Chapter

The Life^{2}Well Project: Investigating the Relationship between Physiological Stress and Environmental Factors through Data Science, the Internet of Things and Do-it-Yourself Wearables

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Abstract

This chapter reports a study conducted by students as an independent research project under the mentorship of a Research Scientist at the National Institute of Education, Singapore. In the Life^{2}Well Project (Learning at the intersection of AI, physiology, EEG, our environment and well-being) identical units of a wearable device containing environmental sensors (such as ambient temperature, air pressure, infrared radiation and relative humidity) were designed and worn respectively by five adolescents from July to December 2021. Over the same period, data from these sensors was complemented by that obtained from smartwatches (namely blood oxygen saturation, heart rate and its variability, body temperature, respiration rate and sleep score). More than 40,000 data points were eventually collected, and were processed through a random forest regression model, which is a supervised learning algorithm that uses ensemble learning methods for regression. Results showed that the most influential microclimatic factors on biometric indicators were noise, and the concentrations of carbon dioxide and dust. Subsequently, more complex inferences were made from Shapley value interpretation of the regression models. Such findings suggest implications for the design of living conditions with respect to the interaction of microclimate and human health and comfort.

Keywords: physiological response to microclimate, random forest regression analysis, the internet of things, citizen science, environmental sensor, wearables

1. Introduction

Climate change has been one of the most urgent problems to confront in the 21st century. The fifth report of the Intergovernmental Panel on Climate Change

(IPCC) confirms that human influence on the climate system is clear and growing, with impacts observed across all continents and oceans [1]. Climate change has been degrading the quality of life for every creature on Earth. Glaciers have shrunk, ice on rivers and lakes is breaking up earlier, plant and animal ranges have shifted and trees are flowering sooner [2].

From the United Nations World Urbanization Prospects in 2017, 4.1 billion people were living in urban areas [3]. This means over half of the world (56% in 2020) live in urban settings. Urbanization is happening rapidly and it also accounts for global climate change. The rapid and large-scale urbanization leads to severe land-use conversion and impacts ecosystem services [4]. The latter refer to the direct and indirect contributions of ecosystems to human well-being. With ecosystems being damaged, human well-being is also affected. In the context of this pressing problem, urban microclimate studies have been gaining prominence due to rapid urbanization [5].

A microclimate is a small area within the surrounding larger area with a different climate [6]. Any given climatic region therefore comprises many other types of microclimates, which vary in characteristics from the region as a whole. Because our planet in general is broadly conducive to life, we – as humans – have populated its land masses. Comparing the human scale to that of the various habitats in which we live, the difference of these scales means that changes in the climates of these habitats may disproportionately affect the conduct of our daily activities.

That is the reason why the authors felt compelled to explore the relationships between microclimate and our physical and mental well-being. It is self-evident that climate change has various effects on the well-being of a person. As human beings we are conscious and aware of our surroundings, and our responses to changes in microclimate may affect our emotions. To elaborate, climate change might precipitate changes to micro-climates to the extent that for those inhabiting these biomes, the changes might be detrimental to physical and mental well-being. For instance, a study by Liu et al. [7] concluded that "the increasing research interest in thermal comfort and health has heightened the need to figure out how the human body responds, both psychologically and physiologically, to different microclimates".

This chapter reports a study conducted by students as an independent research project under the mentorship of a Research Scientist at the National Institute of Education, Singapore. In the Life^{2}Well Project (Learning at the intersection of AI, physiology, EEG, our environment and well-being) identical units of a wearable device containing environmental sensors (such as ambient temperature, air pressure, infrared radiation and relative humidity) were designed and worn respectively by five adolescents from July to December 2021. Over the same period, data from these sensors was complemented by that obtained from smart-watches (namely blood oxygen saturation, heart rate and its variability, body temperature, respiration rate and sleep score).

Among others, our work was inspired by earlier work of [8], in which they concluded that modified urban microclimates have a deep impact on the comfort of inhabitants. Palme and Salvati lamented that while there have been various studies conducted on the effects of urbanization on microclimate and how microclimate has changed human health in efforts to redesign and restructure urban areas., there have been relatively fewer studies on the relationships between microclimate and human health and emotions.

We see one of the potential contributions of our work to be our use of self-designed, low-cost, wearable units for measuring microclimate. The relatively low cost of these wearables has positive implications on the affordance of scalability, and – consequently – on crowd-sourced citizen science in this as yet under-reported field of the relationships between microclimate and well-being.

2. Review of literature

2.1 The importance of microclimate

Microclimate has been defined as the suite of climatic conditions measured in localized areas near the earth's surface [9]. Microclimate includes environmental variables such as temperature, light, wind speed, and moisture. It has been critical throughout human history, providing meaningful indicators for habitat selection and other activities [10]. Regardless of the global biomes in which we live, it is specifically microclimate that our bodies respond to, and not to the descriptors of the respective climatic region as a whole. For example, farmers have long used localized seasonal changes in temperature and precipitation to schedule their agricultural activities. Microclimate directly influences ecological processes and reflects subtle changes in ecosystem function and landscape structure across geographical scales [11].

As an example related to human health, microclimate in urban areas affects our thermal comfort [8]. However, relationships between microclimate and biological processes are complex and often nonlinear. For example, plant distribution can be perceived as a function of light, temperature, moisture, and vapor deficit [10]. Therefore, just a subtle change in microclimate could cause detrimental effects on human emotions and health, aside from just thermal comfort.

2.2 Effects of urbanization on microclimate

Rapid urbanization, especially in developing countries, has led to large flows of migration to urban areas [12]. According to a 2021 report authored by the market research firm Statista, the degree of urbanization worldwide was at around 56% in 2020 [13]. With rapid urbanization, changes to the urban environment and climate are inevitable [14]. The rate of urbanization is very high and anthropogenic effects on the climate of Earth are difficult to predict.

At local scales, activities associated with land use and land cover changes and urbanization induce impacts such as changes in atmospheric composition in water and energy balances and changes in the ecosystem [15]. By definition, ecosystems are interconnected, therefore a small change in any component can result in non-linear effects elsewhere. For example, according to a study conducted by Xiong et al. [16] in 2015 on the influence of different air temperature step-changes on human health and thermal comfort, perspiration, eye-strain, dizziness, accelerated respiration and heart rate were all sensitive self-reported symptoms.

