Developing a rating dashboard for healthy classrooms

Lianrui Sun

Computer Science, Worcester Polytechnic Institute

Interactive Qualifying Project

Instructor: Shichao Liu

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Contents

Abstract

This study addresses the significant gap in understanding the impact of indoor classroom environments on student learning by developing a dynamic rating database for assessing classroom healthiness. Utilizing Awair Omni sensors, the project monitored temperature, air quality, humidity, noise, and lighting across ten classrooms at Worcester Polytechnic Institute. The methodology combined quantitative data from environmental sensors with qualitative feedback via student surveys. Findings revealed that while most classrooms met basic environmental standards, improvements were necessary in temperature regulation, humidity levels, and CO_2 concentrations to foster optimal learning conditions. The study highlights the critical influence of the physical classroom environment on academic performance, recommending upgrades to HVAC systems, improved ventilation, and enhanced feedback mechanisms to create healthier learning spaces. By bridging the gap in indoor environmental monitoring, this project lays the groundwork for future research and implementation strategies to enhance educational outcomes through optimized classroom environments. The investigation underscores the profound impact of indoor classroom conditions on students' learning efficiency, proposing targeted interventions to facilitate temperature control, humidity levels, CO2 concentration, and overall air quality.

1. Introduction

The advent of meteorological stations and user-friendly weather applications has transformed how we interact with our outdoor environment. In today's digital age, we can easily access a wealth of meteorological data. According to the data from the World Meteorological Organization, there are approximately 11,000 stations on land making observations at or near the Earth's surface, at least every three hours and often hourly, of meteorological parameters such as atmospheric pressure, wind speed and direction, air temperature, and relative humidity. In addition to the parameters mentioned, air quality data, monitoring pollutants like PM2.5, PM10, ozone, nitrogen dioxide, and sulfur dioxide, are also collected at many of these stations, further enriching our understanding and enabling more comprehensive environmental assessments and health advisories. Such rich information on the outdoor environment allows us to take strategies to mitigate the adverse impact of the outdoor environment on our daily lives.

However, while we have made remarkable progress in understanding and monitoring the outdoor environment, there is a significant gap in our knowledge when it comes to indoor spaces where people spend 90% of their lifetime (Klepeis, N.E., Nelson, W.C., Ott, W.R., Robinson, J.P., Tsang, A.M., Switzer, P., Behar, J.V., Hern, S.C. and Engelmann, W.H., 2001). In the learning environment, students spend most of their lives in classrooms. These learning environments are essential to students' academic pursuits. For instance, Worcester Polytechnic Institute (WPI) states that students invest a significant amount of their time, upwards of 15-17 hours per week, in academic activities within these spaces. Despite this, the quality of the classroom environment has remained largely uncharted territory in terms of environmental monitoring.

The impact of the classroom environment on students' academic performance is an issue that deserves our attention. Research from Nigeria has highlighted a noteworthy correlation between the learning environment and students' academic achievement in the education system (Usman, Y. D., & Madudili, C. G., 2019). Similarly, a study conducted by an Australian Faculty of Business and Economics found that even seemingly minor factors, such as the comfort of the chairs and the room's temperature, can significantly affect students' alertness and engagement. One student in the study commented, "They turned the heaters on, and it is just more comfortable than with my bed at home... you cannot help but fall asleep" (Closs, 2022). At the same time, indoor lighting is also one of the significant factors directly linked to the student's learning efficiency. The researchers employed a survey, gathering data from 150 students participating in the Alpha course in Malaysia, and found a significant, positive relationship between the lighting quality in learning environments and students' learning performance (Samani, 2012). Additionally, noise is another critical factor that significantly impacts students' learning efficiency, highlighting the importance of considering acoustic conditions in educational environments (Xiong, L., Huang, X., Li, J., Mao, P., Wang, X., Wang, R., & Tang, M., 2018).

The initial step in enhancing the physical environment of classrooms is monitoring various physical environmental parameters to increase public awareness about how indoor environments fluctuate based on time, building type, and occupancy levels. In this project, I deployed Internet of Things (IoT) environmental sensors in ten WPI classrooms and developed an online dashboard to display the monitored data publicly for each classroom. Additionally, questionnaires were distributed to gather students’ feedback on their satisfaction with the classroom environment.

2. Background

The National Center for Education Statistics mentions (Alexander D., Lewis L., 2014) that over half of the U.S. public schools in the 2012-2013 timeframe acknowledged a need for infrastructural investments to upgrade their facilities to a satisfactory level. The most frequently identified structural shortcomings pertained to window fittings, plumbing systems, and climate control/air circulation. According to a study (Cayubit, 2022), a student's academic achievement is influenced by the learning atmosphere regarding academic drive, instructional methodologies, and student participation. Given this, it is pivotal for professionals like educational psychologists, school counselors, administrators, educators, and other key players in the educational sector to mold the academic environment to make it more apt for instruction. In the subsequent sections, we will discuss how various environmental aspects, like air quality, temperature, humidity, lighting, and acoustic comfort, are crucial in determining student outcomes.

2.1 Temperature

It is well-established that our environment profoundly impacts our cognitive abilities. Room temperature influences perception, attention, memory, learning, and thinking, among various environmental factors. Deviations from an optimal temperature range can directly lead to reduced learning performance (Xiong, L., Huang, X., Li, J., Mao, P., Wang, X., Wang, R., & Tang, M., 2018). When the brain is forced to expend energy on maintaining homeostasis due to extreme temperatures, it has fewer resources available for cognitive functions. Cold environments can cause blood vessels to constrict, reducing blood flow to the brain and slowing neural activity (Tran, L. T., Park, S., Kim, S. K., Lee, J. S., Kim, K. W., & Kwon, O. , 2022). Conversely, hot environments can induce lethargy and discomfort, making concentration difficult (Taylor, L., Watkins, S. L., Marshall, H., Dascombe, B. J., & Foster, J., 2016). Quantitative data correlated thermal sensation or satisfaction ratings and relative learning outcomes. When students reported feeling "slightly warm," their performance was satisfactory. However, a cold, uncomfortable environment negatively impacted students' learning efficiency more than a warm, uncomfortable setting did (Closs, 2022).

Research from China underscores the critical importance of maintaining a stable temperature for optimal learning outcomes (Wang, D., Xu, Y., Liu, Y., Wang, Y., Jiang, J., Wang, X., & Liu, J., 2018). Unstable temperatures can significantly affect student performance, especially when the ambient temperature falls below 22°C or rises above 29°C. Their findings indicate that the optimal range for peak learning performance lies between 24°C and 26°C. Instead of considering temperature value, it is essential to emphasize perceived thermal sensation because this perception can vary based on different regions and individual preferences (Zhang, N., Cao, B., Wang, Z., Zhu, Y., & Lin, B., 2017). Their research points out a notable decline in learning outcomes when the indoor temperature deviates by more than 3°C from the vote value of thermal sensation.

2.2 Relative Humidity

In a study conducted by Razjouyan et al. (Razjouyan, J., Lee, H., Gilligan, B., Lindberg, C., Nguyen, H., Canada, K., ... & Najafi, B., 2020), the impact of indoor air humidity (IAH) on stress levels among office workers was explored through the lens of heart rate variability. The study tracked heart rate variability over three consecutive days among office workers. It was observed that those who spent their workdays in environments with relative humidity (RH) levels ranging from 30% to 60% exhibited approximately 25% less stress, as inferred from lower heart rate variability, compared to their counterparts who were exposed to drier conditions for most of their time. This discovery underscores the potential stress-reducing benefits of maintaining optimal RH levels in the workplace. Research (Wolkoff, P., Azuma, K., & Carrer, P., 2021) suggests that a significant factor in the decline of cognitive work performance may be attributed to symptoms resembling those of dry eye, particularly under conditions of low IAH. The instability of the precorneal tear film induced by dry air conditions leads to hyperosmolarity and triggers an inflammatory response cascade, as detailed by Wolkoff in various studies. The literature also indicates that many office workers experience eye fatigue during tasks requiring high visual and cognitive effort, such as working with visual displays under suboptimal lighting conditions (Koh, 2016).

This kind of impact is not only seen in the work environment but also affects the efficiency of students in the learning environment. There is a study (Liu, C., Zhang, Y., Sun, L., Gao, W., Jing, X., & Ye, W., 2021) comprehensively investigated how indoor relative humidity impacts undergraduate students' learning through both subjective assessments and objective physiological measurements, focusing on factors such as thermal discomfort, fatigue, distraction, and learning efficiency. Undergraduate students are more likely to feel uncomfortable in high-humidity environments, but they perform worse academically in low-humidity environments. In low-humidity environments, the overall academic performance of undergraduates decreases due to dryness of the mucous membranes of the eyes and respiratory tract. At 40% relative humidity, fatigue, reading speed, and distraction decreased by 23.3%, 12.2%, and 61.1%, respectively, compared with 20% relative humidity.

2.3 Air Quality (CO_2, TVOCs, PM2.5) and Ventilation

In educational environments, air quality can be compromised by pollutants, suboptimal ventilation, and elevated carbon dioxide levels, potentially affecting students' attentiveness and cognitive performance. Daisey (Daisey, Joan M, Angell, William J, & Apte, Michael G., 2003) points out that many classrooms might not meet the current ventilation standards set by ASHRAE, as suggested by data on ventilation rates and CO2 concentrations. Another research from Satish et al. (Satish, U., Mendell, M. J., Shekhar, K., Hotchi, T., Sullivan, D., Streufert, S., & Fisk, W. J., 2012) shows that elevations in indoor CO2 levels, achieved by adding ultrapure CO2 while maintaining other variables constant, were linked to notable declines in decision-making capabilities. When CO2 concentrations were raised to 1,000 ppm from 600 ppm, there was a significant decrease in six out of nine decision-making performance indicators. At a CO2 concentration of 2,500 ppm, compared to 600 ppm, there was a reduction in seven out of nine performance indicators, with the percentile ranks for specific metrics dropping to levels indicative of marginal or ineffective performance. These results suggest that CO2 can directly affect performance in ways that might have significant economic implications, potentially put specific individuals at a disadvantage, and could restrict how much the outdoor air ventilation rate per person in buildings can be decreased to conserve energy. Further research is needed to validate these outcomes. These results suggest that lower CO2 concentrations, particularly at or below 600 ppm, are associated with better performance in decision-making tasks. Therefore, striving to maintain CO2 levels close to 600 ppm in indoor environments could be considered optimal to avoid negative impacts on human cognitive functions and decision-making performance.

