiration time, and the respiratory pause (Fig. 4) [40],[53].

2.2 Conceptual Design

A practical physiologically-controlled thermal comfort delivery system requires an unobtrusive continuous monitoring of the various thermal comfort biomarkers. This could be achieved by using sensors embedded in already used office objects such as chairs and tables. Additionally, the system could take advantage of wearable sensors embedded in consumer products such as smartwatches and fitness devices. The proposed system (Fig. 5) would contain the following interdependent sub-systems:

1. **Physiological signal recording** —The physiological signals (ECG, EDA, ST, BVP, etc.) are recorded using unobtrusive sensors embedded in office objects and in other wearable devices. This stage is critical to the performance of the entire system because the quality of physiological signals is susceptible to inaccuracies.

2. **Signal processing** —In real world settings, signals are easily corrupted by Nyquist noises, electromagnetic noises, and other interferences that distort the recorded signal. These noises should be removed by suitable filters before being used.

3. **Data fusion** —The recorded physiological signals come from different sources and under different recording methods. The principal objective of data fusion is to extract relevant information from two or more signals and to combine them into one signal that provides a systematic description of the recorded data in a way that would not be otherwise achieved by an individual signal [54].

4. **Feature extraction** —Extraction of the relevant physiological descriptors discussed in Section 2.1.

5. **Thermal comfort prediction** —The extracted physiological indices could be used as input to a machine learning model to estimate the comfort level of each occupant. For example, in our previous study [55], we developed a machine learning model that could predict thermal state (cold, neutral, and hot) with up to 93.7% accuracy.

6. **Personalized thermal comfort provision** —After predicting and estimating the thermal comfort level (step 5), thermal comfort is provided using a personalized set of devices. This would create a micro-climate around that person. For optimum performance, the cooling and warming would be localized to a few body points (such as the neck, the wrists, and feet) that influence most thermal comfort perception.

7. **Energy optimization** —There is no need to cool or warm an entire room (Fig. 1) when there are not enough people
present. Instead, a combination of personalized and centralized comfort systems could be used to minimize the energy consumption. To this end, constrained optimization algorithms may be used to minimize the energy consumption with respect to the number of room occupants, their comfort expectations, and, if applicable, the battery level of their comfort providing wearable devices (Fig. 6). Distributed control algorithms may also be used to ad-

Fig. 5 A simplified depiction of the proposed system’s subsystem pipeline.

Fig. 6 Schematic of the proposed energy-comfort optimization system: comfort level of each user is estimated from his/her physiological signals to optimally adjust thermal comfort at lower energy.
just the various thermal comfort actuators. This approach would also help in reducing energy peak demand, which is a major problem for electricity suppliers. This could be achieved by automatically charging battery-powered comfort devices when the electricity peak demand is low so that they can be used when the electricity peak demand is high.

3. Preliminary Study

The long term objective of our ongoing research is to assess if and how physiological signals discussed in Section 2.1 could be used to predict thermal comfort level. This study is limited on HRV and respiration signals which are used to assess how they are affected by the variation of the thermal environment and to identify how this is correlated with thermal comfort levels.

3.1 Material and Method

3.1.1 Experiment protocols

We conducted experiments on 17 healthy male subjects (age: 22.35 years ± 1.08 years, weight: 59.75 kg ± 7.78 kg, BMI: 20.07 ± 2.26). Before the experiment, the subjects were requested to abstain from eating, drinking coffee, smoking or doing extensive physical exercise at least 2 hours before the start of the experiment. We conducted three experiments for each subject in three types of environments, whose thermal settings correspond to a cold, a neutral, and a hot thermal sensation on the PMV index scale. All experiments were conducted between 9:00 a.m. and 6:00 p.m. to account for the change in circadian rhythm in heart rate variability due to the time of the day. We recorded the electrocardiogram (ECG) and the respiration signal were recorded at a sampling rate Fs = 1000Hz using a multichannel wireless system (WEB-7000, Nihon Kohden, Japan) and saved to a computer for further processing. The ECG was obtained using electrodes attached to each subject’s chest. The experiment lasted for about 30 minutes. At the end of the experiment, the subjects were requested to fill out a post experiment survey about their thermal sensation using a 0 to 10 visual analog scale (VAS) index.

3.1.2 Feature extraction

The two recorded signals were processed as follows:

1. The ECG signal was filtered by a bandpass finite impulse response (FIR) filter (3 Hz to 45 Hz), and the inter-beat (RR) interval (IBI) signal is extracted from a raw ECG using the Pan and Tompkins [56] algorithm. The heart rate (the number of heart beats per minute) was calculated from the RR signal.