Due to global climate change and intensifying urban heat island effects, urban living environments have deteriorated, becoming increasingly detrimental to human thermal comfort and health, not only psychologically, such as in terms of thermal sensation, mood, and concentration, but also physiologically by way of, for example, sunburn, heat stroke, and heat cramps [7] They also cautioned that "global climate change and intensifying heat islands have reduced human thermal comfort and health in urban outdoor environments". Other studies on re-naturing cities have found that changes to urban microclimate can potentially exacerbate the risks of meteorological hazards such as heatwaves. Heat-related issues pose an impact not only to the environment but also lead to heat-related human health problems and in extreme cases, cause deaths [15]. This is only one aspect of how microclimate can affect humans.

3. Materials and methods

3.1 Collecting microclimate data

To collect microclimate data, a small portable device that could be worn on the waist was designed in order to measure the following ambient environmental conditions:

- Noise level
- Infrared radiation through light intensity
- The amount of dust
- Carbon dioxide concentration
- Temperature
- Relative humidity
- Air pressure.

In total, five such devices were built by the authorial team. Each device was worn by the first and second authors and by their adolescent peers. The devices measured 12 cm by 6 cm by 2 cm respectively, and contained a low-cost sensor for each of the preceding environmental variables listed, together with a battery with sufficient capacity to power the sensors over the course of a typical day. The device could be secured to a belt by two regular clothes clips.

Every 15 minutes, each device would automatically log its measurements in to a designated cloud-based spreadsheet. At the same time, the device would ping the nearest publicly-accessible weather station (as provided by the Singapore Meteorological Service) for the wind speed and wind direction prevailing at that time. **Figure 1** shows schematics of the components, and **Figure 2** shows an assembled device.

3.2 Collecting data on mental state and health

Biometric data was collected using three Huawei Honor Band 6 smartwatches and two Fitbit Sense smartwatches. Each smartwatch measured:

- SpO2: the oxygen saturation in blood, which is the amount of oxygen-carrying hemoglobin in the blood relative to its capacity; and
- Heart rate.

These two variables were used by both types of watches to generate a so-called stress score (the latter pertinent to waking moments and arbitrarily indexed from 1 to 100).

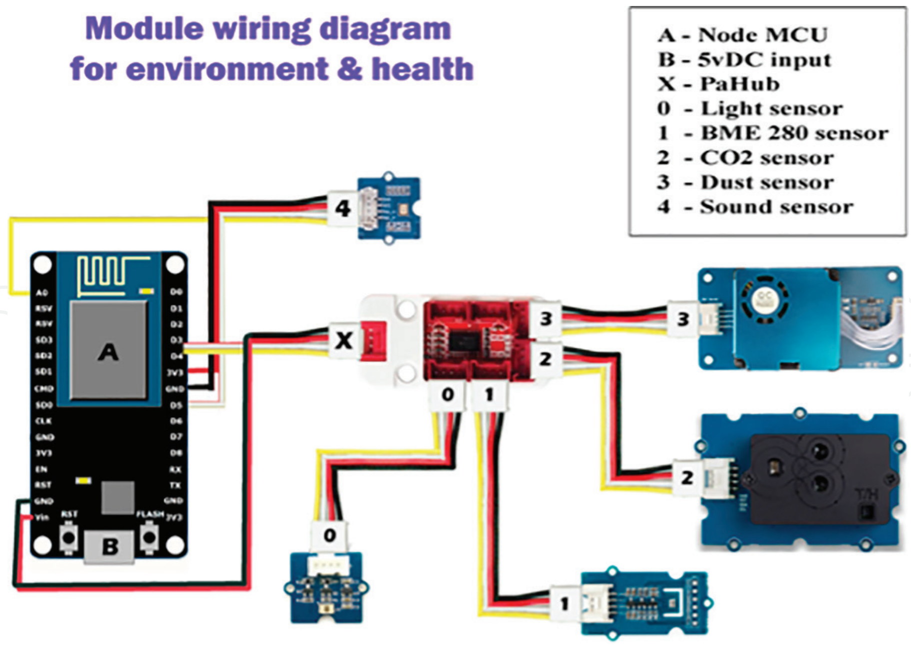

Figure 1.
Schematic of sensors for the wearable.

Figure 2.
Assembled wearable device..

In addition, the Fitbit Sense watches were able to measure:

- Skin temperature at the wrist (indicated as degrees Celsius off the baseline of core body temperature);
- Respiration rate (measured in breaths per minute); and
- Heart rate variability, which is the physiological phenomenon of variation in the time interval between heartbeats.

Heart rate variability was – in turn – indicated through the variables of:

- Root mean square of successive differences between successive beat-to-beat intervals (rMSSD)

- Low frequency, which indicates long-term variations in heart rate and reflects activity from both the sympathetic and parasympathetic branches of the autonomic nervous system; and

- High frequency, which indicates short-term variations in heart rate and reflects activity from the parasympathetic branch.

Finally, the Fitbits used the duration of deep sleep, resting heart rate, and restlessness while supine, to suggest a sleep quality score (indexed from 1 to 100). According to Fitbit, this sleep score takes into account sleep duration, sleep quality, and restoration.

As a proxy for the state of mind of the five participants during their waking hours, they voluntarily self-reported against a ten-point Likert scale twice a day, once in the morning and the other before sleep. In earlier work by [17], it has been recognized that there is a high degree of connectivity among the neural structures of the brain and its systems. Emotions and cognition, although having separate features and influences, are dialectic, integrated and co-mingled in the brain. It has been suggested that emotions play a central role in the evolution of consciousness, influence the emergence of higher levels of awareness and largely determine the content and focus of consciousness throughout one's lifespan [17]. As such, by attempting to explore the connections between participants' feelings and corresponding biometric data, we can perhaps glimpse how participants respond physiologically and affectively when they are in a specific microclimate.

Given this background, the self-report online form consisted of four questions. Two questions invited the five participants to report their emotional and physical health based on prevailing microclimate at the time, against a ten-point Likert scale, while the other two questions invited them to elaborate on their respective responses in prose.