When addressing air quality in educational environments, it is critical to consider CO_2 levels, the presence of Total Volatile Organic Compounds (TVOCs), and delicate particulate matter (PM2.5). These pollutants can significantly impact student health and cognitive functions, emphasizing schools' need for comprehensive air quality management. As highlighted by research (Manisalidis I, Stavropoulou E, Stavropoulos A and Bezirtzoglou E, 2020), short-lived effects of indoor pollution can range from mild discomfort, including eye, nose, and skin irritations, wheezing, and breathing problems, to severe conditions like asthma, bronchitis, and cardiovascular and lung diseases. Evidence suggests that even minimal air pollution can substantially impact learning efficacy.

2.4 Noise

Classroom noise, originating from outdoor factors like passing vehicles and internal disruptions such as students talking, can notably hinder understanding and memory retention. An ideal sound environment ensures effective communication between the teacher and pupils. Based on a study (Minelli, G., Puglisi, G. E., & Astolfi, A., 2022), only a meager 5% of studies analyzing the classroom's auditory environment's effect on student outcomes were deemed suitable. Many were disqualified due to a lack of real-world relevance or not meeting specific criteria. Fifty-six research papers presented empirical data on classroom sound settings and student performance. However, only thirty-eight of these fit the review standards. The focus was solely on classrooms with typical lessons catering to students with standard hearing capabilities. A recommended analytical framework emerges from this study, linking room acoustics' impact on tasks to achievements in learning, comprehension abilities, speech clarity, and individual perceptions.

The studies suggest specific conditions to optimize student performance. A reverberation time between 0.6 and 0.7 seconds is suitable for all age groups, with a signal-to-noise ratio (SNR) of 12 dBA or higher. The equivalent continuous noise level (LNeq) shouldn't surpass 35 dBA for students under 12 and 40 dBA for those above. A Speech Transmission Index (STI) of at least 0.65 is recommended for younger students, whereas this requirement reduces to 0.60 for older students.

2.5 Lighting

Illumination has a profound impact on learning efficacy through various means, such as facilitating visual tasks, modulating the body's circadian rhythms, influencing mood and perception, and assisting in vital chemical processes in the body (Boyce, P., Hunter, C., & Howlett, O., 2003).

Research exploring the impact of varied lighting intensities on the prescription error rates by pharmacists was carried out by Buchanan et al. in 1991. The study observed a decline in mistakes when the illumination on the working surface was comparatively brighter (Buchanan, T. L., Barker, K. N., Gibson, J.

T., Jiang, B. C., & Pearson, R. E., 1991). During this research, three distinct light intensities were assessed (450 lux, 1,100 lux, 1,500 lux). The error rate for dispensing medications was lower (2.6%) at a lighting intensity of 1,500 lux (the peak level) compared to a 3.8% error rate at 450 lux. Such results align with data from different contexts, which indicate that as illumination enhances, task efficiency follows suit (Boyce, P., Hunter, C., & Howlett, O., 2003).

Moreover, there are over 11 robust research studies that highlight the potency of bright illumination in alleviating depressive symptoms among those with seasonal affective disorder and those working night shifts. Most of this research focuses on the benefits of artificial bright light in combating depression. The light intensities for these treatments generally vary between 2,500 lux and 10,000 lux (Beauchemin, K. M., & Hays, P., 1996). To curate an optimal learning ambiance for learners — serving both their educational needs and mental well-being — Acknowledging that lighting varies from dawn to dusk, we need to have dynamic lighting control in our classroom to maintain the best lighting conditions.

2.6 Summary

Understanding indoor environmental factors is essential, especially when considering that the classroom is not just a passive setting but an active component in the learning process. It is a space where knowledge is imparted, ideas are exchanged, and creativity is nurtured. For these reasons, ensuring that the classroom environment is conducive to learning becomes imperative. For college students, the environment can be an important learning motive that plays a significant role (Cayubit, 2022). However, despite our awareness of these factors and their impact, there is limited empirical data regarding the real-time status of classrooms. A majority of the current assessment methods are reactive rather than proactive. We need a systematic, continuous, and comprehensive method of monitoring these factors, akin to how we monitor our outdoor environment. The current state of technology offers promising solutions to this challenge. With advancements in sensor technology, data analytics, and the Internet of Things (IoT), we are poised to integrate comprehensive monitoring systems within classrooms. These systems can provide real-time feedback to educators, administrators, and students, enabling immediate corrective actions.

In the following sections, we will delve deeper into the potential of such monitoring systems, exploring their design, implementation, benefits, and challenges. We hope that by shedding light on this issue, we can foster a paradigm shift in how we perceive and address the classroom environment, ensuring that every student can learn optimally for their well-being and academic success.

3. Methodology

We are utilizing a mixed-methods approach, gathering both quantitative data from environmental sensors and qualitative feedback from students via an online survey. For the data collection part, we will use Awair Omni placed in each classroom to collect indoor environmental data and store it on the official server. In addition, we will use Qualtrics to design an online questionnaire and post QR codes in the surveyed classrooms to collect student responses.

3.1 Data Collection

3.1.1 Selection of Rooms

Ten classrooms distributed across four buildings (Atwater Kent Laboratories, Fuller Lab, Salisbury Laboratories, and Olin Hall) were selected based on their varying architectural styles, usages, and capacities. Those are the selected classrooms:

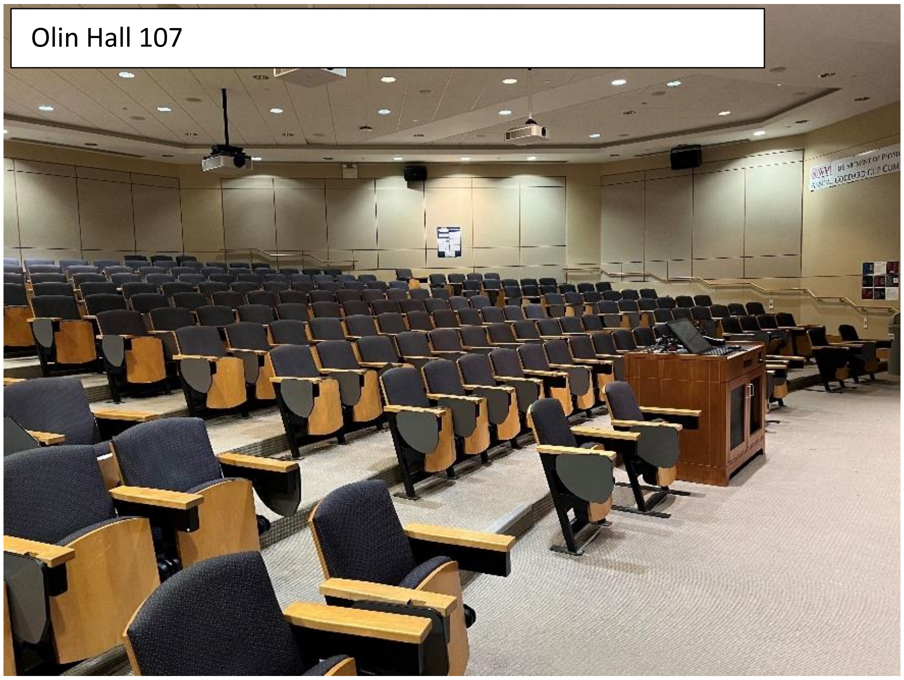
1. Salisbury Laboratories
2. Atwater Kent Laboratories
3. Fuller Laboratories
4. Olin Hall
5. Unity Hall

