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Processing and Configuring Smart and Sustainable Building Management Practices in a University Building in Australia

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Abstract: Australia's building energy use accounts for a significant portion of the country's energy consumption and greenhouse gas emissions. Buildings consume energy for a variety of purposes, including space heating, cooling, lighting, and powering electronics. Smart and sustainable building management practices allow buildings to be managed and operated more efficiently and sustainably. This study investigated the energy consumption and building management performance of a university building in Sydney, Australia. The experiment was performed by monitoring occupant comfort and building performance feedback with a push-pull mobile phone application and portable sensor technologies. The results showed that several factors influenced the occupants' environmental comfort level, including temperature, lighting, noise, air quality, air movement, and relative humidity. Nevertheless, the ambient office temperature has a significantly higher impact on occupants' comfort level. Results also showed that the local temperature experienced and preferred by individual occupants may vary, even under identical thermal conditions. The outcomes also confirmed strong correlations between the comfort and concentration levels (r(231) = 0.61, p = 0) and between the comfort and productivity levels (r(231) = 0.62, p = 0). Temporal analysis also revealed lower comfort levels between 13h00 and 16h00 and higher comfort levels between 10h00 and 12h00 and 17h00 and 19h00. The findings of this research indicated that $\leq$4% of total annual building energy consumption costs may be saved by more effectively and efficiently managing office thermostat control. More accurate and zone-based energy analysis could also reveal higher energy savings through smart occupant feedback-oriented thermostat and lighting control in commercial and office buildings.

Keywords: smart building management; sustainable building; occupant comfort; building energy

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1. Introduction

The increasing consumption of fossil fuels has become a major global concern over the past few decades. Fossil fuel consumption elevates carbon dioxide (CO_2) emissions which, in turn, contribute significantly to rising average global temperatures. According to the Paris Agreement, Australia must reduce its 2005-level CO_2 emissions by 26–28% by 2030 and reach net zero CO_2 emissions by 2050. Considering the limitations of fossil fuel-based energy resources and their negative impact on the global climate, more efficient energy use to reduce overall load is crucial [1].

Buildings are one of the largest consumers of energy resources. Buildings account for ~40% of the total energy consumption and are responsible for more than 30% of the CO_2 emissions worldwide. In Australia, ~23% of the total greenhouse gas (GHG) emissions originate from the building sector and are forecast to consume nearly 50% of the carbon budget of Australia by 2050 [2]. A substantial proportion of this energy is utilized to enhance thermal comfort in the indoor environment. In developed countries, the energy used for heating, ventilation, and air conditioning (HVAC) systems currently account for >50% of the total energy consumption in a building, and this percentage is growing. Approximately 15–30% of this energy is wasted as the result of inefficient HVAC operation [3]; this is particularly true in non-residential buildings [4,5]. Therefore, energy operation and management system optimization are essential to improve building energy performance. At the same time, energy optimization must also consider building occupant health, comfort, and productivity [6,7].

Recent research demonstrates that the behavior of building occupants is critical to energy efficiency programs, and behavior-change initiatives can be highly cost-effective and successful strategies for promoting energy savings [8]. However, individual experiences of and preferences for temperature, air quality, humidity, and lighting levels vary widely. Building occupants usually rely exclusively upon their subjective sense of comfort to guide their behavior. Moreover, individual microclimates differ considerably across building zones, and even between adjacent spaces within the same building zone. Because environmental comfort is a key driver of worker productivity and wellbeing [9], building energy management systems must seek to optimize energy use while providing a satisfactory comfort level for all occupants and across all environmental factors.

Most recently, digital twin (DT) platforms and the Internet of things (IoT) have emerged as intelligent, controlling, energy-saving technologies [10]. They enable communication among connected devices and regulated functions [11]. IoT devices integrated into DT systems record performance data and actuate control responses [12]. They have the capacity to provide real-time energy monitoring and response in buildings, and to continuously collect status data and inform occupants across multiple building zones. This technology can then be integrated with building management systems (BMS) [13] to provide improved building management automation. However, fixed/hard-wired building performance sensors may not generate a sufficient concentration of data points to register environmental differences across microclimates [14]. The sensors currently in use also tend to focus on a limited range of environmental factors. Occupants themselves are often excluded from the information feedback flow, and undergo limited (if any) post-occupancy user evaluation. However, recent advances in sensor technology have made it possible to provide low-cost, wireless devices that incorporate multiple sensors and continuously monitor multiple environmental factors. Wireless devices are portable and enable the collection of microclimate performance data from different locations at various times to improve post-occupancy evaluation, sustainability, and building energy management [15].

This study aims to highlight the potential impact of relative differences in indoor microclimates on building energy consumption, and the comfort and behavior of building occupants. The experiment was performed by monitoring occupant perceptions of comfort with a push-pull mobile phone application and recording the microclimate environmental building performance using portable sensor technologies. This pilot project investigated the energy consumption and microclimate building management performance of a university building in Sydney, Australia, and evaluated environmental comfort feedback from the occupants working in different office locations within this building.

2. Literature Review

Temperature is a key factor in thermal comfort and is influenced by various factors such as air temperature, radiant temperature, humidity, and air movement. Air quality, on the other hand, refers to the purity of the air we breathe, which is affected by factors such as pollution, allergens, and ventilation. Humidity refers to the amount of moisture in the air, and can have an impact on both thermal and air quality comfort. Lighting level, on the other hand, refers to the amount of light in a space, which can affect visual comfort and also impact mood and productivity. Given the different factors that contribute to each of these aspects of comfort, it is important to consider them separately in order to create an environment that is comfortable and conducive to productivity and well-being. By addressing each of these factors individually, it is possible to create a space that meets the needs and preferences of a wide range of individuals.

User behavior and energy consumption are strongly related to the occupancy model, lighting management, window provision, air conditioning, and thermostat settings [16]. To improve the performance and lower the energy consumption of buildings, the management of HVAC systems, building features, and appliance use must each be considered [17].

A previous study used statistical methods to assess room temperature satisfaction and environmental conditions in office buildings [18]. That study found that the interactions of occupants with their environment is better described by the internal, rather than the external, ambient temperature. Another investigation showed that productivity and performance are higher when occupants are working under electric lighting [19]. An examination of the associations between personal comfort systems and the general environmental and HVAC systems in office buildings highlighted that the local temperature experienced and preferred by individual occupants can vary, even under the same environmental thermal conditions [20].

