Creative Construction Conference 2018, CCC 2018, 30 June - 3 July 2018, Ljubljana, Slovenia

Application of heart rate variability for thermal comfort in office buildings in real-life conditions

Santiago Fernandez^a, Ignacio Lázaro^a, Aitor Arnaiz^a, Gulben Calis^b

^a Intelligent Information Systems IK4-TEKNIKER Eibar, 20600, Spain

^b Ege University, Department of Civil Engineering, 35100 Izmir, Turkey

Abstract

In the context of building energy efficiency, occupants' preferences can be considered as a source of information complementary to those in traditional building management systems (BMS). The general availability of wearable devices in recent years has increased interest in this ecosystem of technologies, as well as in their practical applications and those that can potentially derive from them. This study aims at investigating the applicability of wearable heart rate sensors for evaluating aspects of mood associated to stress/comfort, and in particular in relation to thermal comfort. A procedure for data gathering and analysis is proposed and tested in an office building in real-life conditions. First results show that no clear pattern of comfort vs. discomfort can be observed in data during testing. In addition, some of the challenges of applicability of the technique in real-life conditions are discussed in the study.

© 2018 The Authors. Published by Diamond Congress Ltd., Budapest University of Technology and Economics
Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2018.

Keywords: Building management systems; energy efficiency; wearable device; heart rate variability; occupant comfort.

1. Introduction

Thermal comfort is an important criterion in design, operation and commissioning of commercial and residential buildings. Thermal comfort is stated as a key factor that affects not only comfort but also health and wellbeing, which hints at broader feelings or perceptions of satisfaction and happiness. However, building systems might not operate fully adequately due to increasing demand on maintaining occupant comfort. Today, most buildings and system components are designed based on the standards, which define the range of thermal environmental conditions acceptable to a majority of users. Given the fact that these systems operate according to code defined occupant comfort ranges, they might not necessarily reflect the real comfort levels of occupants. Recent studies show that thermal comfort standards, such as ASHRAE 55 [1] and ISO 7730 [2], underestimate the percentage of dissatisfied users in indoor environments [3, 4, 5]. Subsequently, occupants interact with building systems to ensure that their comfort levels are met. Therefore, occupants' satisfaction and preferences need to be considered as a complementary source of information in the operation of buildings.

To determine satisfaction, and thus, comfort levels of occupants, surveys are widely used to provide feedback with respect to thermal perceptions. However, low participation to the surveys might cause misleading results, and thus, wrong strategies to maintain comfort in buildings. Recently wearable devices have emerged as an alternative source for obtaining user comfort and state through monitoring Heart Rate Variability (HRV). HRV is the variability in heartbeat intervals, which corresponds to the time between successive heartbeats. HRV has been studied as a potential indicator of various clinical conditions [6] and user states as well as comfort, such as stress [7], mental strain [8], bipolar disorder [9], and others. Wearable devices have directly brought a large interest around the

potential applications of monitoring physiological parameters in a convenient and personalized way in sectors such as sports and health, among others.

This study provides an initial feasibility assessment for the applicability of wearable heart rate sensors for evaluating aspects of mood associated to stress/comfort, and in particular in relation to thermal comfort in buildings. An office building in Eibar, Spain was selected as a test bed and field studies were carried out to investigate the applicability of wearable sensors, and thus, HRV for obtaining user comfort in indoor environments. The following sections of the paper present the literature review, describe the case study, analyze the initial results and finally provide discussions and conclusion.

2. Literature review

Wearable devices have emerged as an alternative source for exploring user comfort and state through monitoring Heart Rate Variability (HRV). Recently, wearable devices are evolving very fast and some big companies are pushing great efforts on improving them. These devices incorporate new sensors for monitoring the health of the users and new methods for integration of the data provided in third parties' applications by means of standards in communication protocols like Bluetooth Low Energy or supplying aggregated data by means of a public API. Along with this interest, a renewed one has originated about the study of psychological human aspects using wearable devices, in particular from physiological indicators of arousal, stress, fatigue, etc., which can be linked to the field of affective computing. Concisely, affective computing studies the identification of emotions and mood and, thus, comfort of users by systems and devices [10].