Figure 1: The map of the WPI campus with five selected building

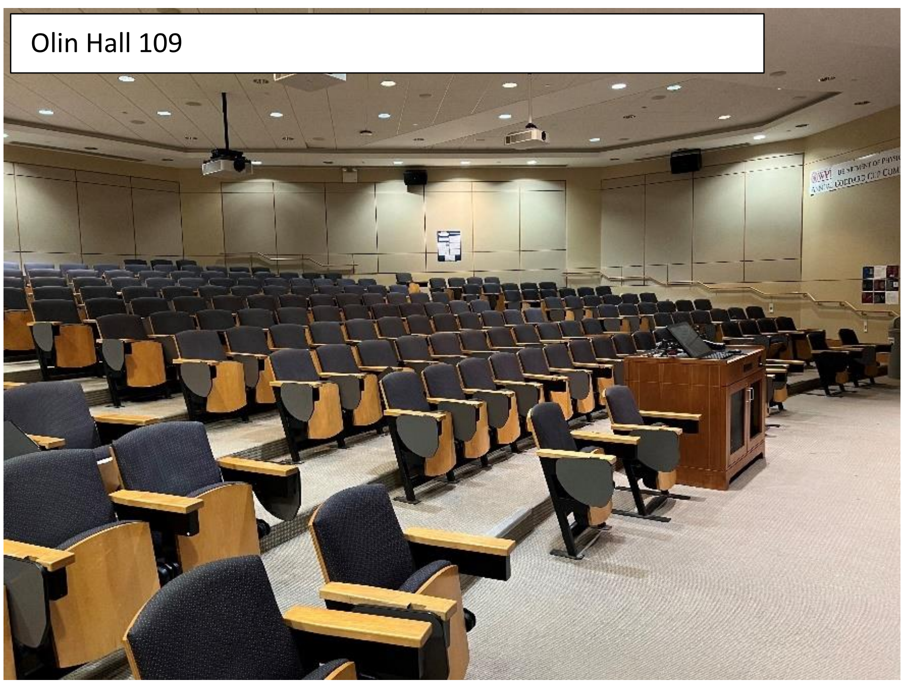
Table 1: Selected Classrooms

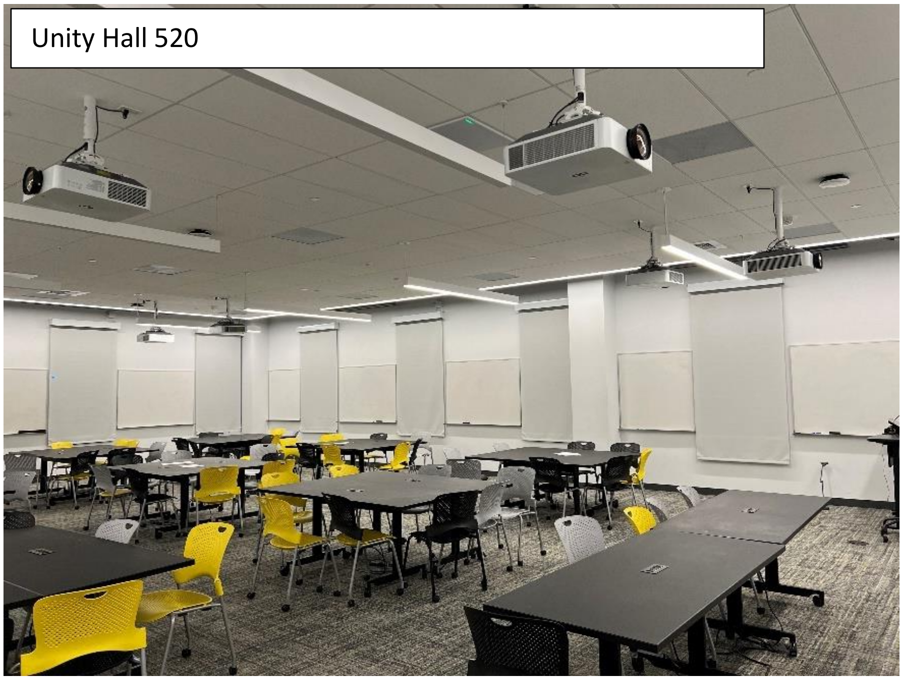
Image
Atwater Kent Laboratories 116 
Atwater Kent Laboratories 233 