Yu et al. [21] proposed a method of facilitating the assessment of building energy-saving potential by amending building user behavior and providing versatile approaches to building energy end-use patterns related to occupant behavior. Haldi and Robinson [22] reported that occupancy patterns and indoor temperature, as well as external parameters, such as outdoor temperature, wind speed and direction, relative humidity, and rainfall, affect window opening and closing behavior. Light switching patterns, when occupant controlled, have been shown to be governed primarily by the routine and habits of occupants rather than the level of illumination required [16].

In the commercial sector, it is estimated that total annual energy consumption could vary by up to 150% because occupant behavior can be so uncertain. Even an energy parameter driven by a single occupant, such as ventilation and heating, can influence building energy performance by as much as 40% [23]. Various types of human behavior influence building energy performance. Social interaction, eco-feedback, gamification [24,25], IOT-based sensors [26], and mobile applications [27] have all been implemented to evaluate these relationships. The rationale behind each strategy is largely the same, namely, to associate different user behavior with the amount of potential energy saved.

Abdallah et al. [6] aimed to create an adaptive wearable thermal comfort system by developing a mobile application that uses sensors built into cell phones and wearable devices to gather location, air and skin temperature, and heart and perspiration rate data. This information is used to evaluate the predicted mean vote (PMV), which represents the average thermal sensation for a large group of people within a space index. Aryal and Becerik-Gerber [28] compared the relative accuracy of environmental and physiological sensors to predict individual thermal sensation and satisfaction. The addition of environmental sensor data provides more accuracy than when physiological sensors are used alone. Labeodan et al. endeavored to improve lighting efficiency by installing chair sensors in an office building and found that mechanical switch-based chair sensors were more effective than passive infrared (PIR) sensors for occupant-driven lighting system control [29].

A range of sensor categories is now available on the market. Primarily, however, only motion sensors and occupant counters have been widely adopted under current building management practices. Moreover, the use of sensors is limited in the main to high-rise, multi-tenant buildings. Hence, the present project investigated the feasibility of using smart phones and small, low-cost, portable multifactor sensors that can be positioned according to study and occupant preferences. The aim of this work is to demonstrate the impact of indoor microclimate changes on environmental comfort levels and on building energy consumption in commercial and office buildings. A push-pull mobile phone application is developed and tested to efficiently and frequently poll the perception of comfort from individual occupants. Low-cost, portable sensors are deployed to monitor and report environmental building performance at the microclimate level.

3. Methodology

3.1. Research Design and Sampling Approach

This study builds on a previous study defining and demonstrating a conceptual framework for how smart technology can be deployed to improve the environmental performance of existing buildings [30]. The current study adopted the proposed framework to determine the feasibility of implementing the smart technology configuration in a real-world scenario.

Participants in the study were invited from a group of current research students and administrative employees at a university in Sydney, Australia. As this was a pilot project rather than an investigation of a particular cohort, participants were selected on a first-response basis, limited to the number of portable sensor devices (12 in number) available for the study. Participants did not receive any payment or inducement. They worked in a variety of dedicated office spaces on campus. Participants were anonymized, and all associated data was coded using a randomized participant identification number. Prior to conducting the experiment, ethics approval for conducting research involving people was sought and obtained from the UTS Human Research Ethics Committee. Each participant was provided with a project information sheet and signed the consent form before participation. A total of 75% of all participants registered as female, and 25% registered as male. Half the participants were between the ages of 30 and 39 years, and one-quarter of the respondents were under 30 years of age.

3.2. Data Collection

Data for this study was derived from (a) portable microclimate sensors, (b) occupant perceived comfort level feedback, and (c) building energy consumption and management protocols. Data was collected for the period from 15 January to 6 April 2021.

The participants occupied 8 different office spaces, across 2 floors of the building. A total of 75% of the office spaces had multiple occupants. Each space was served by a different HVAC unit, with a temperature set point between 22 °C and 23 °C. During the study period, the HVAC systems were scheduled to operate between 8:00 am and 6:00 pm on workdays only, and were operated by motion detectors or manual switches outside those hours. The building had an east-west orientation, with 7 of 12 offices having east-facing windows. All windows had manual window shades available.

3.3. Portable Microclimate Sensors

Microclimate data was collected from portable internal and external microclimate sensor devices manufactured by Hibou (Sollentuna, Sweden) [31]. The sensor devices gathered and reported air quality, humidity, temperature, ambient pressure, ambient light, and UV light level data in the workspace over the experimental period. Each sensor was configured to return data for each variable at 2 min intervals, 24 h per day and 7 days per week. The occupants were consulted regarding the placement of the Hibou device at an appropriate location in their personal work space/desk. Thus, relevant data was collected from twelve indoor sensors. In addition, one sensor was placed outdoors at the building entrance, and collected equivalent data to that collected by the indoor sensors, but specific to the immediate climate of the building itself.

3.4. Occupant Comfort Level Feedback

User feedback data was collected using a combination of: (1) a pre-experiment questionnaire, (2) a main experimental survey, and (3) a post-experiment questionnaire. The pre-experiment questionnaire collected information about the participant preferences and their office context. The main experimental survey collected comprehensive data regarding the occupant perceptions of current comfort levels and the factors influencing it. The post-experiment questionnaire compiled participant feedback regarding their experiences with the mobile application and the experimental study overall.

In the pre-experiment questionnaire, information was collected relating to the immediate office space design and key features (desk location, window provision, etc.), along with participant feedback about the preferred working environment. This data was used to compare occupant feedback and sensor data to identify the major explanations for participant comfort level feedback. Information about the office location and orientation, as well as window orientation(s), was collected from the university facility management team.

The main experimental survey collected feedback using a proprietary mobile phone application, developed and evaluated in association with KnowHowHere Ltd. (Sydney, NSW, Australia), https://www.knowhowhere.com (accessed on 15 December 2020)) [32]. This Sydney-based start-up specializes in unique IoT application platforms. Participants were required to install this free mobile application so they could provide comfort level feedback during the experiment. The application prompted user responses at various times and used geo-location to prompt only when participants were actually in the building location.