Practical applications of the evaluation of psycho-physiological human aspects by systems and devices require various technologies. Wearable devices are attached to human body and are typically based on novel small sensor devices with efficient communication and energy consumption capabilities, for instance embedded in smart textiles, strap bands or wristbands. Many wearable devices connect to a gateway forming what is known as a body area network (BAN). The gateway is in many cases a smartphone, which also provides software application and interfacing capabilities. Often, the smartphone communicates with remote systems as well. These remote systems or cloud may provide long-term data, aggregated data, additional analysis and reporting, and potentially provide access to authorized parties, such as for example trainers or medical doctors advising the user. Software algorithms for data processing and interpretation are also one of the key technologies needed, see for example [11] for a review. In particular, physiological correlations of emotions and mood rely on models for their interpretation.

HRV is the variability in heartbeat intervals, which corresponds to the time between successive heartbeats. Heartbeat interval is called RR interval as well, since so called R peaks in an electrocardiogram (ECG) waveform are used as a signal of the occurrence of a heartbeat. Extraction of RR intervals from ECG may require substantial processing, especially due to the fact that some measurements are spurious (ectopic beats) or noisy. Normal beats are extracted and the intervals measured are called NN intervals. HRV measurements are derived from NN intervals. Extraction of RR intervals from photoplethysmography (PPG) waveforms obtained by optical sensors is a more recent research topic [12]. A joint European and North American Task Force published a paper with guidelines for measuring, interpreting and clinical use of HRV [13]. The paper includes a classification and recommendations on various measurements of HRV from NN intervals.

Various time domain methods such as statistical and geometric methods are described along with frequency domain methods. Some are simple calculations, such as the mean NN interval (MEANN) whereas others use statistical methods, involving calculations of variance, differences or proportions, such as the standard deviation of NN intervals (SDNN) or the square root of the mean squared differences of successive NN intervals (RMSSD). The third type of time domain method converts the series of NN intervals in geometric patterns and characterizes their properties. For instance, the HRV triangular index characterizes the density distribution of NN intervals by means of dividing the integral of the distribution by its maximum value.

Frequency domain methods distinguish between extracting short-term spectral components (typically five minute interval recordings) and long-term spectral analysis (twenty-four hours periods). The ratio between low frequency (LF) and high frequency (HF) components (LF/HF) are among the short-term components, whereas a long-term indicator is the slope of the spectrum obtained from a twenty-four hours interval. It should be noted that there are several existing tools for HRV analysis that implement HRV indicators, such as for instance Kubios (www.kubios.com) and HRVAS [14], among others.

HRV is related to the regulation of cardiac functions, and is responsive to modulations in sympathetic and parasympathetic nervous system. Due to this characteristic, HRV has been studied not only as a clinical tool [15] but

also as a potential variable, which is sensitive to various situations, such as stress [6] or thermoregulation. As an example, Flouris et al. [16] studied HRV data in cold-induced vasodilatation experiments through water immersions at 42°C and 12°C water temperature. Liu et al. [17] studied HRV using LF/HF ratio for air temperatures between 21°C and 30°C in a climate chamber under controlled conditions. The results show that LF/HF values are higher at discomfort level compared to comfort level. Some researchers studied HRV along with other measurements. Yao et al. [18] measured HRV, skin temperature and electroencephalography (EEG). Four ambient temperatures ranging between 21°C to 29°C were tested in a climate chamber. The authors concluded that there is a qualitative relationship between thermal comfort and the measurements. Xiong et al. [19] measured biochemical markers (interleukin-6 and heat stress protein 70), oral temperature, skin temperature, blood oxygen saturation, respiration rate, heart rate and heart rate variability. The experiment was carried out in a climate chamber containing two rooms connected by a door. Each room was kept at a different temperature, ranging from 5°C to 15°C, so that there was a temperature step when moving from one room to the other. The results show that interleukin-6, oral and skin temperature, HR and HRV could be potential indicators for the effects of temperature steps. Furthermore, a relationship between subjective perceptions and physiological measurements was observed based on the correlation analysis.