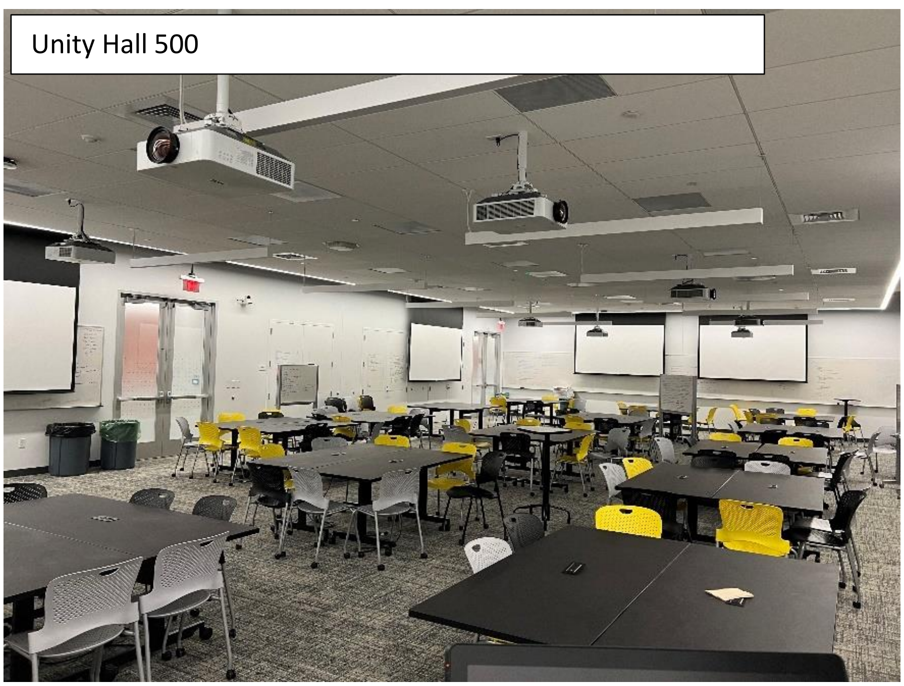
Olin Hall 107



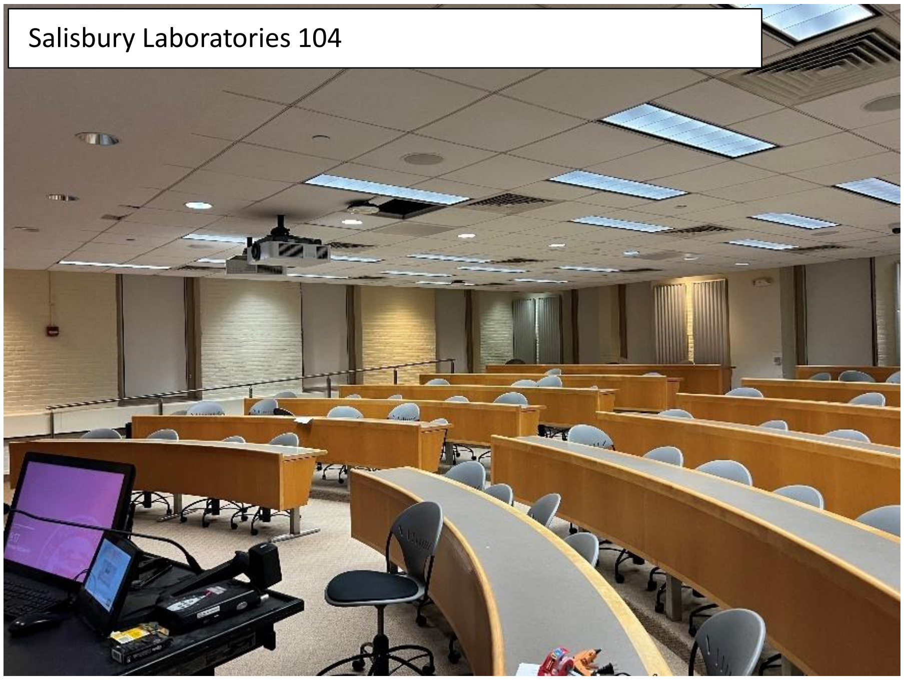
Olin Hall 109



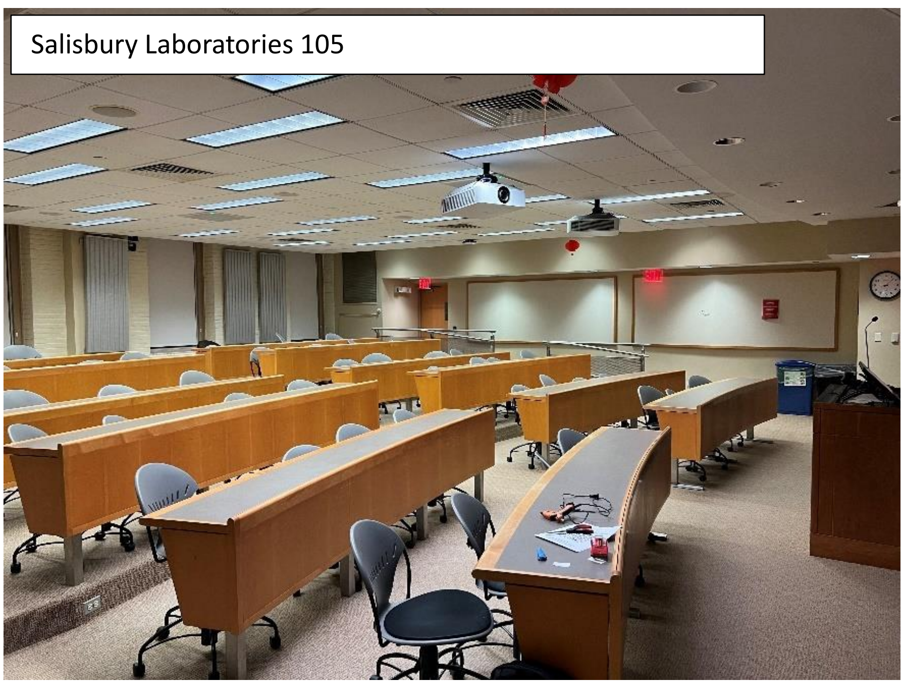

Unity Hall 520

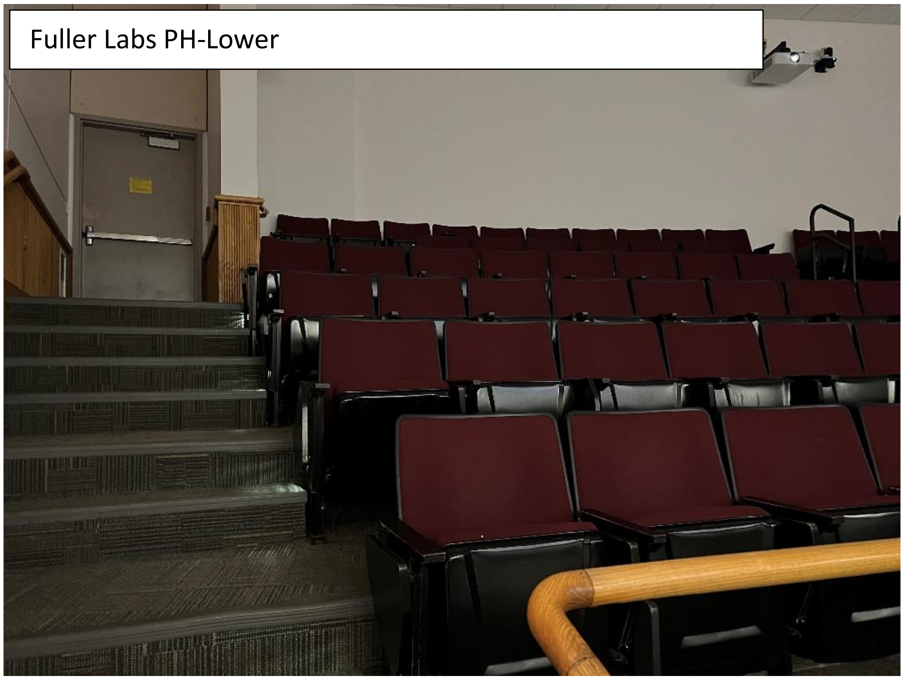

Unity Hall 500

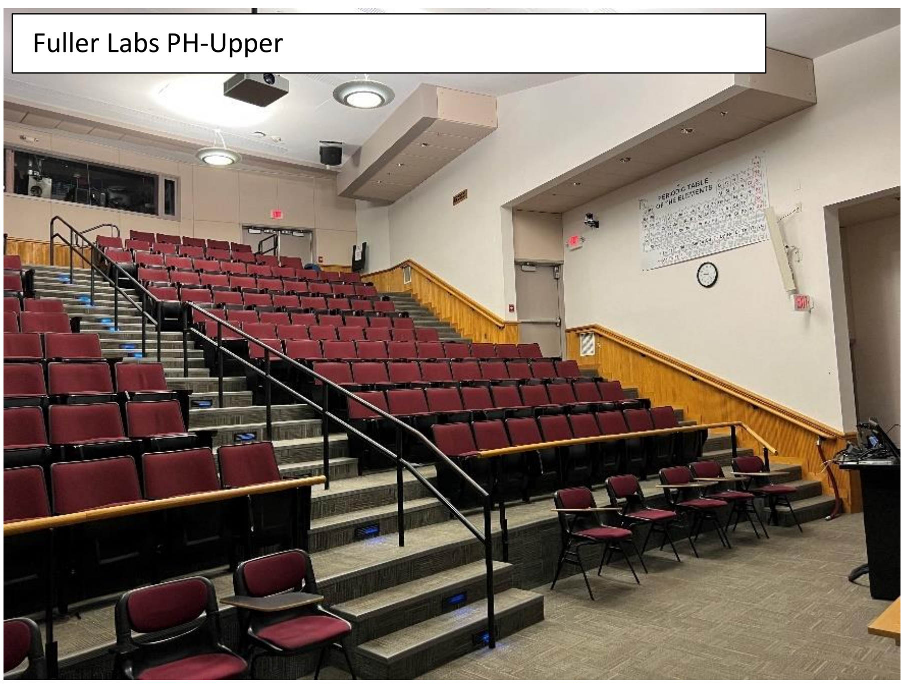
Salisbury Laboratories 104



Salisbury Laboratories 105







Regarding classroom selection, we prefer large classrooms located in significant buildings. Larger classrooms affect more students than smaller classrooms. We have found more variability and uncertainty in data when collecting data from smaller classrooms or classrooms located in specific locations. For example, during the winter months, it is clear that the indoor temperature in specific classrooms is often affected by outside weather. This is evident when people constantly enter and exit the classroom, causing the classroom door to open and close and the temperature to drop dramatically. In order to minimize these uncontrollable factors that could affect the data and to obtain more consistent readings of the indoor environment, we chose classrooms with higher capacities. At the same time, our goal was to collect a large amount of data. We anticipated a limited number of participants in the indoor comfort survey. Therefore, placing sensors and questionnaires in large classrooms was critical to collecting accurate feedback for subsequent data analysis. The selected classrooms are located in significant buildings and are more representative and research-worthy. Salisbury Laboratory, for example, faces complex challenges. During the 2023 B semester, two air quality problems occurred within two weeks. The cause was a chemical program in the lab that severely degraded air quality, adversely affecting student learning and life.

3.1.2 Sensor Deployment

Advanced IoT sensors, Awair Omni, were installed in these classrooms to monitor parameters indicative of the indoor environment. This includes temperature (°C/°F), relative humidity (%), CO_2 (ppm), TVOCs (ppb), PM2.5 (µg/m³), noise (dB), and light (lx).

Table 2: Technical Accuracy of Awair Element Sensors

Sensor	Sensor Model	Type	Range	Resolution	Accuracy
Temperature	Sensirion SHT31	CMOS	0 - 90°C (32 - 194°F)	0.015ºC	±0.2°C
Relative	Sensirion	CMOS	0 - 100% RH	0.01% RH	±2% RH

Humidity	SHT31				
Carbon Dioxide (CO_2)	Amphenol-Telaire T6703	NDIR	400 - 5,000ppm	1ppm	±75ppm or 10% (whichever is greater)
Volatile Organic Compounds (TVOC)	Sensirion SGP30	Multi-pixel metal oxide gas sensor	20 - 36,000ppb	1ppb	±15%
Fine Dust PM2.5	Honeywell HPMA115S0	Laser-based light scattering sensor	0 - 1,000 µg/m³	1 µg/m³	±15 µg/m³ or 15% (whichever is greater)

Placing IoT sensors in the classroom, especially at the back, can effectively gather consistent and stable data. Choosing the rear of the classroom reduces the risk of the sensors being disrupted during typical classroom activities, such as lectures or interactive sessions. The front of the classroom is often a hub of activity, so sensors placed there might be obstructed or inadvertently tampered with. Furthermore, positioning these sensors in the corners further minimizes potential damage. Corners are typically areas with reduced foot traffic, making them less prone to accidental bumps or knocks. They are also less accessible, which can deter unnecessary tampering by curious students. However, placing the sensor in a corner also adversely affects readings, such as inaccurate air quality, noise, and light monitoring. Therefore, we must balance obtaining accurate data while protecting the lab equipment and not interfering with student learning.

However, classrooms have another challenge, particularly those with limited electrical outlets. It has been observed that students have a significant demand for charging their electronic devices, and if sockets are scarce, they might unplug devices that are not theirs to meet their charging needs. Labeling is crucial to mitigate this risk for your IoT sensors. By placing a clear label on the sensor, such as "Do Not Unplug - Classroom Sensor," you inform students of its importance. A more detailed message explaining the sensor's role in maintaining classroom conditions can further emphasize its significance and deter unplugging. It is also worth considering that, to ensure the consistent operation of these sensors, a stable internet connection is essential. Depending on the infrastructure available, this connection can be via Wi-Fi or a wired connection.

Figure 2: Awair Sensor in Fuller Labs PH-Upper

3.1.3 Data Retrieval

The sensors are programmed to record data regularly, offering a detailed temporal profile. Data will be stored securely in a cloud server and accessed periodically for analysis. At the same time, we will use the API to design a data visualization webpage to observe the classroom environment continuously.

3.1.4 Survey Design

The survey captures students' email, classroom number, comfort level, and time spent in different environments (dorm, outdoor, school building for learning/working). In addition, a QR code will be displayed prominently in each classroom, allowing students to access the survey digitally on their devices. Before accessing the main survey, students will receive a detailed consent form explaining the study's purpose, data collection procedures, and confidentiality guarantees. Only after granting consent will the respondents proceed to the actual survey questions.

Figure 3: Survey QR Code in SL104

3.2 Data Analysis and Visualization Website

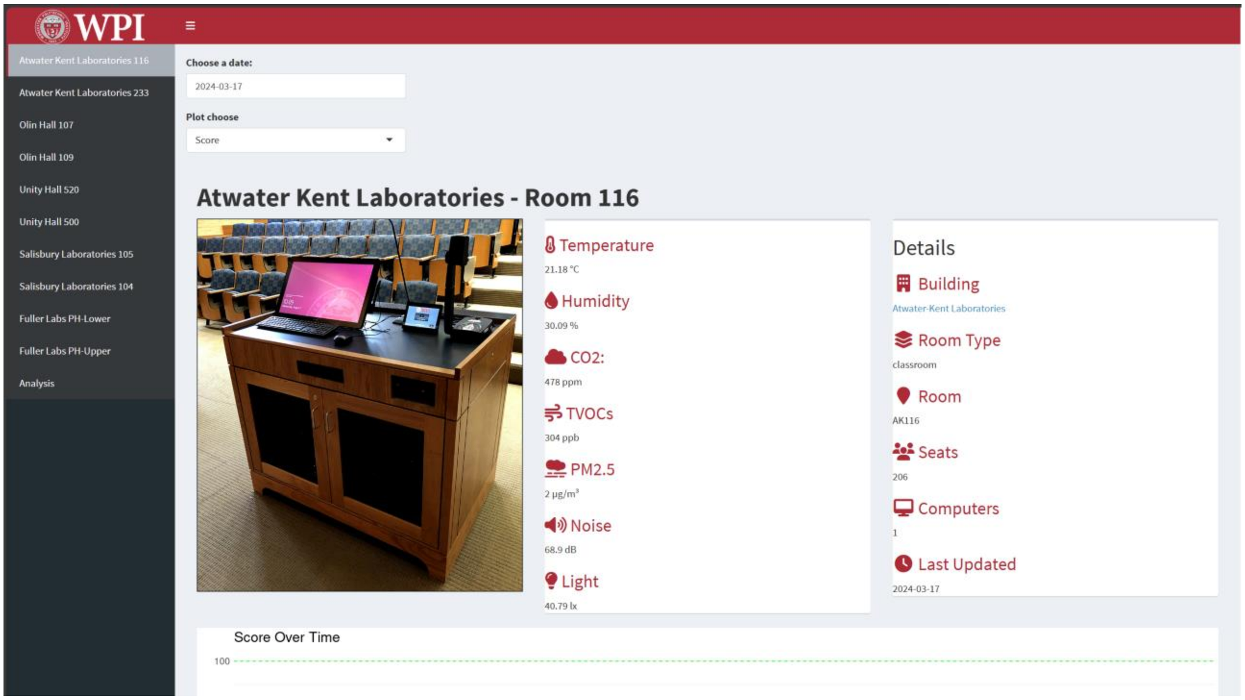


Figure 4: Data Analysis and Visualization Website in Shinyapp.io (https://lianruisun.shinyapps.io/WPIClassroomDashboard/)

In order to provide safer and easier access to our indoor environmental data, we have designed a data visualization website. On the site, users can see environmental visualizations for ten classrooms. This includes real-time environmental data, classroom profiles, and historical data visualizations. The whole can be divided into three parts: front-end UI design, back-end server design, and data analysis. In the front-end design, we used WPI's official red color as the main style (sRGB: R172, G43, B55, and the secondary grey color also took WPI's official color and used WPI's logo. This series of designs makes the interface more WPI style. In the main interface, we used the dashboard in Shinyapp as the mainframe and customized the colors by changing the CSS file. In the server design, we used Awair's API to realize real-time monitoring of the indoor environment of the classroom. At the same time, by collecting and uploading data manually, we can achieve the generation of data visualization in the backend. We deployed the website on the shinyapp.io accessible server to make the website public. In data analysis, we unify the format of a large amount of data through algorithms, then filter it through time, and finally visualize the filtered data. The whole process achieves efficiency and accuracy.