The survey questions focused on the perceived alertness, concentration, productivity, and comfort levels of the occupants in their offices. The participants were asked to rate the temperature, air quality, humidity, lighting, and noise levels of their offices. Participants were also able to note the use of window blinds, whether office doors were open or closed, the layers of clothing being worn, and so on. Figure 1 shows the survey question logic and flow.

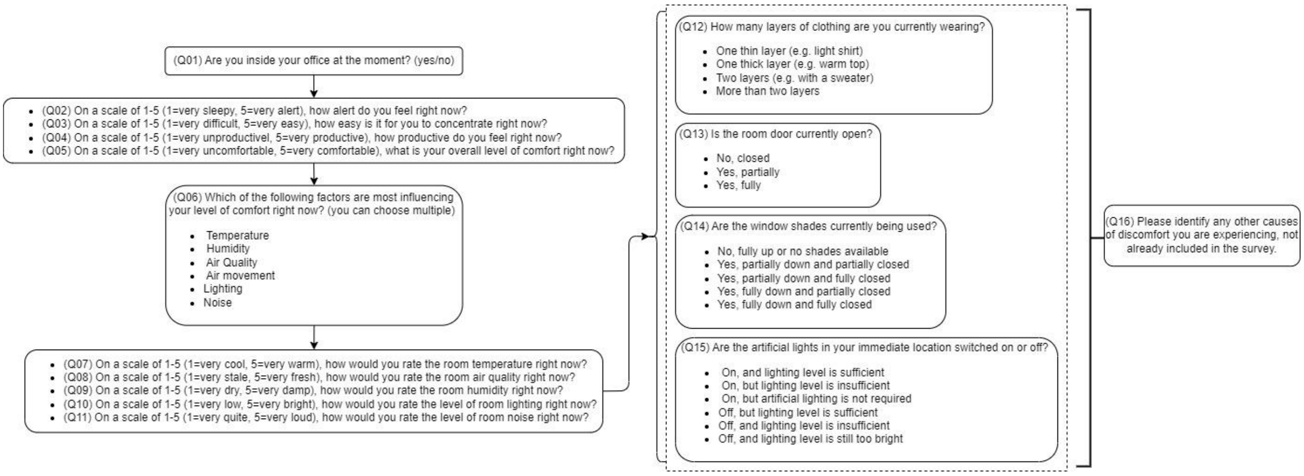

Figure 1. Survey Questionnaire Logic and Flow.

A follow-up survey was conducted at the end of the study period to evaluate the experience of participants with the mobile application and assess their overall comfort level in their office spaces. This post-experiment questionnaire focused on the primary motivations for the participant attending on campus during the study period, and their overall experience with the mobile application. It was also used to determine the opinions of participants regarding the practicality of applying the smart technology more generally.

3.5. Building Energy Consumption

The Building Services and Facilities Management, and the Sustainability and Quality Group of the University both supported the study by furnishing energy consumption data for the study building and providing access to the building energy management systems. The university subscribes to a smart building and energy management system which provides readings for each individual energy meter at 15 min intervals. The relevant data were directly extracted, audited, and compiled into a common database for analysis. Information regarding the conditions under which the air conditioning system operated (times, target temperatures, control variables, and so on) was also provided.

3.6. Data Processing and Analysis

A common application database built around an open-source data management system within the KnowHowHere platform was utilized to manage the data. Cluvio [33] ran custom R scripts atop SQL queries, and generated interactive dashboards and analytics reports to render the data into a format that could be displayed in the KnowHowHere mobile app. The KnowHowHere platform and its associated database management systems coupled building performance and user comfort data. The Microsoft PowerBI tool (Microsoft Corp., Redmond, WA, USA) was used for data visualization and temporal analysis. Data collected from the mobile phone application were exported in csv file format and imported to SPSS v. 26 (IBM Corp., Armonk, NY, USA). The analyses were based on the aggregate-level frequency data and included a total of 244 completed survey responses from the 12 participants over the study period.

The data were processed using several different analytical techniques. Most of the data analysis was based on whole count tables and frequencies calculated as percentages. Participant ratings for different variables were determined using a five-point Likert rating scale. Cross-tabulations were used to examine data relationships that might not be readily apparent during survey response analysis. The cross-tabulations facilitated the comparison of at least one variable with at least one other. Pearson's correlation coefficient analyses were conducted to identify statistically significant relationships among variables.

4. Results and Discussion

A total of 12 internal sensor devices were deployed, and each collected data particular to the microclimate associated with each participant. In addition, one sensor device was located immediately outside the study building to collect information regarding the external microclimate associated with the building. Occupant perceived comfort level feedback was collected using: (1) a pre-experiment questionnaire; (2) an experimental survey; and (3) a post-experiment questionnaire. A total of 12 pre-experiment and 12 post-experiment questionnaires were received. A total of 244 experimental survey submissions were logged from all participants over the study period.

4.1. Pre-Experiment Questionnaire Results

Preliminary assessment of participant feedback regarding room temperature indicated that 55% preferred an ambient temperature of 22–23 °C, and 36% of participants preferred a higher room temperature range of 23–25 °C. Male participants usually preferred lower temperatures (<23 °C), whereas female participants felt more comfortable at higher temperatures (>23 °C). This part of the survey disclosed a discrepancy between the expressed preferred temperature and the set-point temperatures for associated zones of the building. Hence, the set-point office temperature settings may have to be reconsidered from a purely occupant comfort perspective. Energy optimization needs to balance often competing energy saving and user comfort targets. Most respondents indicated that the offices had moderate levels of air quality and humidity.

Responses also indicate that the office lighting was too bright for 27%, and too dim for 18% of respondents. Certain respondents stated that the lighting was especially inadequate at nighttime. A total of 54% of the respondents reported that the natural office lighting was insufficient. Moreover, the overall office noise level was excessive for 45% of the respondents, indicating that installation of sound insulation could improve workspace comfort satisfaction. Figure 2 shows that 27% of the participants were satisfied with the overall environmental comfort of their offices, 64% of them reported a moderate level of satisfaction, and 9% were dissatisfied.