4. Findings

In total 43,579 data entries are collected from July to December 2021; after cleaning, 43,434 data points were used. Reference values for carbon dioxide concentration are approximately 400 ppm, for PM2.5 dust 10 μg/m3 annual mean, and atmospheric pressure at sea-level is 1013.25 millibars (see, for example, [18–20]. From historical records, the diurnal temperature range of Singapore is 25 deg. C to 33 deg. C; relative humidity in the island nation ranges from 60–90% typically. From June to September, the climate of Singapore is influenced by the southwest monsoon, after which is the inter-monsoonal period of relatively weaker winds.

Data was analyzed using the Python libraries Sklearn and SHAP. Correlations were drawn based on a best-fit line graph between each respective microclimatic and biometric/well-being variable.

Random forest regression models were then performed. Random forest regression are supervised learning algorithms that use ensemble learning methods for regression. In turn, an ensemble learning method is a technique that combines predictions from multiple machine learning algorithms to make a more accurate prediction than a single model; in the case of the study reported, it used multiple regression models. Finally, outlier events were identified for subsequent investigation if necessary.

To measure the respective contributions of the various predictors (the microclimate variables) against the actual values, Shapley summary plots were generated from the training data. Shapley values can be thought of as the average of the marginal contributions across all possible permutations within a given model. Simply put, Shapley values decompose a prediction to show the impact of each feature, by showing how much each feature contributed to the overall predictions.

The sections below elaborate on the respective contributions of each of the microclimatic variables measured in this study to selected biometric indicators and indicators of well-being of interest. Within each section, a Shapley summary plot showing the contributions of the various microclimate variables to the given biometric/well-being indicator is presented.

In the Shapley plots, variables are ranked in descending order of importance, and the situation of each dot along the x-axis shows whether the effect of that value is associated with a higher or lower prediction. Simple exponential smoothing was used on the models. Each environmental feature had its smoothed counterpart with the format: "(feature)_", which was derived from values of that feature from preceding hours, with older values being exponentially less important than the current value. For example: for f(t), we have f(t-1), f(t-2), ... affecting it, but f(t-1) will be of more importance to f(t) than f(t-2), f(t-3),... exponentially.

The features "0", "1", ... "23" represent the hours of the day that data points were recorded, while "31" to "37" are days of the week (Monday to Sunday), which correspond to the time of recording of those data points. These features are binary, so 1 or high means true and 0 or low means false. For example, if a data point was recorded on 6 AM on a Monday then "6" and "31" would be 1 and the remaining binary features would be 0. Finally, the color shows whether that variable is high (red) or low (blue) for that observation. In this way, Shapley summary plots combine feature importance with feature effects.

5. Associative relationships of microclimate and physical health

5.1 Heart rate

Figure 3 shows the Shapley Summary Plot of the associations of microclimate with the variable 'heart rate'.

From **Figure 3**, the variable 'heart rate' is most strongly associated with the variable 'carbon dioxide concentration' (feature importance of 0.15), followed by the variable 'sound' (feature importance of 0.14) and by three variables which affects heart rate co-equally (feature importance of 0.08), namely 'ambient temperature', 'dust concentration' and 'air pressure'. From the above Shapley Summary Plot, the lower the carbon dioxide concentration, the lower the heart rate. As for sound, the higher the sound in the surrounding microclimate is, the higher the heart rate level. Similarly, the higher the pressure and dust concentration are, the higher the heart rate level while heart rate value decreases when ambient temperature increases. An interesting observation is that heart rate dropped from 5 pm onward.

5.2 Heart rate variability (rMSSD)

In the context of heart rate variability, rMSSD refers to the physiological phenomenon of variation in the time interval between heartbeats. **Figure 4** shows the Shapley Summary Plot of the associations of microclimate with this variable.

From **Figure 4**, the variable 'root mean square of successive beat-to-beat interval differences' ('rMSSD') is most strongly associated with the variable 'sound' (feature