Besides personal comfort, benefits of this research on subjects' thermal comfort may be linked to novel devices [20], the development of alternative HVAC/building designs and even productivity [21]. However, existing studies in this domain are mainly conducted in climate chambers and, thus, there is a need to explore the applicability of HRV in real life conditions.

3. Materials

3.1. Test bed description

An office building, which is located in Eibar, Spain, is selected as the case study. Under the Köppen climate classification, Eibar is included in C zone and Cfb type, which is known as temperate oceanic climate with mild temperatures and warm summers. The tests were conducted in a large open space area (Figure 1), which is a shared office with desks. The room has 2043 m² floor area with 200 to 250 occupants daily. Heating and cooling is central and there is mechanical ventilation. The front wall of the area is covered with panels of glass from the floor to the ceiling. The roof stands out of the building floor, and thus, mitigates the effects of direct sunlight especially in the afternoon.

Fig. 1. Test bed setting: (a) image (b) floor plan of mid-section (c) floor plan

3.2. Methodology

The procedure devised regarding data processing and analysis is depicted in Figure 2. An ECG sensor on a chest strap is used to gather occupants' heart rate data, in particular the RR interval. Then, an analysis of the RR interval is performed and various HRV indicators are extracted. Next, data was aggregated and analyzed in terms of differences with respect to the previous day.

Fig 2. Procedure flow for utilizing HRV in real-life situations

In particular, data is gathered by the wearable device provided with an electrical sensor to record the electrical activity of the heart. The device has a software to obtain the signal of the specific values of Heart Rate and RR interval. Then, the data is published by the wearable device under the standard protocol “Bluetooth Low Energy” (BLE), using the Generic Attributes Profile – GATT [22] and more specifically by the profile related to the Heart Rate version 1.0 [23]. This means that any application that supports the “Bluetooth Low Energy” protocol and the Heart Rate Profile is able to get these data for processing as needed. Once the BLE application detects data under the Heart Rate Profile gets the data and publishes it onto a cloud service. The cloud service is in charge of two main tasks, the first one is storing the data received in a storage database and the second one is executing the analysis of the data collected for a specific period of time. Then, the data stored are utilized for further specific analysis and reporting.

In this study, short-term recordings are taken into account for analysis. Regarding HRV indicator computation, a five minutes period is selected according to the Task Force recommendations [13]. Before further calculations, from each period of RR data values those differing more than 20% with respect to the previous RR value in the series are removed. If a minimum number of data values are not preserved for calculation of LF/HF, the period is discarded and the HRV indicators are not calculated from that period [24]. Otherwise, the HRV indicators such as the following are computed:

- The mean of NN interval values (MEANNN).
- The standard deviation of the NN interval values (SDNN).
- The square root of the mean squared differences of successive NN intervals (RMSSD).
- The integral of the distribution of NN interval values divided by its maximum (HRV triangular index).
- The ratio between low and high frequency components of the NN interval series (LF/HF).

For calculating the LF/HF ratio, a cubic spline interpolation of the NN interval series is performed followed by re-sampling. Then, the data series mean is removed and a Hanning window is applied before computing the power spectral density (PSD). From the PSD, the low frequency component (LF) and high frequency component (HF) are calculated by means of integrating the PSD values within their respective limits. Finally, LF/HF ratio is calculated.

3.3. On-site measurements

Heartbeat data gathering can be done by means of several types of devices. To select the proper wearable devices to be used, there are some relevant criteria to be taken into account: accuracy, periodicity of monitoring and user comfort. The measurement accuracy is very important since the quality of measurement directly affects the quality of the signal analysis. The accuracy highly depends on two main factors: the type of sensor, which can be “red infrared light sensor”, “optical”, “contact sensors” and the part of the body where the sensor must be worn, which can be

“chest straps”, “arm”, “finger” [13]. The periodicity of monitoring is very important, because the data analysis requires a minimum set of data in order to guarantee the validity of the analysis conducted. The comfortability of the wearable device is very important for the success of the test, since the more comfortable the device is, the more the user is engaged in wearing the device.

There are several types of health monitors depending on the way of monitoring the signals, which can be either by continuous monitoring or by synchronization monitoring. Continuous monitoring sends multiple measures by second, providing a huge amount of data to be processed allowing a more complete set of data to get more precision in the analysis. Synchronization monitoring sends one measure per second, in the best cases. So, it is required to assess if this set of data is enough for the analysis.