4.2. Main Experiment Survey Results

The main experiment was conducted between 15 January and 6 April 2021, which covers the late summer and early autumn seasons in Australia. Several factors influenced the respondent level of environmental comfort. Figure 3 shows that the clearly most influential factor was temperature (74%), followed by air quality (33%) and noise (27%). Other influential factors were humidity (13%), air movement (11%), and lighting (10%). Detailed analyses of the sensor data and participant feedback regarding these factors are presented in the following subsections.

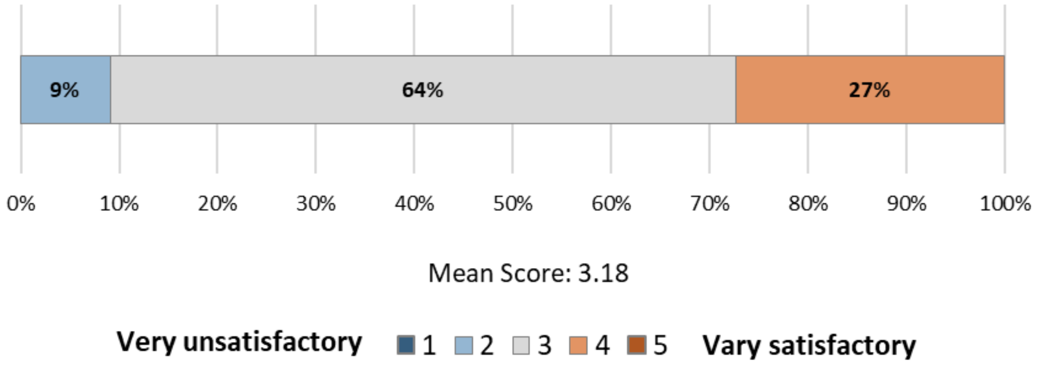

Figure 2. Preliminary evaluation of the overall environmental comfort of the offices.

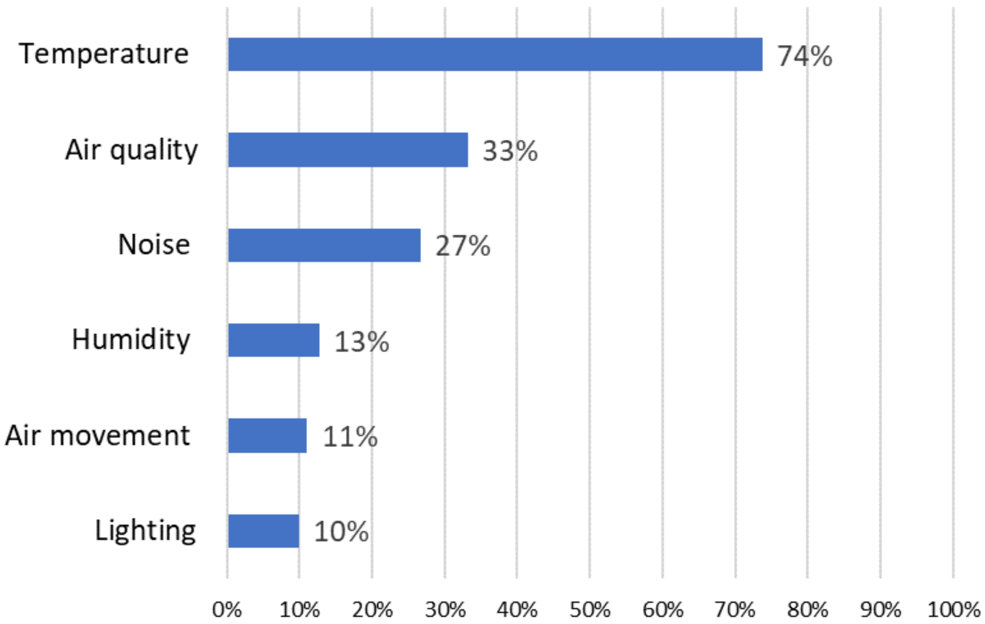

Figure 3. Factors influencing respondent comfort level (n = 244).

4.3. Temperature

The average temperature recorded across all sensor devices for the duration of the study was 24.9 °C. The external sensor reported an average outside temperature of 21.2 °C. The time series of the average temperature data for all participant sensors is shown in Figure 4. The results show that participants experienced average microclimate temperatures that were either the same or lower than the average outside temperature of the building, for approximately 80% of the time.

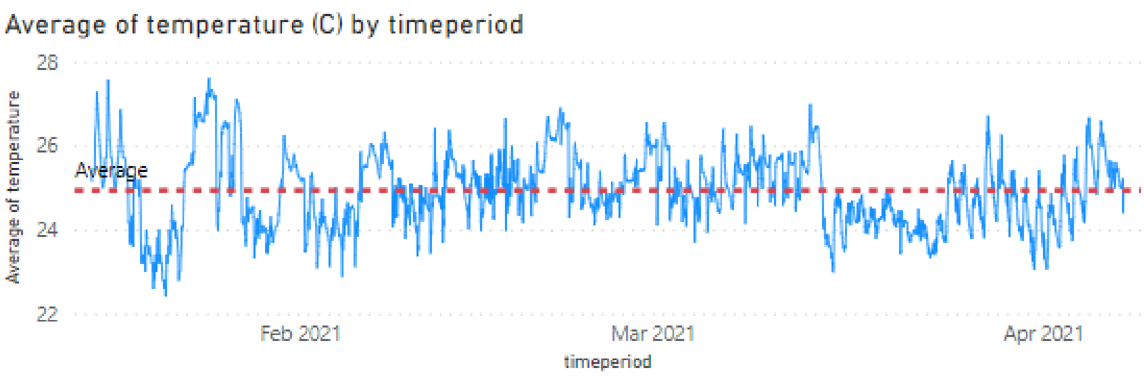

Figure 4. Average participant sensor temperatures.

Participant ratings of the room temperature (on a scale of 1 to 5, where 1 was very cool and 5 was very warm) showed that 36% of the respondents considered their offices to be very warm, while 36% considered them to be very cool. However, 28% of the respondents considered the room temperature to be reasonable. During the study period, 28% of the participants wore one thin layer of clothing, 36% wore one thick layer of clothing, and 36% wore two layers of clothing. As the survey was conducted during the late Summer and early Autumn (with daily temperature average peaks in Sydney ranging between 24 and 27 °C), the fact that 72% of the participants wore one or two thick layers of clothing indicates that the indoor temperature was not properly adjusted to their comfort level. Respondent feedback also showed that it is important to monitor microclimates, as they influence participant comfort level, and adjustments to improve comfort levels could also potentially reduce energy expenditures in commercial buildings.