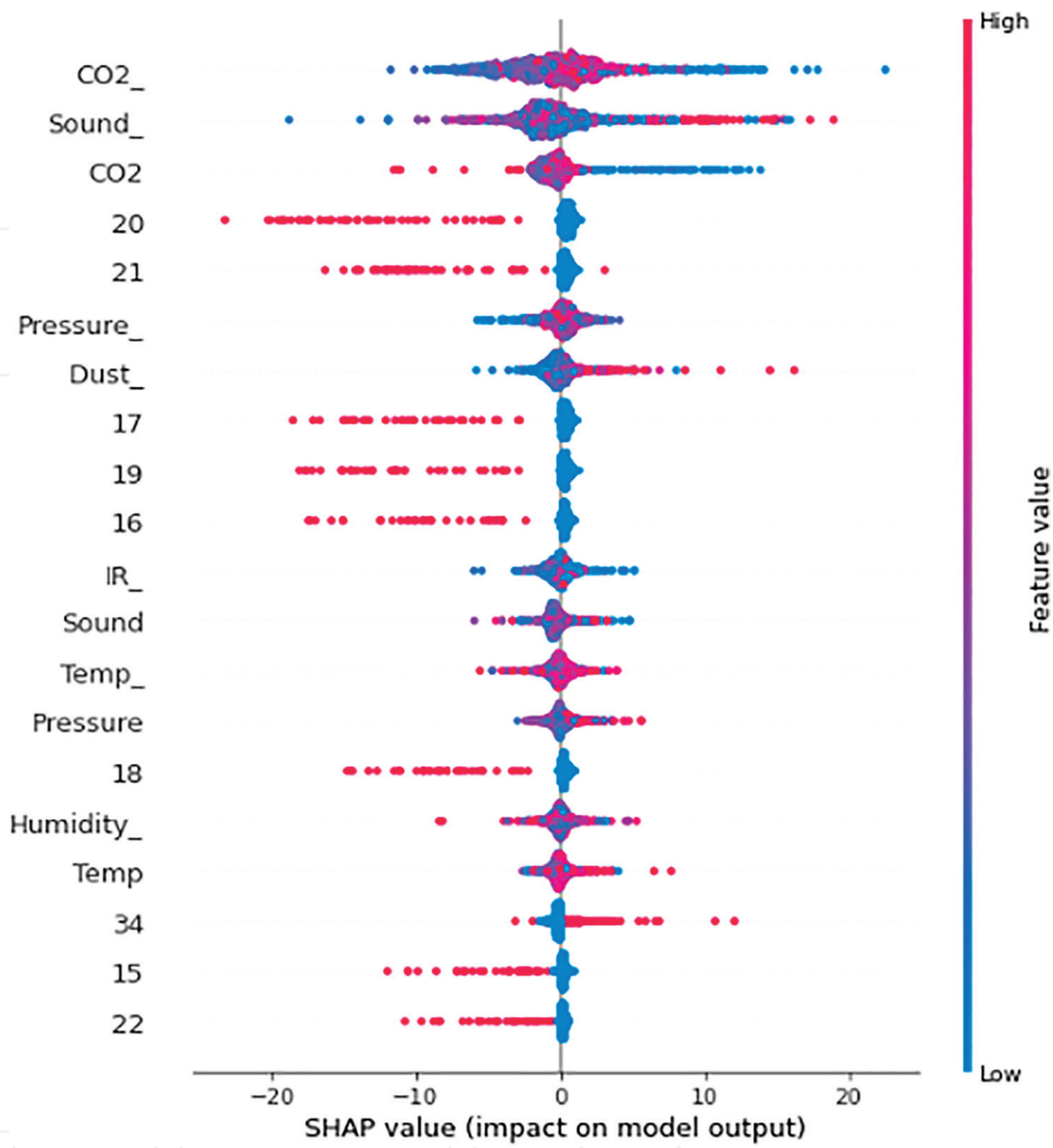

Figure 3.
Shapley summary plot of microclimatic factors and heart rate.

im-portance of 0.46), followed by the variable 'dust concentration' (feature importance of 0.09), then co-equally (feature importance of 0.07) by the variables 'ambient temperature' and 'wind direction'. From the above Shapley Summary Plot, the higher sound is, the lower the rMSSD is. The higher dust concentration is, the lower the rMSSD. Similarly, the higher the ambient temperature and the more westerly the wind, the lower the rMSSD.

5.3 Skin temperature at the wrist

Figure 5 shows the Shapley Summary Plot of the associations of microclimate with the variable 'skin temperature at the wrist'.

From **Figure 5**, the variable 'skin temperature at the wrist' is most strongly associated with the variable 'sound' (feature importance of 0.21), followed by the variable 'dust concentration' (feature importance of 0.13) and the variable 'ambient

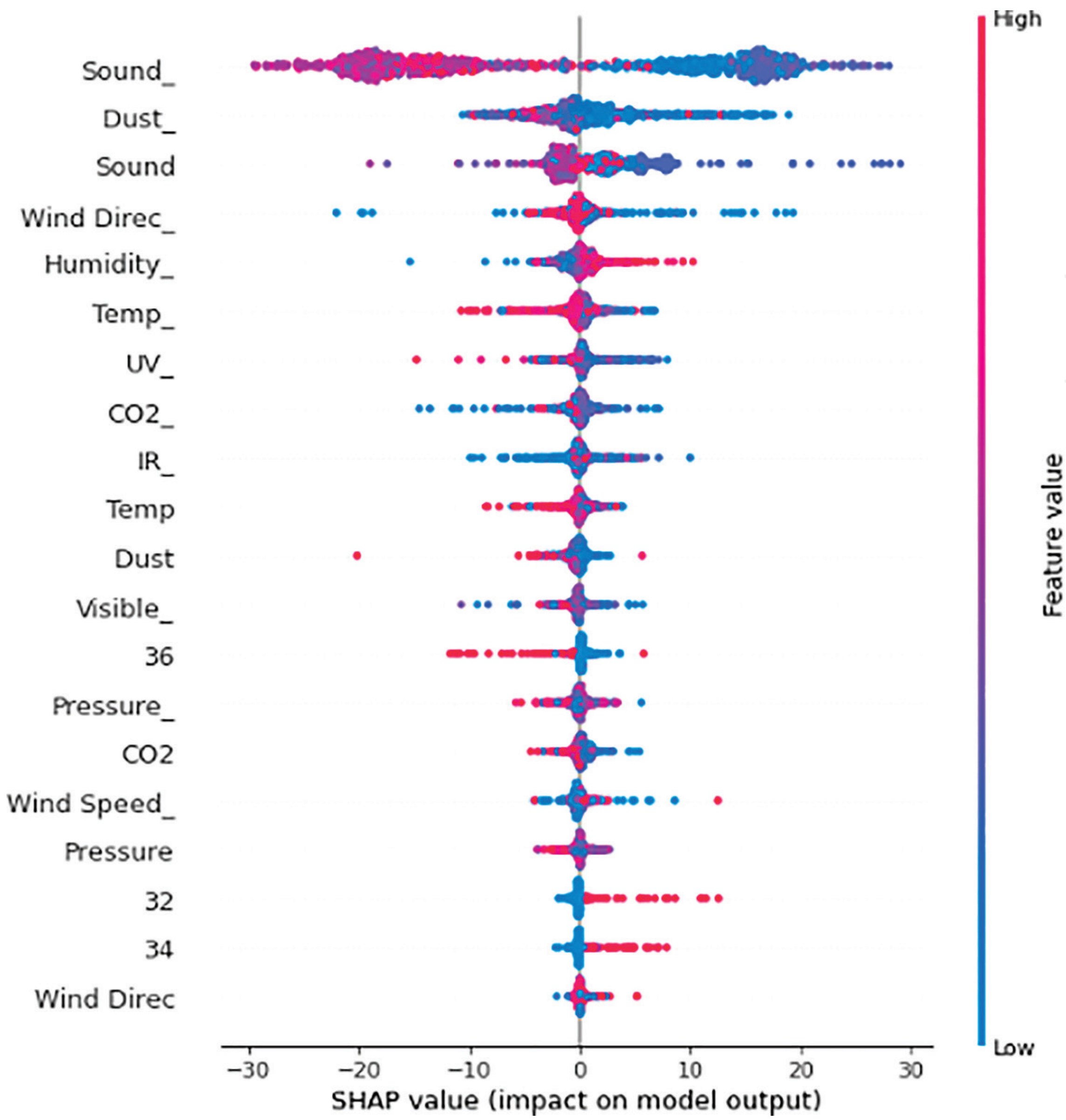

Figure 4.
Shapley summary plot of microclimatic factors and rMSSD.

temperature' (feature importance of 0.12). From the above Shapley Summary Plot, the higher sound is, the higher the skin temperature. In attempting to interpret this, one might consider sound to be a proxy indicator of the nature of one's immediate environment, which – in turn – may have attributes which results in physiological responses, including with respect to skin temperature. The lower amount of dust concentration present is, the higher the skin temperature. The higher ambient temperature is, the higher the skin temperature but it rises at a lower rate.