In this study, HRV and RR intervals were measured via the “Zephyr Bioharness HxM Smart”, which is worn on the chest (Figure 2, left image). The device is selected due to its characteristics with respect to accuracy, periodicity of monitoring and quality of the data. The operating limits of the device are -10 to 50 °C and 5 to 95% with respect to indoor temperature and relative humidity, respectively. Data is gathered by the wearable device provided with an electrical sensor to record the electrical activity of the heart. The device includes a software library to obtain the signal of the specific values of Heart Rate and RR interval. In addition, a smartphone powered with Android operative system with an application that supports BLE has been developed for recording the signal and translate into data. The characteristics of the measurement system are presented in Table 1.

Table 1. Specifications of the test equipment.

	Parameter		
	Heart Rate	Transmit	Frequency
Measuring range	25 to 240 BPM	10 m	2.4 to 2.4835 GHz

Two subjects participated in tests from February to September 2017. Morning and afternoon sessions lasting two hours each were scheduled. It should be noted that participants were volunteers and were aware of the purpose and procedure of data collection. The procedure defined for the tests requires the users to carry the wearable devices under normal working conditions, and, thus, no special activity was defined for the tests. Accordingly, participants were conducting their usual office activities during the tests. These activities comprise working on a computer, reading/writing, thinking/analyzing, having meetings with colleagues, etc. It should be noted that occasional movements around the office are also included. In some cases, sporadic episodes were reported or provoked, regarding thermal stress or discomfort (e.g. feeling cold), wearing extra clothing that increases thermal insulation, or sustained proximity to heaters/coolers, as they may be useful for the analysis of deviations from normality. Descriptions of tests and reported sporadic episodes are listed in Table 2.

Table 2. Description of the tests

Test ID	Date	Duration (min.)	Reported sporadic episode
1	February 8 th , 2017	120	Feeling cold
2	May 12 th , 2017	120	Provoked hot feeling (Wearing extra clothing (thermic/winter shirts and a sweater).
3	September 14 th , 2017	60	Portable fan heater used to provoke a hot feeling.

4. Results

A procedure for further data processing is devised in order to aggregate data and oriented towards assessing normality and potentially providing warnings. For data aggregation, influence of the time of the day and intra-/inter-subject variability is considered. Regarding the influence of time of the day, it is known that heart rate activity presents a cyclic daily pattern. Therefore, the approach taken is that data collected is to be aggregated (mean value) and compared to data in the same time-frame of the day (i.e. morning hours). Regarding intra-subject variability, the variation (difference) of the aforementioned aggregated (mean) value at the same time-frame of different days is to be computed for each subject separately. In summary, the proposed methodology is to compute the differences of aggregated HRV values between different time periods for each subject separately, and to obtain an aggregate of the

overall trend for a building or room via the observed individual trends. When the trend departs from the average in the short-term (i.e. tentatively, two standard deviations from the data in the previous five days), a warning is issued.

Daily differences of two different subjects within four days in a week are illustrated in Figure 3. Data was gathered during morning hours. As can be seen, mean values are relatively steady, in spite of an important dispersion in point measures. It should be noted that the time-frame used for data aggregation was 30 minutes, in spite of potentially increasing daily variability in average values with respect to that showed in Figure 3, in order to assess any daily differences and warnings that may occur at the time of reported episodes and tests.

Figure 3. (a) Daily difference in RMSSD (b) LF/HF ratio

Since no clear differences or patterns were observed on aggregated data, the series of actual values of HRV indicators calculated every five minutes was analysed with respect to a number of relevant episodes and tests reported, looking for trends and changes in the value of the HRV indicators during those situations with respect to values in normal situations. However, no clear pattern of comfort vs. discomfort was observed in the data either for the episodes or tests reported. In particular, LF/HF ratio showed a constant trend before, during and after all episodes, including sporadic ones with hot or cold feeling (other HRV parameters showed a pattern similar to normal state sessions, which means that no sporadic episodes were reported).