4.4. Air Quality and Air Movement

The average air pressure for all participant sensors was 101,287 ± 0.6 hPa. The external sensor showed an average outside pressure of 101,489 hPa. Overall, the indoor air pressure was ~200 hPa lower than the outdoor air pressure. However, the survey results demonstrated that the participants did not notice changes in air pressure.

A period analysis indicated that the average particulate matter (PM 10—unit μg/m^3; resolution = 0.3 μg/m^3 ± 10%) measured by all participant sensors was 2.37 μg/m^3. The external sensor showed the average outside PM 10 was 42.4 μg/m^3, with minimum and maximum measurements at 26.4 μg/m^3 and 77 μg/m^3, respectively. The average volatile organic compounds (VOC) level measured by all participant sensors was 0.8 ppm. The external sensor reported an average VOC level of 1.1 ppm. Thus, the air quality metric returned by the indoor sensors indicated no major issue regarding the office air quality, and demonstrated that the air handling equipment and air flow management of the building were effective in cleaning the intake air.

Participant air quality ratings indicated that 32% of the respondents had access to fresh air while they were in their offices. Another 43% of them reported that the office air quality was satisfactory. Nevertheless, 25% of the participants perceived the air quality to be poor, noting that the air was stale. A total of 90% of all respondents preferred to keep their office doors closed during working hours, primarily to exclude outside noise. However, the same participants who most often noted the air to be stale were also among those who kept their door closed, indicating that air quality may be improved by increasing the air circulation. A temporal analysis (Figure 5) revealed that the air quality was never rated "very fresh" between 14h00 and 17h00.

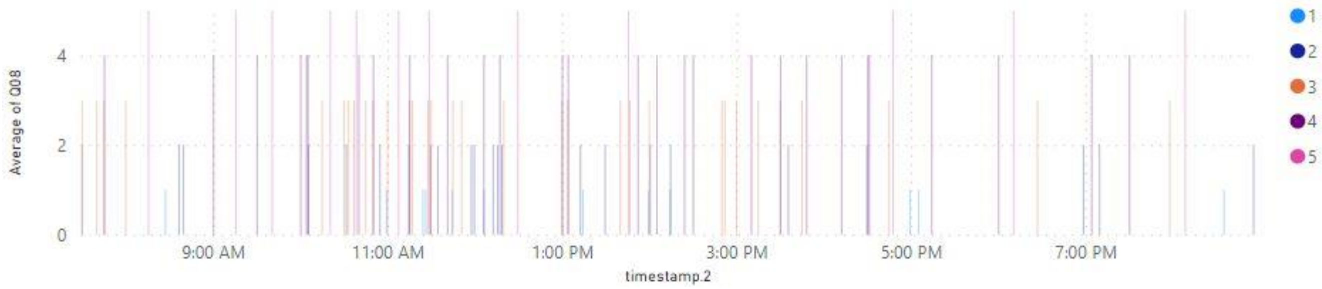

Figure 5. Average room air quality rating (1 = very stale, 5 = very fresh) during daytime hours.

4.5. Humidity

According to the sensors, the average humidity (% relative humidity (RH) ± 3%) in participant offices was 52.1%. The external sensor showed an average outside humidity of 63.3%. The sensor data indicated that 80% of all participants were subject to higher than average humidity in their offices. Figure 6 shows that 41% of all respondents perceived moderate office humidity, while 42% claimed that their offices were damp, and 16% perceived that their offices were dry.

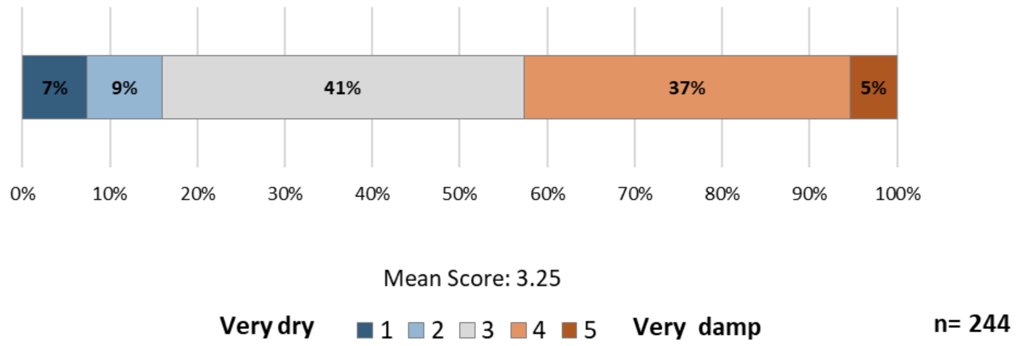

Figure 6. Participant office humidity ratings.

4.6. Lighting

The external sensor returned an average ambient light level of 178 klx ± 100 mLux, while participant sensors indicated an ambient light level in their offices in the range of 27–224 klx. Hence, the office light level varied quite markedly around the average ambient light level for many participants.

Office lighting was rated as too bright by 32% of the respondents and too dim by 8% of respondents. Nevertheless, 60% of the respondents perceived the overall lighting level to be adequate. The participant sensor and feedback data demonstrated that the rooms with above average light levels were oriented in an east-facing direction.

Cross-tabulation of the ratings to the questions regarding lighting revealed that most respondents who rated the lighting as normal or bright kept their window shades up and also used artificial lighting. However, the temporal analysis revealed no significant correlation between time of day and light level. Most participants considered the offices too bright during nighttime hours, indicating that the lumen level of the artificial lighting may be too high. Individual analyses disclosed that the location of the desk in the office space had negligible impact on participant perception of office lighting, with some participants located further from the windows also rating their office lighting as bright. Thus, lighting comfort was related primarily to the level of artificial lighting, rather than office orientation.

4.7. Noise

The sensor devices did not measure the noise levels. However, most participants (62%) reported high levels of perceived office noise. The remaining 38% of respondents considered the office noise level to be acceptable.