5.4 Self-reported physical state

Figure 6 shows the Shapley Summary Plot of the associations of microclimate with the variable 'self-reported physical state'.

From **Figure 6**, the variable 'self-reported physical state' is most strongly associated with the variable 'sound' (feature importance of 0.17), followed by the variable 'carbon dioxide concentration' (feature importance of 0.15) and by the variable 'dust

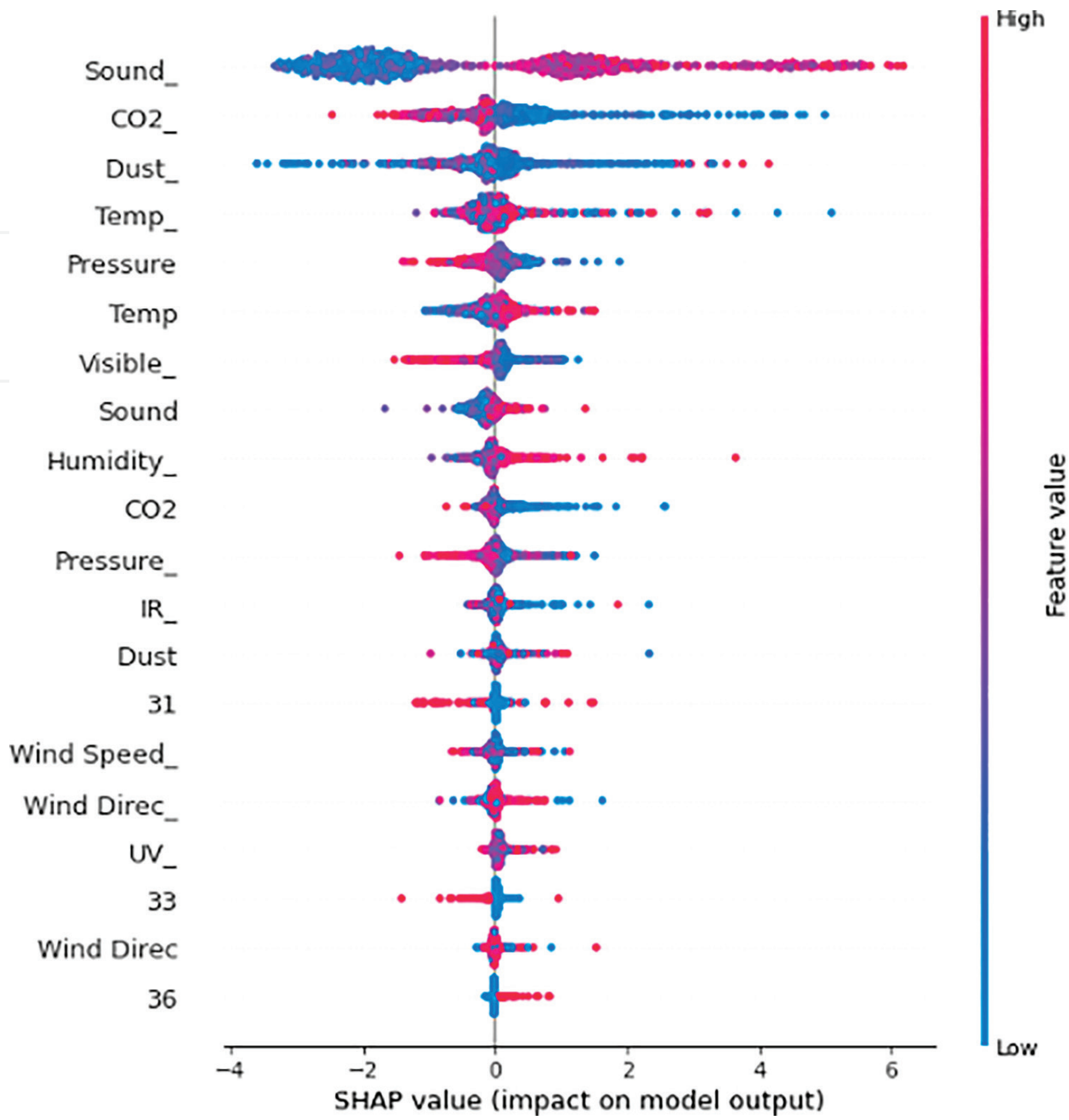

Figure 5.
Shapley summary plot of microclimatic factors and skin temperature.

concentration' (feature importance of 0.13). From the above Shapley Summary Plot, the higher level of sound, the higher the value of self-reported physical state. Similarly, the higher carbon dioxide concentration is, the higher the value of self-reported physical state. Finally, as dust concentration decreases, the value of self-reported physical state increases.

6. Associative relationships of microclimate and mental health

6.1 Stress score

The variable 'stress score' is generated by the smartwatches and is derived from oxygen saturation and heart rate. **Figure 7** shows the Shapley Summary Plot of the associations of microclimate with this variable.