Values for the HRV indicators in the sporadic episodes listed in Table 2, and also in a week with no reported or provoked episodes are shown in Table 3. For test IDs 1 and 3 in Table 2, values of the indicators are shown before, during and after the test. A whole session was spent on test ID 2, therefore the values of the indicators are shown for the testing day and for the day before the testing day. In Table 3, within test differences are not pronounced, maybe with the exception of higher standard deviation of SDNN and RMSSD in tests 2 and 3. There is a trend toward lower values in all indicators as the year advances (February (test 1), May (test 2), July (normal state week) and September (test 3)).

Table 3. Values of the HRV indicators

Test ID		MEANN (ms)	SDNN (ms)	RMSSD (ms)	HRV triangular index	LF/HF
1	Before	1072 ± 316	88 ± 69	53 ± 47	22 ± 11	3.2 ± 0.5
	During	1148 ± 316	95 ± 55	54 ± 38	25 ± 9	3.0 ± 0.5
	After	1155 ± 279	89 ± 39	51 ± 20	23 ± 10	2.9 ± 0.4
2	Day Before	912 ± 30	58 ± 19	46 ± 25	18 ± 5	0.7 ± 0.0
	Testing day	819 ± 30	56 ± 69	43 ± 53	13 ± 3	0.7 ± 0.0
3	Before	797 ± 0	23 ± 8	16 ± 0	10 ± 3	0.9 ± 0.0
	During	754 ± 7	38 ± 18	31 ± 28	11 ± 2	0.9 ± 0.0
	After	823 ± 4	28 ± 2	18 ± 3	10 ± 2	0.9 ± 0.0
Normal state week		843 ± 32	41 ± 15	24 ± 13	14 ± 4	0.8 ± 0.0

5. Discussion and Conclusion

In the context of building energy efficiency, this paper reviews the feasibility and potential of heart rate variability for assessing aspects of user state associated to stress/comfort, and in particular in relation to occupant's thermal comfort. Then, a procedure devised for usage of the technologies in real-life situations is presented and reports on performed tests are provided. The results lead to identify the challenges and potential of applicability of the technique in real-life situations, which are discussed below.

First finding is that a certain amount of variability on physiological data should be expected in real-life situations as compared to experiments performed in a laboratory under well controlled conditions, as found in the literature so far. Factors such as movement and others can cause variability in the data, which can have an effect on the potential to ascertain differences and trends, which then may appear due to changes in comfort level in the conditions studied, and on the potential to build alerts. Acclimatization, circadian rhythms, consumption of food/drinks, localization of climatization systems, individual physiology, age, fitness, sex may have some effect on comfort, and can be an argument in favour of more personalized thermal comfort designs [25]. Also, in favour of more personalized comfort strategies. Both the environment and individual differences represent a challenge in real-life situations. In this study, this challenge is approached by means of data aggregation mechanisms, which aim to normalise for individual differences and by looking at short term data for minimizing the impact in the analysis of potential modifications occurring in the environment and occupants.

Regarding the heart rate variability, some limitations in terms of lack of standard methodology, consensus and reliability have been discussed by researchers [7, 26, 27]. There is a certain overlap in terms of characterization of for example stress and comfort, and it is not yet clear which are accurate parameters. Studies on the use of additional sensors may potentially be beneficial as well in order to complement measurements such as HRV and to contribute to put additional factors in context in real-life situations.

Overall, during the usage of the solution proposed, notable dispersion has been observed in the HRV indicators, especially in time-domain indicators (MEANN, RMSSD, SDNN, HRV triangular index). For LF/HF ratio, it is plausible that data is stabilized when following the guidelines for testing (mainly following the daily period for testing and doing usual office activities). Therefore, a preliminary stage of data normality has been achieved in some cases. Nonetheless, no clear pattern of comfort vs. discomfort has been observed in data for the episodes or anomalous situations reported. Last, the very limited number of participants in the sample should be augmented to provide more concrete evidence concerning the validity of the measurement system with respect to the variability of the data registered in daily situations. In this sense a new test with a similar methodology but a broader basis (from 15 to 20 participants) is expected to be conducted at two different sites during next months.