4.8. Comfort Level

The questionnaire focused on understanding participants' perceived alertness, concentration, productivity, and comfort in their offices. Figure 7 evaluates all participant feedback regarding their alertness level in their offices. A total of 61% of respondents felt alert or very alert. However, 14% of all participants claimed that it was difficult or very difficult for them to remain alert on the job. Figures 8 and 9 show that 18% of all respondents found it hard to focus on their work, while 20% of them felt unproductive in their offices.

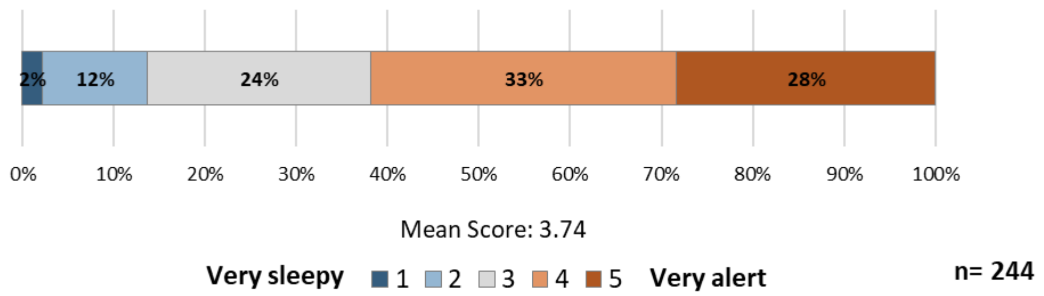

Figure 7. Evaluation of feedback regarding participant alertness level.

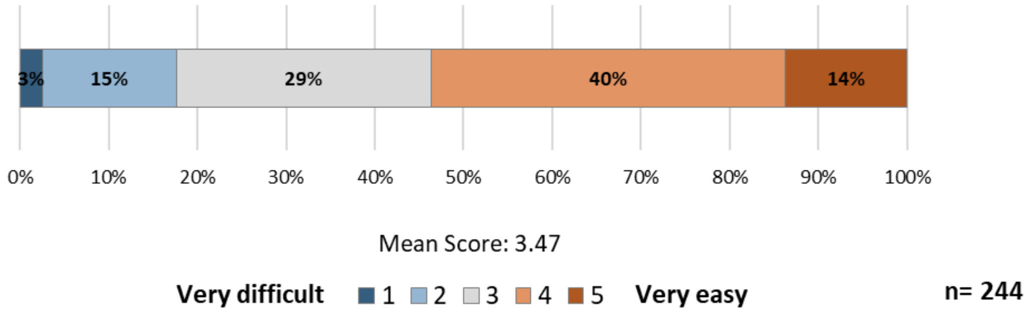

Figure 8. Evaluation of participant feedback regarding concentration level.

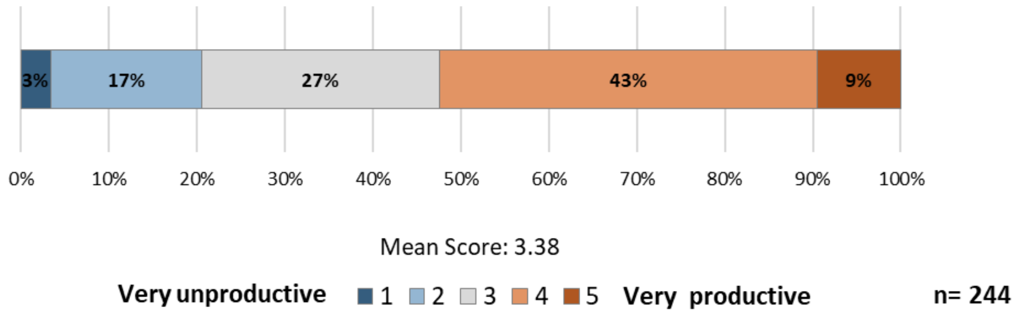

Figure 9. Evaluation of participant feedback regarding productivity level.

Pearson's correlation coefficients (PCCs) were calculated to understand the associations among the workplace/office comfort, alertness, concentration, and productivity levels. PCCs are used, as they provide a common statistical measure of linear correlation between two sets of data. There were strong correlations between the comfort and concentration levels (r(231) = 0.61, $p = 0$) and between the comfort and productivity levels (r(231) = 0.62, $p = 0$). There was a moderate correlation between the comfort and alertness levels (r(231) = 0.45, $p = 0$). Figure 10 shows these associations.

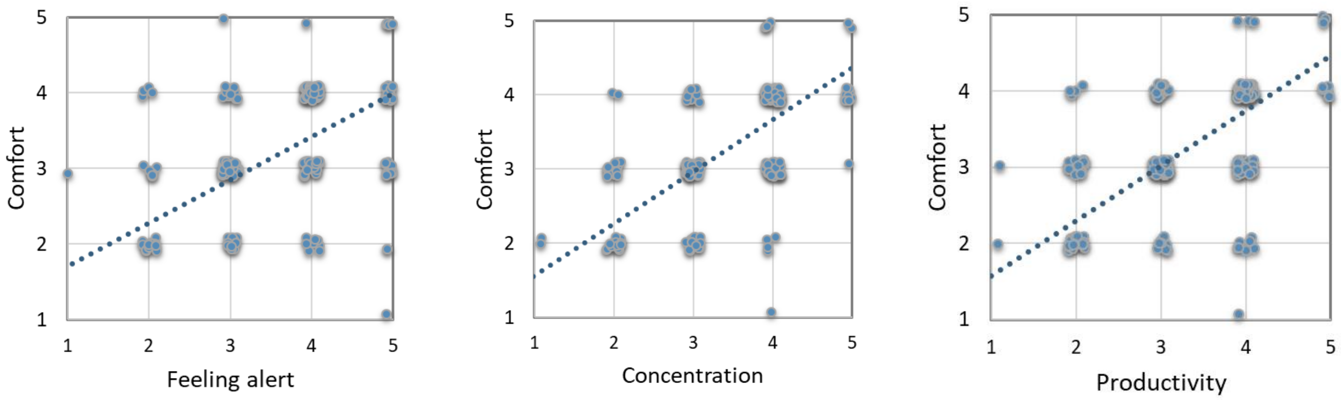

Figure 10. Correlations among workplace comfort, alertness, concentration, and productivity levels (1 = negative experience; 5 = positive experience).