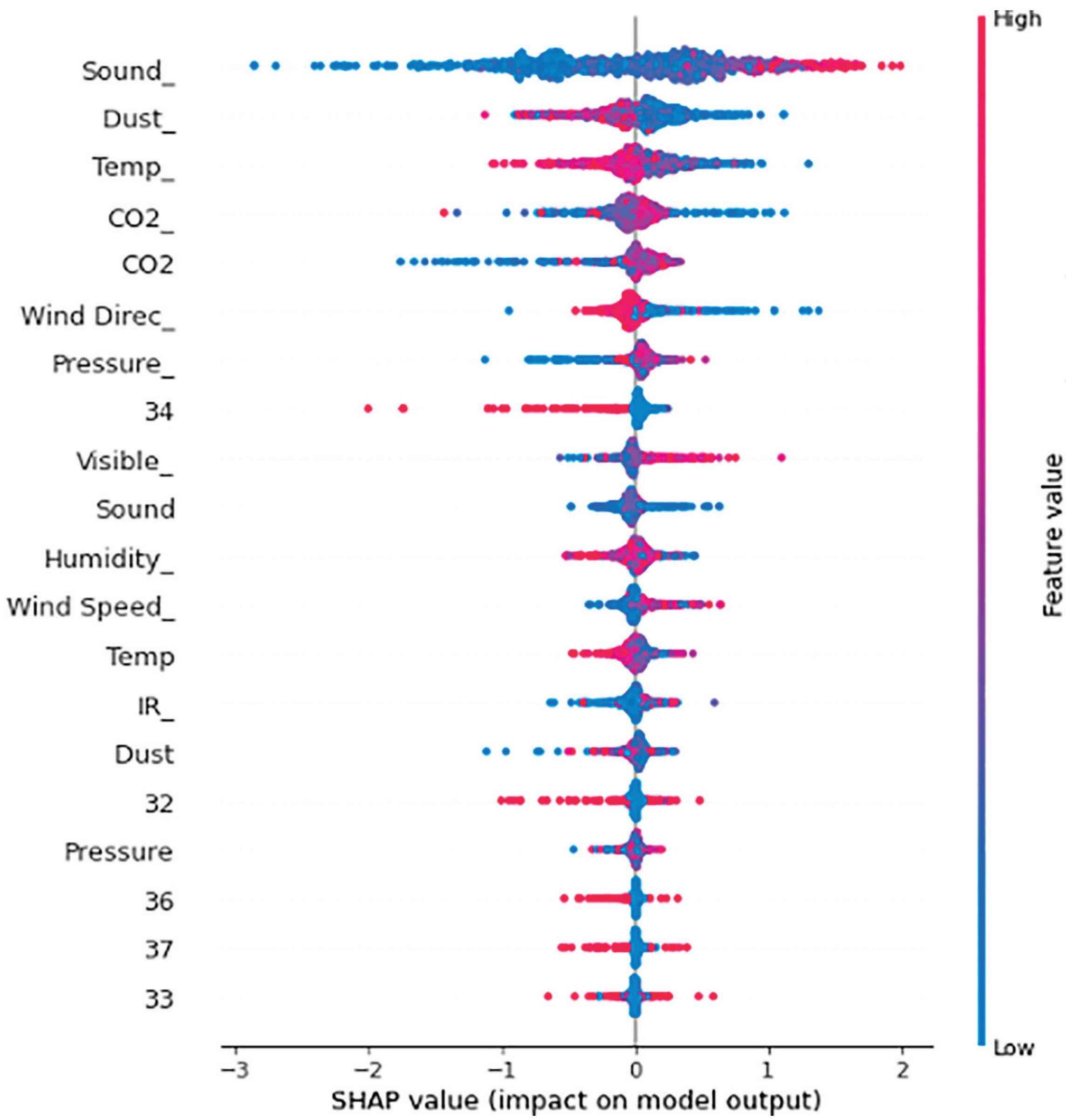

Figure 6.
Shapley summary plot of microclimatic factors and self-reported physical state.

From **Figure 7**, the variable 'stress score' is most strongly associated with the variable 'infrared radiation' (feature importance of 0.363), followed by the variable 'carbon dioxide concentration' (feature importance of 0.226) and by the variable 'ambient temperature' (feature importance of 0.104). The higher the infrared radiation, the higher the stress level. As for carbon dioxide concentration, the higher the concentration, the higher the stress level is. For ambient temperature, the lower the temperature, the lower the stress level is.

6.2 Self-reported mental state

Figure 8 shows the Shapley Summary Plot of the associations of microclimate with the variable 'self-reported mental state'.