Research on HRV and thermal comfort is currently alive in the state-of-the-art literature. A joint position statement by the e-Cardiology ESC Working Group and the European Heart Rhythm Association co-endorsed by the Asia Pacific Heart Rhythm Society presents advances on the HRV indicators [28]. More recently, further studies in practical application [29] and in laboratory experimentation and machine learning-based classification modelling [30] have been published.

Acknowledgements

This work has received funding from HIT2GAP “Highly Innovative building control Tools Tackling the energy performance gap” project of the European Union's Horizon 2020 research and innovation programme under grant agreement number No. 680708.

References

- [1] ANSI/ASHRAE Standard 55-2010: Thermal Environmental Conditions for Human Occupancy ASHRAE, Atlanta, GA, USA, 2010.
- [2] ISO 7730:2005(E): Ergonomics of the Thermal Environment-Assessment of the Influence of the Thermal Environment Using Subjective Judgment Scales, Switzerland, 2005.
- [3] G. Calis and M. Kuru, “Assessing user thermal sensation in the Aegean region against standards”, *Sustainable Cities and Society*, vol. 29, pp. 77-85, 2017. DOI: 10.1016/j.scs.2016.11.013
- [4] L.D. Pereira, D. Raimondo, S.P. Corgnati and M.G. da Silva, “Assessment of indoor air quality and thermal comfort in Portuguese secondary classrooms: methodology and results”, *Building and Environment*, vol. 81, pp. 69-80, 2014. DOI: 10.1016/j.buildenv.2014.06.008