2. From the RR interval signal, we computed the pNN50, pNNx is an HRV index that measures the percentage of consecutive RR interval pairs that are greater than 50 milliseconds (Eq. (1)).

\[
pNNx = \frac{1}{N-1} \sum_{i=1}^{N} |R_{i} - R_{i+1}| > 50.
\]

In cardiology, pNN50 is believed to measure the cardiac tone modulation [41].

3. From the respiration signal, we extracted the respiratory center frequency, the breath time, and the respiratory pause time.

3.2 Thermal Comfort Level Quantification

The transfer entropy (TE) [57] was used to establish a relationship between the respiration signal, the pNN50 and the level of thermal comfort. TE is a measure of information exchange between two systems and helps in obtaining qualitative insights into the structure of the two systems. It can be used to distinguish information shared by the two systems by ignoring inter-signal static correlation [57]. For two process X and Y, the entropy rate measures the required additional information to represent the next observation. The entropy rate measures the supplementary information required to represent the signal if a new point Xn+1 is added to the original signal. If the new signal is independent of the signal Y, the entropy rate is expressed by conditional probability (see Eq. (2)).

\[
E_{1} = - \sum_{X_{n+1},X_{n},Y_{n}} p(X_{n+1},X_{n},Y_{n}) \log \left( p(X_{n+1}|X_{n},Y_{n}) \right).
\]

When the next observable value depends on the previous observation Yn, the previous equation (Equation (2)) is simplified as

\[
E_{2} = - \sum_{X_{n+1},X_{n},Y_{n}} p(X_{n+1},X_{n},Y_{n}) \log \left( p(X_{n+1}|X_{n}) \right).
\]

The transfer entropy TE is a difference between the two equations.

\[
TE = \sum_{X_{n+1},X_{n},Y_{n}} p(X_{n+1},X_{n},Y_{n}) \log \left( \frac{p(X_{n+1}|X_{n},Y_{n})}{p(X_{n+1}|Y_{n})} \right). \tag{4}
\]

The expression in Equation (4) is asymmetric and can be expressed in two equations. The transfer entropy from X to Y and from Y to X are given by equations (5) and (6) respectively.

\[
TE_{X\rightarrow Y} = \sum_{X_{n+1},X_{n},Y_{n}} p(X_{n+1},X_{n},Y_{n}) \log \left( \frac{p(X_{n+1}|X_{n},Y_{n})}{p(X_{n+1}|Y_{n})} \right) \tag{5}
\]

\[
TE_{Y\rightarrow X} = \sum_{Y_{n+1},Y_{n},X_{n}} p(Y_{n+1},Y_{n},X_{n}) \log \left( \frac{p(Y_{n+1}|Y_{n},X_{n})}{p(Y_{n+1}|X_{n})} \right) \tag{6}
\]

In this study, to study the relationship between comfort and thermal comfort perception, we calculated the TE from the pNN50 to the respiratory pause time and the TE from the respiratory pause time to pNN50.

3.3 Results and Discussion

3.3.1 Heart rate variability

There is a noticeable change in HRV variability between the three environments. The probability density of the RR intervals shows that time difference between successive heart beats (the RR intervals) is highest in the cold environment and sharply decreases in the hot environment (Fig. 7). Unsurprisingly, the heart rate increases in the hot environment and decreases in the cold environment (Fig. 8). This is in line with previous studies that showed that the heart rate increases with an increase in temperature and is correlated with the metabolic rate [38] which is known to influence thermal comfort.

3.3.2 Transfer entropy

The transfer entropy (TE) was used to investigate the causal relationship between the respiration and the heart beat variability, and to
4. Conclusion

The need for efficient thermal comfort provision systems requires a different approach on how thermal comfort is estimated and how it is delivered. To solve this problem, in this paper, we advanced to use personalized and physiologically controlled thermal comfort delivery techniques. We presented a theoretical framework of how this can be achieved, and we surmised some potential physiological thermal comfort biomarkers that could be used as biomarkers of thermal comfort. We also suggested the necessary approach to designing such systems. Our preliminary study shows the potential to use heart rate variability as an indicator of thermal comfort, but further methodologically rigorous studies are needed to validate this. There is also a need to investigate the contribution of other physiological signals (EDA, BP, BVP, and ST) to thermal comfort and to assess which signals are the most useful in predicting the thermal comfort. Our future research will focus on tackling these issues and will culminate in designing, implementing and testing a physiology controlled thermal comfort system and in analyzing its feasibility and practicality.

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