A temporal analysis (Figure 11) revealed that participants reported lower comfort levels between 13h00 and 16h00 and higher comfort levels between 10h00 and 12h00 and between 17h00 and 19h00.

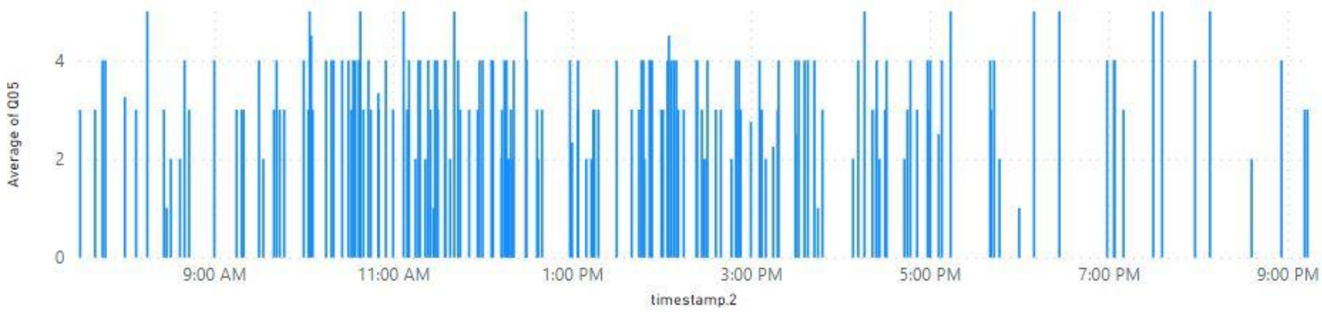

Figure 11. Daytime respondent comfort levels (1 = very uncomfortable; 5 = very comfortable).

4.9. Post-Experiment Survey Results

A total of 44% percent of all respondents claimed they could accurately express their comfort or discomfort level during the experiment. The remaining 56% provided neutral feedback regarding their relative comfort level during the survey, but did not claim that their responses were inaccurate. The respondents were then asked how likely they were to recommend that their colleagues participate in this experiment. A total of 66% said they would probably suggest that their associates participate in a future study. Conversely, 11% indicated that they were unlikely to advise their colleagues to participate in an equivalent study in the future. This level of dissatisfaction with the current study is largely accounted for by issues caused when trying to install the survey app. A very few participants experienced problems installing the app on mobile phones with older (un-supported) versions of the Android OS, and had to complete the surveys using paper-based options.

A total of 88% percent of all participants believed that it would be practical to apply this technology in a more general, commercial context. As this research was performed during the COVID-19 pandemic, all participants had the option of working from home. For this reason, they were asked to specify their primary motivation for attending on campus in person to participate in this study. Participants were able to choose multiple answers for all reasons that influenced their decision to work on campus. Figure 12 shows that 63% of all respondents wanted to take advantage of the opportunity to meet and socialize with colleagues and friends on campus. Notably, 63% of participants also stated that they preferred the comfort of the office settings to alternative settings (at home, for example), which broadly aligns with the general level of satisfaction with comfort levels in the office spaces.

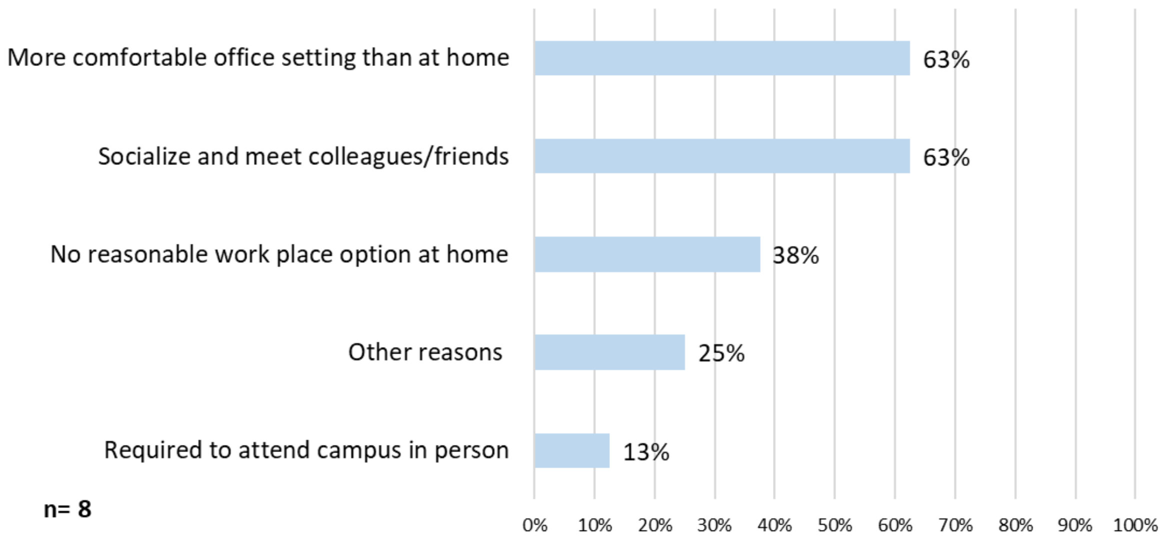

Figure 12. Primary motivations for respondents to appear on campus to participate in the survey.

4.10. Building Energy Consumption

Over the past seven years, the average annual energy consumption of the study building was ~2.5 million kWh. The cost of electricity in Sydney in 2021 was ~30 cents/kWh. Thus, the annual energy expenditure for this building was approximately AUD 750,000. During the COVID-19 pandemic, the average annual energy consumption of the building was only 1.8 million kWh.

Subsequent analyses showed a correlation between building energy consumption rate and the university academic calendar. The energy consumption increased at the onset of the autumn semester in March and peaked in May. The latter is the final month of the semester before the assessment period. There was a decrease in the building energy consumption rate in June during the assessment period. The lowest building energy consumption rates occurred in July during the holiday season between semesters. The foregoing pattern recurred in August, which is the start of the spring semester. The highest building energy consumption rates occurred in October, which is the final month of the spring semester. The assessment period then commenced in November, resulting in a decrease in energy consumption. There was a low building energy consumption rate during the summer semester, between December and February; this is reflective of many staff taking holiday and/or working from home during the Australian summer months.