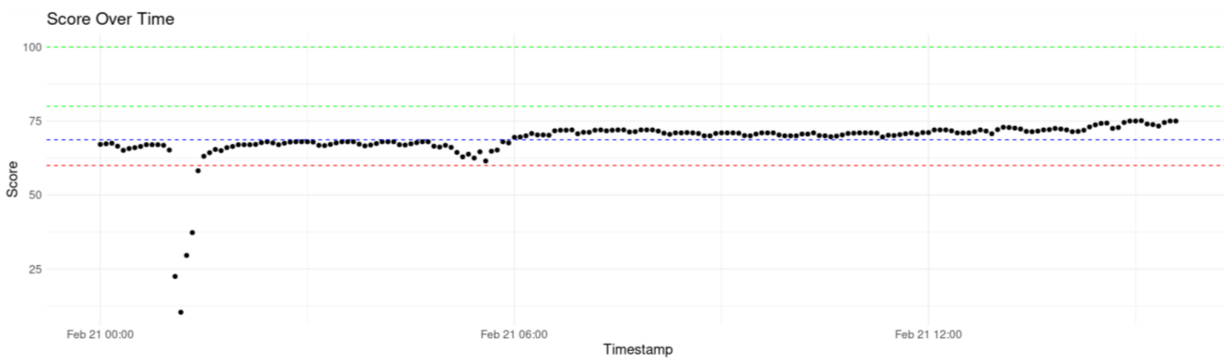


Figure 5: Data visualization of Score on February 21 in AK233

4. Results

We have plotted a table with each classroom as a large unit, each date as a medium unit, and each indoor environmental factor as a small unit, obtaining an x-axis for time (24h) and a y-axis for units. Furthermore, in the table, represent the average. Also, mark the most suitable environmental range. Through our 28 days of data collection from February 1st to February 28th, we obtained indoor environmental data for ten classrooms. We will analyze the health conditions of the classroom based on different factors.

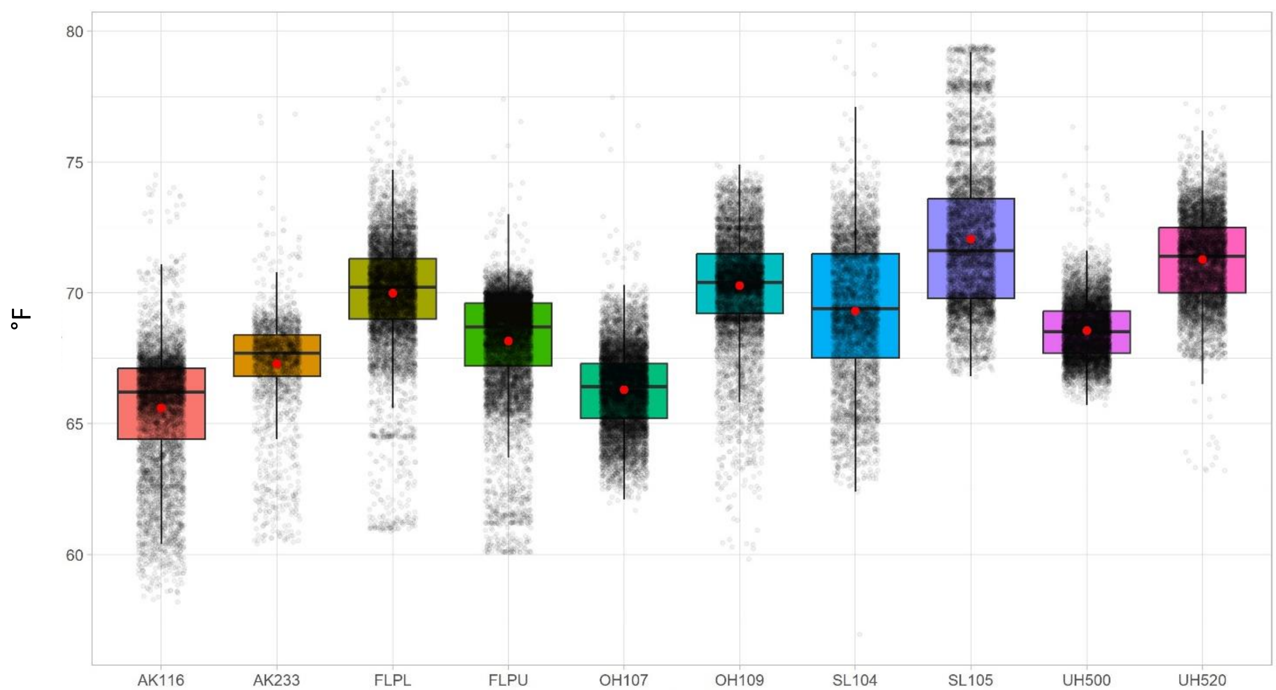


Figure 6: Distribution of Daily Room Temperatures Over 28 days in Various Classrooms (both occupied and unoccupied periods) (Formula: (°C × 9/5) + 32 = °F)

Most indoor temperatures are controlled from 18 to 24 °C (64.4°F to 75.2°F) (Figure 6). However, each classroom exhibited a wide range of temperatures. We hypothesize that this is due to variations in indoor temperatures due to the time of day. Schools do not usually provide air conditioning in the evening, so a significant reduction in classroom temperatures generally occurs at night. However, as our study progressed, the change in the indoor environment's temperature did not decrease significantly when the nighttime data were not calculated. Therefore, we have a second conjecture: that the change in the number of people in the classroom led to a change in the indoor environment. We observed a correlation between the change in CO_2 content, the change in temperature, and the change in noise.

In Figure 7, we find that the indoor temperature appears to increase significantly after 8:00 a.m. The temperature increased from 17 °C to 22 °C, peaking between 3 and 6 p.m. Also, in Figure 8, we found a similar change in the indoor carbon dioxide content. From 8 a.m. onwards, the carbon dioxide level increases significantly and peaks between 3 p.m. and 4 p.m. Also, in Figure 9, we found that the noise level in the classroom also increased significantly.

Therefore, we have used carbon dioxide and noise as judgment criteria to determine whether there are people in the classroom or not so that we can get more effective research data. After our comprehensive consideration, we set the noise and carbon dioxide standard as dynamic changes. Since each classroom has a different structure and the location of the environmental detectors is different, each classroom will have a different unoccupied standard. We use the data from 1 AM to 5 AM as the unoccupied standard for each classroom to get the average noise and carbon dioxide during this time. At the same time, we only count the data that is greater than the unoccupied standard between 8 am and 7 pm so that we can get accurate data during the students' school hours. In the next section, we will analyze the changes in the environment and the effects on people when there are people in the classroom and when there are no people simultaneously.

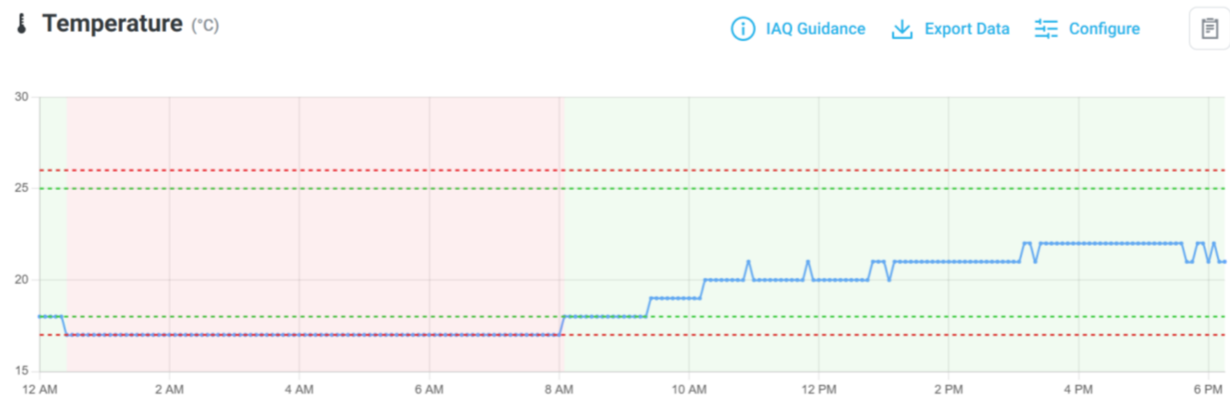


Figure 7: Hourly Room Temperature Profile for Classroom AK116 on February 26, 2024

Figure 8: Hourly CO2 Profile for Classroom AK116 on February 26, 2024

Figure 9: Hourly Room Noise Profile for Classroom AK116 on February 26, 2024

4.1 Temperature

In Figure 10, we obtained the temperature inside each classroom occupied over 28 days. We found that the classroom temperature difference is on the high side. Most of these classrooms were able to stay between 20 °C and 24 °C (68 °F and 75.2 °F). The average temperature of all but three classrooms is below what we expect optimal. In Figure 11, we have tallied the percentage of time that the three worst classrooms were at their optimal temperature. In this case, the blue color represents being between 20 and 24 °C, which is the best study temperature according to the research on the influence of indoor air temperature and relative humidity on the learning performance of undergraduates (Liu, C., Zhang, Y., Sun, L., Gao, W., Jing, X., & Ye, W., 2021), while the red color is labeled outside of that range. We found that three classrooms, AK233, AK116, and OH107, have poor temperature control. AK116 was not even at the optimal temperature 89.5% of the time. We analyzed these poorly performing classrooms more. We found that almost all out-of-range data was below 20 degrees Celsius (68 degrees Fahrenheit). This means that these three classrooms had lower temperatures. We hypothesized that those three classrooms were more affected by the cold temperatures outside, which led to the generalized cold temperatures. We verified the effect of outdoor temperatures on indoor temperatures by comparing the diurnal temperature variations in these three classrooms to other classrooms.