- [5] S.P. Corgnati, M. Filippi and S. Viazzi, "Perception of the thermal environment in high school and university classrooms: subjective preferences and thermal comfort", *Building and Environment*, vol. 42, pp. 951–959, 2007. DOI: 10.1016/j.buildenv.2005.10.027
- [6] U.R. Acharya, K.P. Joseph, N. Kannathal, C.M. Lim and J.S. Suri, "Heart rate variability: a review", *Medical and Biological Engineering and Computing*, vol. 44, pp. 1031–1051, 2006. DOI: 10.1007/s11517-006-0119-0
- [7] D.H. Patil, G. Kumari, P. Daware, V. Shinde and A.P. Raina, "Stress detection using heart rate variability", *International Journal of Emerging Technology and Advanced Engineering*, vol. 5, issue 1, pp. 197–200, 2015.
- [8] M.L. Kinnunen, H. Rusko, T. Feldt, U. Kinnunen, T. Juuti, T. Myllymäki, K. Laine, P. Hakkarainen and V. Louhevaara, "Stress and relaxation based on heart rate variability: associations with self-reported mental strain and differences between waking hours and sleep", *Promotion of Well-Being in Modern Society*, p. 136–139, 2006.
- [9] M. Migliorini, M.O. Mendez and A.M. Bianchi, "Study of heart rate variability in bipolar disorder: linear and non-linear parameters during sleep", *Frontiers in Neuroengineering*, 4:22, 2011. DOI: 10.3389/fneng.2011.00022
- [10] R.W. Picard, "Affective computing", MIT Press, Cambridge, 1997.
- [11] R.A. Calvo and S. D'Mello, "Affect detection: an interdisciplinary review of models, methods, and their applications," *IEEE Transactions on Affective Computing*, vol. 1, pp. 18–37, 2010. DOI: 10.1109/T-AFFC.2010.1
- [12] W.S. Johnston, "Development of a signal processing library for extraction of SpO₂, HR, HRV, and RR from photoplethysmographic waveforms", M.Sc. Thesis, Worcester Polytechnic Institute, 2006.
- [13] Task Force of The European Society of Cardiology and The North American Society of Pacing and Electrophysiology "Heart rate variability: standards of measurement, physiological interpretation, and clinical use", *Circulation*, vol. 93, No. 5, pp. 1043–1065, 1996. DOI: 10.1161/01.CIR.93.5.1043
- [14] J.T. Ramshur, "Design, evaluation, and application of heart rate variability software (HRVAS)", M. Sc. Thesis, The University of Memphis, 2010.
- [15] J. Sztajzel, "Heart rate variability: a noninvasive electrocardiographic method to measure the autonomous nervous system", *Swiss Medical Weekly*, vol. 134, pp. 514–522, 2004. DOI: 2004/35/smw-10321
- [16] A.D. Flouris and S.S. Cheung, "Influence of thermal balance on cold-induced vasodilation", *Journal of Applied Physiology*, vol. 106., No. 4, pp. 1264–1271, 2009. DOI: 10.1152/japplphysiol.91426.2008
- [17] W. Liu, Z. Lian and Y. Liu, "Heart rate variability at different thermal comfort levels", *European Journal of Applied Physiology*, vol. 103, No. 3, pp. 361–366, 2008. DOI: 10.1007/s00421-008-0718-6
- [18] Y. Yao, Z. Lian, W. Liu and Q. Shen, "Experimental study on physiological responses and thermal comfort under various ambient temperatures", *Physiology & Behavior*, vol. 93, pp. 310–321, 2008. DOI: 10.1016/j.physbeh.2007.09.012
- [19] J. Xiong, Z. Lian, X. Zhou, J. You and Y. Lin, "Potential indicators for the effect of temperature steps on human health and thermal comfort", *Energy and Buildings*, vol. 113, pp. 87–98, 2016. DOI: 10.1016/j.enbuild.2015.12.031
- [20] G. Lopez, Y. Kawahara, Y. Suzuki, M. Takahashi, H. Takahashi and M. Wada, "Effect of direct neck cooling on psychological and physiological state in summer heat environment", *Mechanical Engineering Journal*, vol. 3, No. 1, 2016. DOI: 10.1299/mej.15-00537
- [21] R. de Dear, T. Akimoto, E. Arens, G. Brager, C. Candido, K.W. Cheong, B. Li, N. Nishihara, S.C. Sekhar, S. Tanabe, J. Toftum, H. Zhang and Y. Zhu, "Progress in thermal comfort research over the last twenty years", *Indoor air*, vol. 23, No. 6, pp. 442–461, 2013. DOI: 10.1111/ina.12046
- [22] Bluetooth specifications, Generic Attributes Profile (GATT), <https://www.bluetooth.com/specifications/gatt/generic-attributes-overview> [retrieved 2017-10-19].
- [23] Bluetooth specifications, Heart Rate version 1.0, <https://www.bluetooth.com/specifications/gatt> [retrieved 2017-10-19].
- [24] G.D. Clifford, "Signal processing methods for heart rate variability", Ph. D. Thesis, University of Oxford, 2002.
- [25] A.K. Mishra, M.G.L.C. Loomans and J.L.M. Hensen, "Thermal comfort of heterogeneous and dynamic indoor conditions – An overview", *Building and Environment*, vol. 109, pp. 82–100, 2016. DOI: 10.1016/j.buildenv.2016.09.016
- [26] G.D. Pinna, R. Maestri, A. Torunski, L. Danilowicz-Szymanowicz, M. Szwoch, M.T. La Rovere and G. Raczak, "Heart rate variability measures: a fresh look at reliability", *Clinical Science*, vol. 1, No. 13, pp. 131–140, 2007. DOI: 10.1042/CS20070055
- [27] G.E. Billman, "The LF/HF ratio does not accurately measure cardiac sympatho-vagal balance", *Frontiers in Physiology*, vol. 4, No. 26, 2013. DOI: 10.3389/fphys.2013.00026
- [28] R. Sassi, S. Cerutti, F. Lombardi, M. Malik, H.V. Huikuri, C.-K. Peng, G. Schmidt and Y. Yamamoto, "Advances in heart rate variability signal analysis: joint position statement by the e-Cardiology ESC Working Group and the European Heart Rhythm Association co-endorsed by the Asia Pacific Heart Rhythm Society", *Europace*, vol. 17, pp. 1341–1353, 2015. DOI: 10.1093/europace/euv015
- [29] H. Yoo and K. Chung, "Heart rate variability based stress index service model using bio-sensor", *Cluster Computing*, 2017. DOI: 10.1007/s10586-017-0879-3
- [30] K.N. Nkurikiyeyezu, Y. Suzuki and G.F. Lopez, "Heart rate variability as a predictive biomarker of thermal comfort", *Journal of Ambient Intelligence and Humanized Computing*, 2017. DOI: 10.1007/s12652-017-0567-4