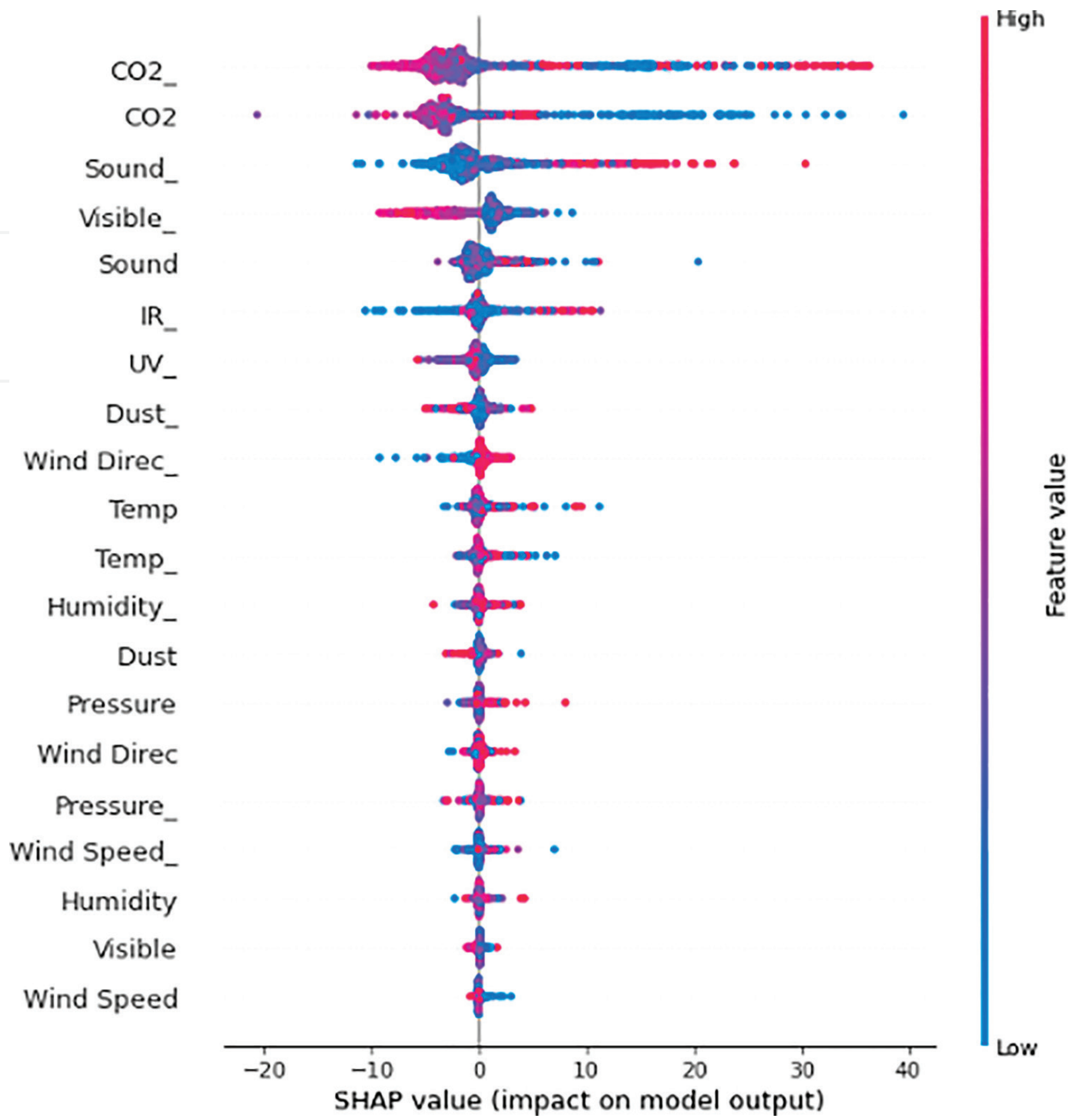

Figure 7.
Shapley summary plot of microclimatic factors and stress score.

From **Figure 8**, the variable 'self-reported mental state' is most strongly associated with the variable 'sound' (feature importance of 0.18), followed by the variable 'carbon dioxide concentration' (feature importance of 0.17) and by the variable 'dust concentration' (feature importance of 0.13). From the above Shapley Summary Plot, the higher level of sound is, the higher the value of self-reported mental state. Similarly, as carbon dioxide concentration increases, self-reported mental state increases. Finally, self-reported mental state value decreases as dust concentration increases.

7. Discussion

The preceding analysis suggests that the more significant microclimatic factors are sound, carbon dioxide concentration and dust concentration. These factors were continually associated with high feature importance scores in both physical and

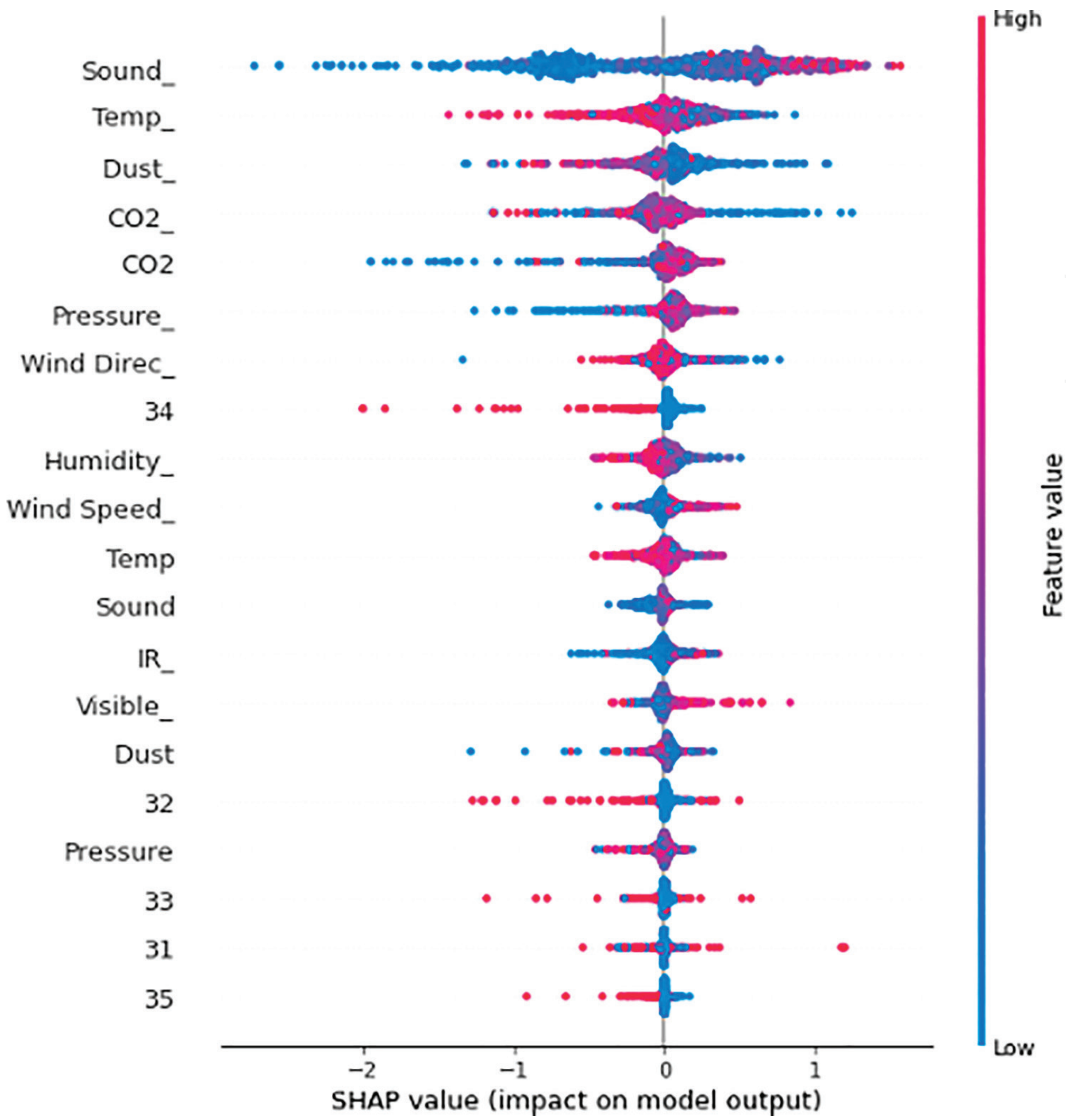

Figure 8.
Shapley summary plot of microclimatic factors and self-reported mental state.

mental well-being measures, and in both objective scores recorded from electronic instruments and more subjective self-report forms.