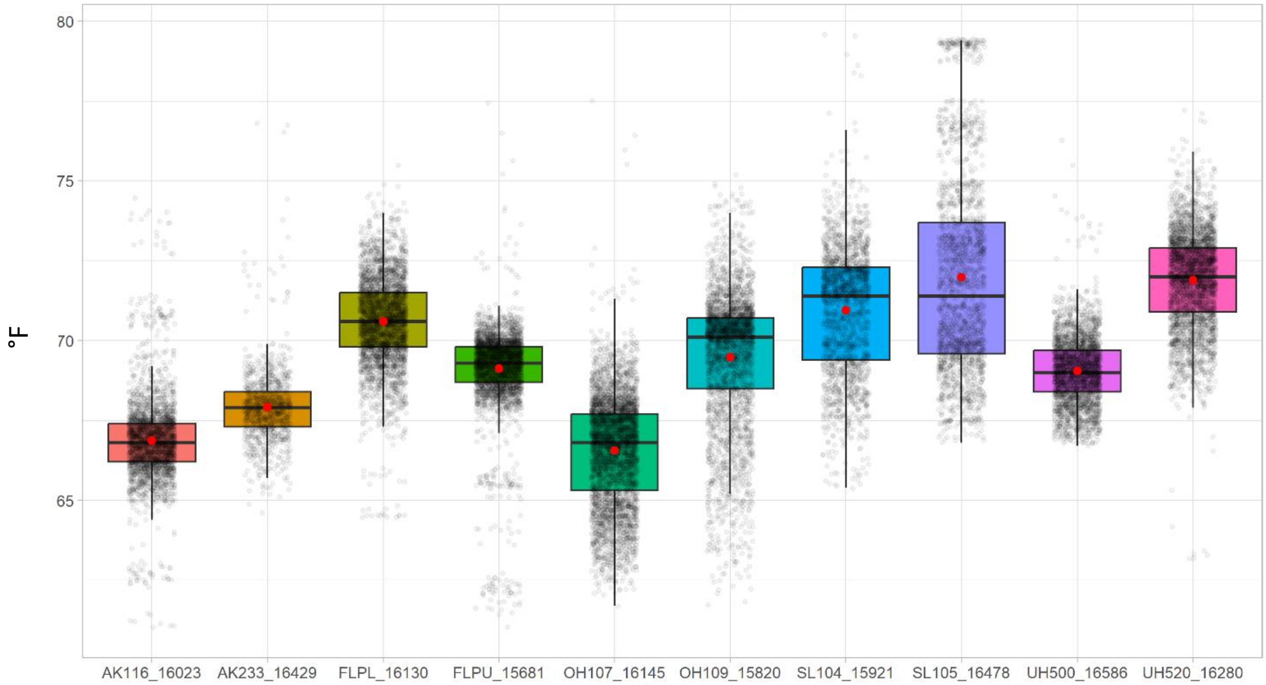
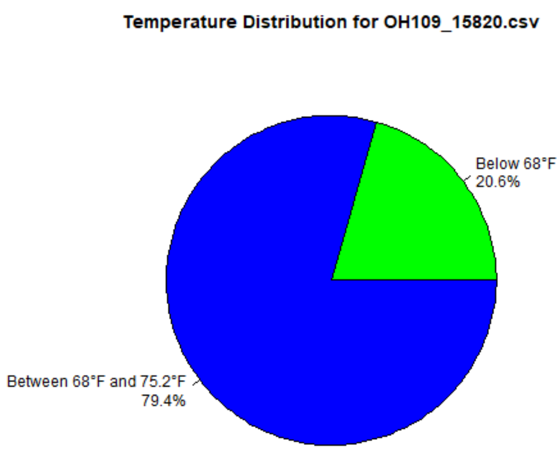
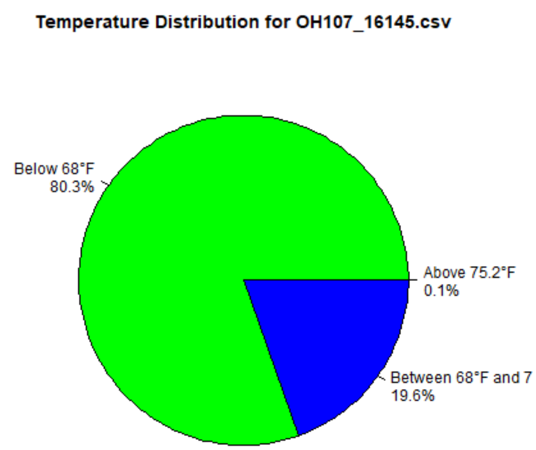
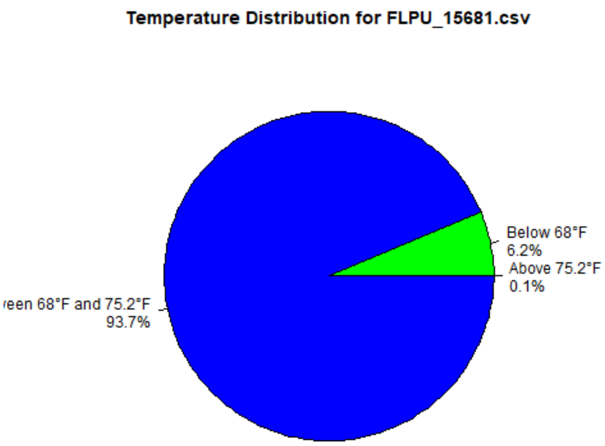
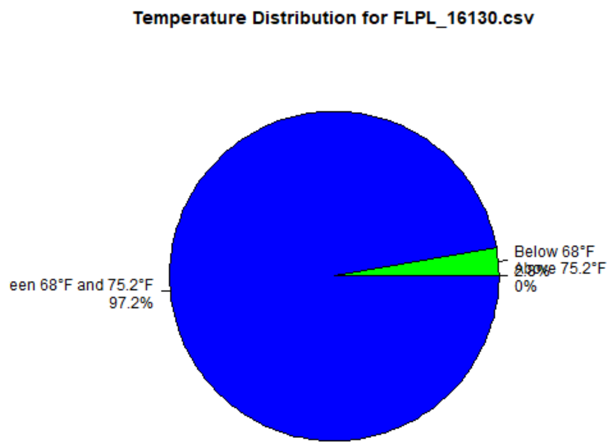


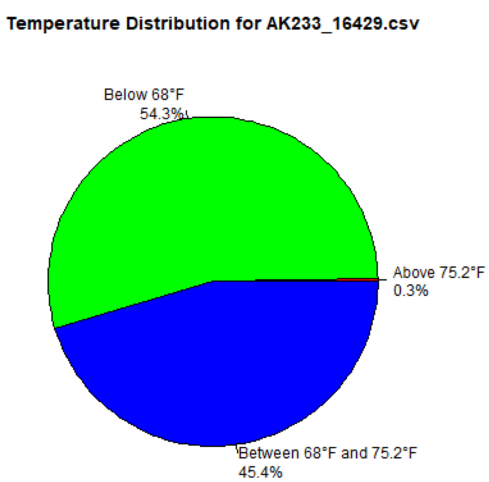
Figure 10: Distribution of Daily Room Temperatures Over a 28-day Period in Various Classrooms when the room was occupied

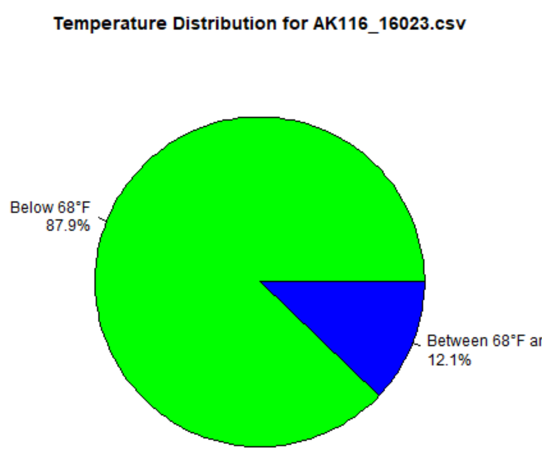





Temperature Distribution for FLPU_15681.csv
Below 68°F
6.2%
Above 75.2°F
0.1%
veen 68°F and 75.2°F
93.7%


Temperature Distribution for FLPL_16130.csv
Below 68°F
Above 75.2°F
0%
een 68°F and 75.2°F
97.2%


Temperature Distribution for AK233_16429.csv
Below 68°F
54.3%
Above 75.2°F
0.3%
Between 68°F and 75.2°F
45.4%


Temperature Distribution for AK116_16023.csv
Below 68°F
87.9%
Between 68°F an
12.1%