In Australia, typical office building HVAC systems account for approximately 40% of the total building energy consumption. Standard lighting generally consumes ≤40% of all energy in commercial premises. However, light-emitting diode (LED) lamps use ≤75% less energy and emit 90% less CO_2 than halogen lamps [34]. Therefore, as the study building was retrofitted with LED lighting, lighting-associated energy consumption was assumed to be 10% of the total building energy consumption. Thus, the combined HVAC system and the lighting loads would account for approximately 50% of the total building energy consumption, at a cost of approximately AUD 375,000/y.

The U.S. Department of Energy estimates a savings of ~1% for each Fahrenheit temperature degree of thermostat adjustment every 8 h. They recommend reducing thermostat settings by 7–10 degrees Fahrenheit below their normal settings for 8 h daily to realize annual energy savings of ≤10% [35]. Similar reductions were estimated by Applied Energy Saving Solutions (AESS) (Clayton South, VIC, Australia https://appliedenergysaving.com.au (accessed on 15 April 2021)). AESS proposed that, in Australia, adjusting the temperature setpoint by 1 °C can lower heating or cooling unit energy consumption by ~10% [36]. Case-specific studies and trials are required to accurately estimate energy savings. In the pilot study, according to the preferred comfort levels reported by participants, more than 50% of the thermostat zones in the offices could be lowered from their current settings by as much as three degrees for 8 h/d. Thus, according to the findings of this pilot study, if 50% of the thermostat zones in the office areas were lowered from their current settings by three degrees for 8 h/d, this could result in a savings of about 50,000 kWh, or 5% of total annual energy costs per year. Powershop (Wellington, New Zealand, https://www.powershop.com.au/carbon-calculator/, accessed on 31 August 2021) [37] is a carbon calculator website customized for Australia, and it estimated that an energy saving of 50,000 kWh could equate to an annual carbon dioxide reduction of 41.00 t for the state of New South Wales alone. Assuming similar rates for all occupants of the building, as much as AUD 15,000 could be saved annually simply by correctly adjusting the office thermostats to suit the individual preferences identified in this study.

5. Conclusions

The aim of this research project was to demonstrate the impact of indoor microclimate changes on the environmental comfort levels of commercial and office buildings and their potential impact on building energy consumption. This pilot study investigated energy consumption and building management performance, and evaluated the environmental comfort feedback of participating occupants in an office structure.

Analysis of the data collected from portable microclimate sensors positioned at various occupant-selected points in the building indicated that the inside temperature was 3.5–4 °C higher on average than the outside temperature. By contrast, the inside humidity, air pressure, light intensity, and volatile organic compound (VOC) levels were lower inside than outside the building. The variation across different office spaces, and even within office spaces, indicate the potential significance of microclimate readings to influence individual comfort levels, as well as studies of user comfort more generally. Although most of the building energy codes, such as ASHRAE Standard 55 [38], are met in the offices, participants still experience discomfort in different microclimates. One reason behind that is that the building occupant codes are designed for a typical human being, while individual preferences could significantly vary. For instance, the research showed that two participants in a single shared room had different comfort level perspectives and preferences. Additionally, the code requirement is that a comfortable zone should sufficiently satisfy at least 80% of its occupants, meaning that there is always room for 20% dissatisfaction. However, the findings of this research indirectly indicated that ≤5% of total annual building energy consumption costs may be saved by more effectively and efficiently managing office thermostat control. This adjustment could lower annual energy consumption by ~50,000 kWh and reduce yearly CO_2 emissions by 41.00 t.

The present study assessed the impact of the microclimate and its associated environmental factors on the comfort level of the occupants. Temperature, lighting, noise, air quality, air movement, and relative humidity can all affect environmental comfort. However, it was ambient office temperature that most affected the occupant comfort level. The female participants usually preferred higher temperatures than the male participants and were comparatively less satisfied with the default temperature settings of their offices than their male colleagues. The foregoing findings should be considered when setting the indoor temperature for office building zones with large numbers of female occupants. The present study also demonstrated that provision of appropriate levels of artificial lighting is significant to occupant comfort. Window direction and daytime sunlight access are important for ensuring adequate lighting. Adjustment of the brightness level of artificial lighting is essential to attenuate the negative effect of excessive nighttime brightness. Evaluation of the impact of the aforementioned factors on building occupant comfort level showed that the environmental conditions of the workspace affect occupant concentration, productivity, and alertness. This supports the findings of numerous other studies showing that increasing occupant comfort may enhance worker productivity and concentration [39]. Labor costs are a significant percentage of expenditure in any business (up to 85%, according to Zhiviv, 2020 [40]). It follows that even small increases in productivity can markedly improve the profitability of an enterprise. However, understanding how and where to make adjustments to improve occupant comfort has been challenging, as environmental comfort assessment is highly subjective, varying widely among individuals as a result of their personal conditions and preferences.

The mobile phone application used by the respondents in this project enabled them to express their comfort level accurately and may therefore be able to assist facility managers to more easily understand how to adjust microclimates in their building. This indicates that the sensor technology utilized in this study may also be feasible for broader application in commercial settings. Hence, the next phase of this research will involve industry partners who will install and evaluate the sensor and mobile phone application in certain commercial office buildings within the Sydney CBD. Additionally, a future direction of research is to study the combined impacts of the environmental measurements on occupants' comfort perception, i.e., how relative humidity and temperature impact each other and whether addressing one of them would be sufficient to increase user comfort.

One of the limitations of this study was the existing number of sensors and their specifications. Although most of the factors impacting the occupants' perception of comfort, such as temperature, humidity, air movement, lighting, etc., were included in the study, there were other possibilities, such as metabolic rate and occupants' health conditions, which were not collected. Hence, it is important to include all the relevant factors for more detailed analysis and to include a larger number of participants for more accurate results. Additionally, comfort is a subjective feeling, which means that an individual's personal perception of comfort in an indoor environment can vary from person to person and can be influenced by a variety of factors such as age, health, activity level, and personal preferences. Hence, subjective comfort is a complex and multifaceted concept that depends on many different factors. Understanding these factors can help individuals and organizations create a more comfortable and productive indoor environment.

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