We acknowledge that the true influence of each value is much more abstract than the assigned Shapley value due to the 'black box' nature of random forest regression; further we also acknowledge that model interpretability does not mean causality. Notwithstanding these caveats, we have chosen to share the Shapley plots in this paper because they allow us to examine the contributions of features in ways that can be easily understood and used to make inferences.

The associations reported in this paper bear out causal linkages reported by similar studies in the field. For example, Kessel et al. [21] have documented positive relationships between ambient temperature and both body core temperature as well as corneal temperature, and Che Muhamed et al. [22] have documented positive relationships between relative humidity and body core temperature.

As for heart rate, Randall and Shelton [23] found that "carbon dioxide excess causes an increase in ventilation volume by virtue of a greater depth of breathing, the frequency decreasing slightly. The heart rate goes up with increasing carbon dioxide concentrations". Verberkmoes et al. [24] have shared that "the influence of atmospheric pressure and temperature on the incidence of acute aortic dissections may be explained by an increase in sympathetic activity, which is responsible for higher blood pressure, and heart rate". Another factor that affects heart rate is dust concentration. As suggested in research by Pope et al. [25], elevated particulate levels were associated with increased mean heart rate, and decreased overall heart rate variability. Sound also plays a part in affecting heartbeat, according to past research – for example, [26] – the higher the noise level, the higher the heart rate. Heart rate drops at night when humans are sleeping. According to Ahmed [27], "a balance of impulse from the sympathetic and the parasympathetic nerves determine a person's baseline heart rate. Interestingly, in experiments where a person's nerve supply is blocked, the heart rate is often higher; this would suggest that the parasympathetic nerve impulses that serve to slow the heart rate down are the predominant force under normal resting conditions. This is particularly evident at night when most people have a significant drop in heart rate".

Heart rate variability has been shown to be influenced by carbon dioxide concentration [28]. Our findings are congruent with studies which have elaborated on how and why heart rate variability is decreased with higher dust concentration [29], and with higher noise levels [30].

In terms of the associative relationships between microclimate and mental health, Mullins and White [31] have observed that "we find that higher temperatures increase emergency department visits for mental illness, suicides, and self-reported days of poor mental health". In a similar paper by Sygna et al. [32], results suggested that "individuals with poor sleep quality may be more vulnerable to effects of road traffic noise on mental health than individuals with better sleep quality". This position is congruent with that of the present study, in which extremes of sound levels were associated with both lower mental well-being and lower sleep quality (the latter as measured through sleep score).

As the present paper is inspired as a response to anthropogenic climate change, the extent to which carbon dioxide concentrations affect health and well-being is of interest. Kajtár et al. [33] have reported that well-being - as well as capacity to focus attention - both decline when carbon dioxide concentration in the air increases nearly tenfold to 3000 ppm.

The preceding parallels between earlier studies and the present study are encouraging, because a foundational paradigm driving our work was that of citizen science and the democratization of small-scale, low-cost research as enabled by data science and the Internet of Things (IoT). We assembled the wearables from off-the-shelf parts and coded them ourselves. Technology has enabled such democratization not only in terms of the (relatively) low cost of hardware and the open source movement in general, but also in terms of recent developments in data science and machine learning. The latter have meant that the large and burgeoning datasets associated with the use of IoT can be accessible and intelligible to wider cohorts of students and researchers. The parallels be-tween our work and earlier studies suggest that – going forward, in a world where anthropogenic climate change is a (sad) reality – meaningful scientific and geographic inquiry can be undertaken by a much wider cross-section of the general public than was once previously possible.

Several opportunities therefore suggest themselves for potential future work, which could take the form of either scaling up or translation to investigate other microclimatic variables (such as the role of infrared radiation on well-being), biometric indicators (such as readings from electroencephalograms) and socio-demographic contexts. These and other possible avenues for future work will go some way to addressing the limitations of the present study, foremost among which was the movement restrictions associated with the necessity to follow COVID-19 protocols throughout the duration of the study. These movement restrictions meant that the microclimates sampled were necessarily limited in variety. It is hoped that possible future extensions of this study in 2022 may not be as constrained.

8. Concluding remarks

The study reported in this paper set out to investigate the associative relationships between microclimate and physiological responses and well-being. We approached the investigation from the perspective of citizen science, conceptualizing, designing and fabricating what we could. We analyzed the resulting datasets informed by contemporary understandings of data science and machine learning.

Our results suggest that sound level, carbon dioxide concentration and dust con-centration feature more importantly in regression models trained on our datasets. These findings are congruent with preceding studies, and we see a primary contribution of our work as the demonstration that – in an age of anthropogenic climate change – broader cohorts of students, researchers, and the general public have potential access to tools, methods and means of analyses that were once deemed only within the reach of a privileged few due to reasons of cost, fragility, and complexity.

It is our hope that our study contributes in a small way to a body of work to help urban planners, designers of living spaces, caregivers – among many others – conceptualize modes of human habitation in sympathy with the needs of our planet, in an era when humankind has more potential than it has ever had to influence biomes in general for better or for worse.

In conclusion, it is important to seek to understand the complex and non-linear relationships between microclimate, physiological response and well-being. This paper has reported a study conducted by students in which wearable devices containing environmental sensors were designed and worn from July to December 2021. Over the same period, data from these sensors was complemented by that obtained from smartwatches. We hope to contribute to the body of literature on the relationships between microclimate and well-being. It is our hope that this wider body will catalyze subsequent studies to address health problems arising from climate change, in order to boost productivity and life satisfaction in the not too distant future.

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