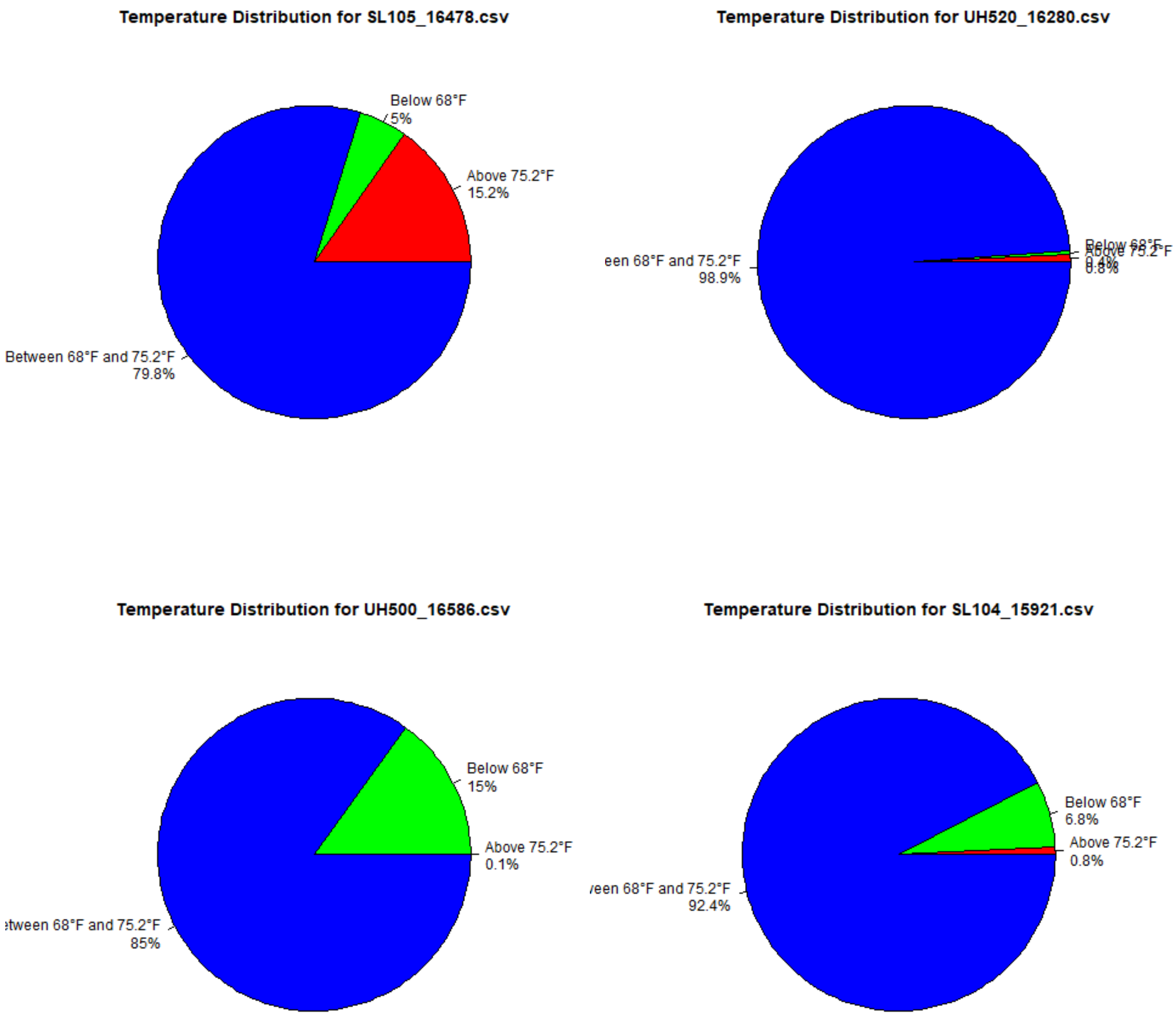


Figure 11: Comparative Distribution of Daily Room Temperatures

In Figure 12, we found that these three classrooms showed a similar pattern of cooling at night and that this one pattern was reflected for more than one day. However, none of the other classrooms with better temperature control showed this sudden drop in temperature at night (Figure 13). Thus, we determined that these three classrooms would be more susceptible to outdoor temperatures.

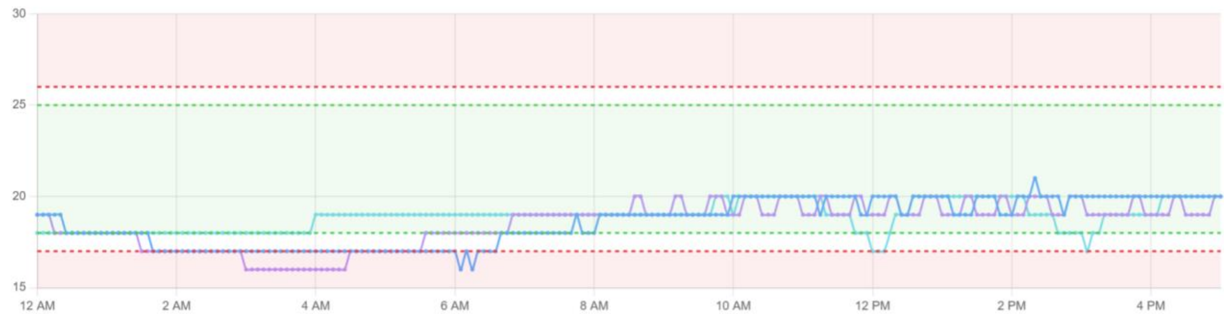


Figure 12: Hourly Room Temperature (°C) Profile for Classroom AK116, AK233 and OH107 on February 20, 2024

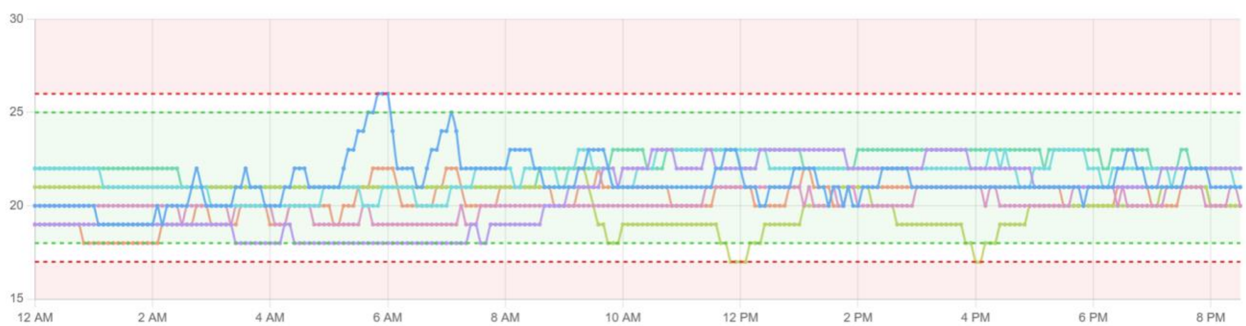


Figure 13: Hourly Room Temperature (°C) Profile for Classroom UH500, UH520, SL104, SL105, OH109, Fl PH-up, and FL PH-low on February 20, 2024

4.2 Relative Humidity

Based on the above research, we set the optimal humidity range at 30% to 60%. According to Figure 14 and Figure 15, we did not find a relationship between the occupancy of the classroom and the humidity, but every classroom showed lower humidity. One of the classrooms with the highest average humidity, AK116, had an average humidity of just under 30%. This means that WPI has poor control over classroom humidity. In the meantime, we have noticed that most classrooms are experiencing extremely high humidity levels. This was most noticeable in OH107, reaching more significant than 60%. As we dug deeper into these extremes, we found that most of the data came from 2/28/2024 and some other times, and what they all had in common was that it was raining that day. Therefore, we ensured the data's stability and accuracy and analyzed them more closely.

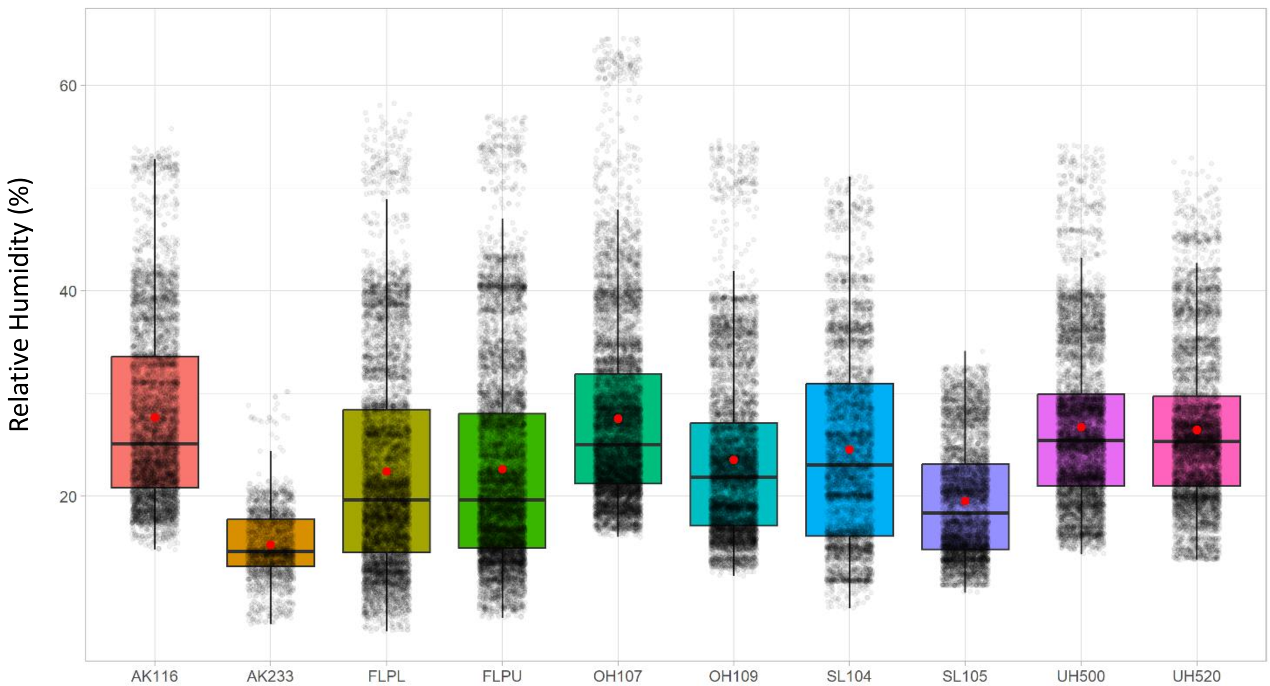


Figure 14: Distribution of Daily Humidity Over 28 days in Various Classrooms (both occupied and unoccupied periods)

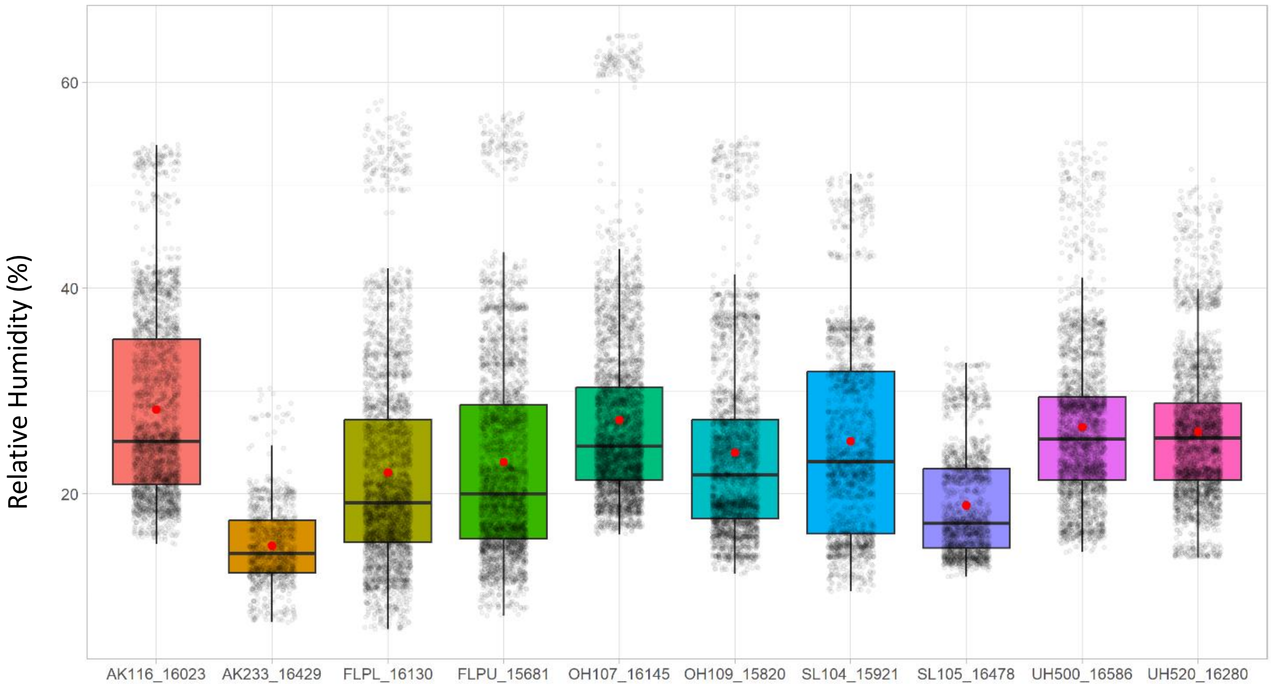
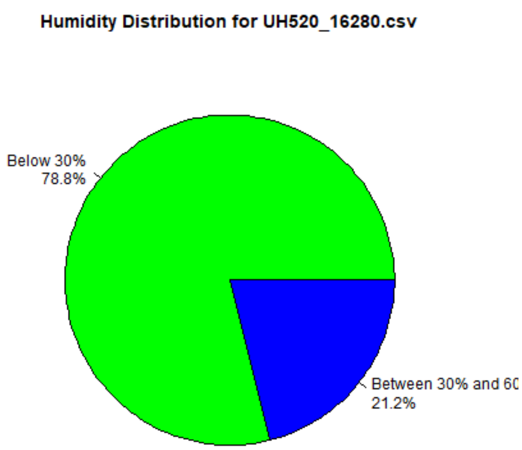
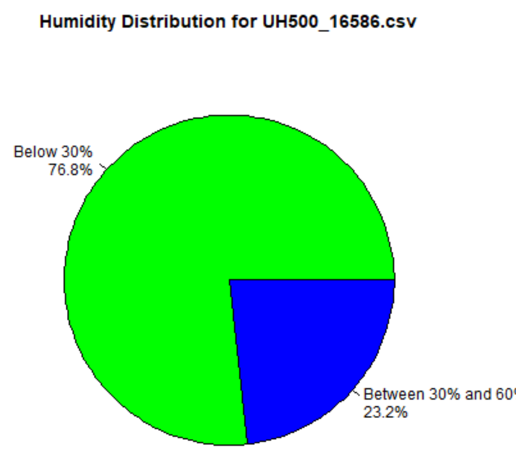
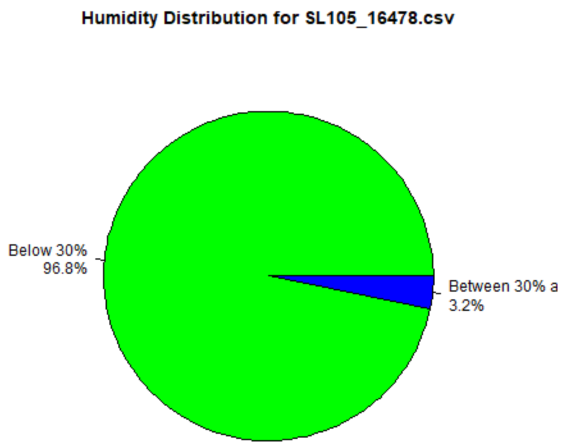


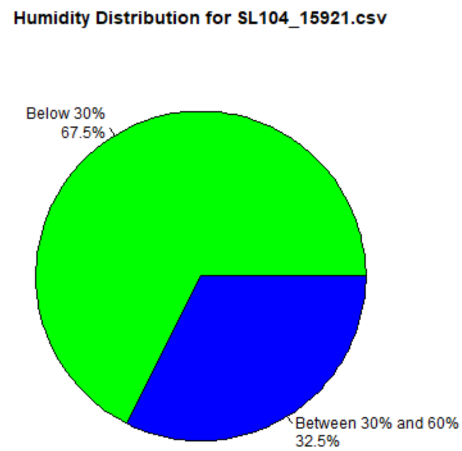
Figure 15: Distribution of Daily Humidity Over 28 days in Various Classrooms when the Room was occupied

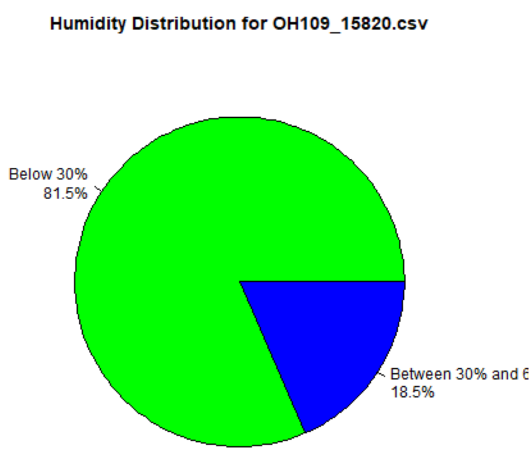
According to our statistics (Figure 16), all classrooms are below 30% humidity most of the time. AK233, in particular, was even 99.8% of the time below 30% humidity. Too low a humidity level can cause students to lose concentration and reduce learning efficiency. One of the most significant effects of low humidity is eye discomfort. The impact of low RH on the front part of the eye should be carefully considered by individuals who spend extended periods in dry. Enhancing the environmental conditions in such areas, like classrooms is crucial. The study from Abusharha (Abusharha, A. A., & Pearce, E. I., 2013) shows that the surrounding environmental conditions significantly affect the tear film. Tear film characteristics undergo considerable alteration when subjected to a dry atmosphere. Parameters such as Tear Layer Thickness (LLT), rate of evaporation, eye comfort, tear stability, and secretion are negatively impacted by low relative humidity (RH). After being exposed to a low-humidity environment for an hour, specific parameters of the tear film (such as evaporation rate, Non-Invasive Tear Break-Up Time (NITBUT), LLT, and eye comfort) shifted from normal levels to those indicative of dry eye syndrome. Consequently, these environmental factors could lead to disorders of the ocular surface and might impair vision-related functions, including contrast sensitivity and sharpness of vision. Also, there is another research (Sunwoo, Y., Chou, C., Takeshita, J., Murakami, M., & Tochihara, Y., 2006) indicated that a significant increase in blink frequency in environments with low RH (10% and 30%) compared to normal conditions (50% RH). This increase suggests that low RH causes ocular surface dryness, prompting a physiological response to blink more frequently in an attempt to lubricate the eye. Blinking helps spread tears evenly across the eye's surface, crucial for maintaining eye health and comfort. Increased blink frequency is a direct response to eye dryness, a symptom of discomfort that likely intensifies with prolonged exposure (Sunwoo, Y., Chou, C., Takeshita, J., Murakami, M., & Tochihara, Y., 2006).

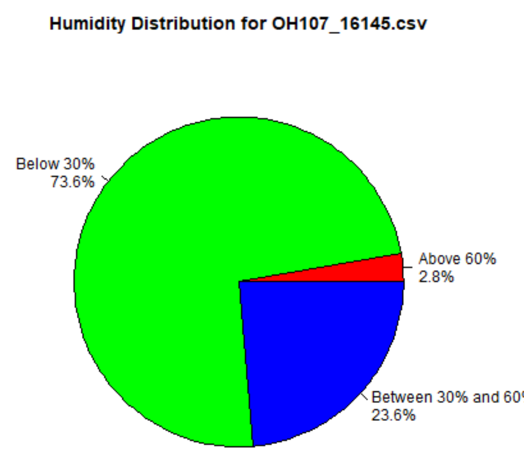





Humidity Distribution for SL105_16478.csv
Below 30%
96.8%
Between 30% a
3.2%


Humidity Distribution for SL104_15921.csv
Below 30%
67.5%
Between 30% and 60%
32.5%


Humidity Distribution for OH109_15820.csv
Below 30%
81.5%
Between 30% and 6
18.5%


Humidity Distribution for OH107_16145.csv
Below 30%
73.6%
Above 60%
2.8%
Between 30% and 60
23.6%

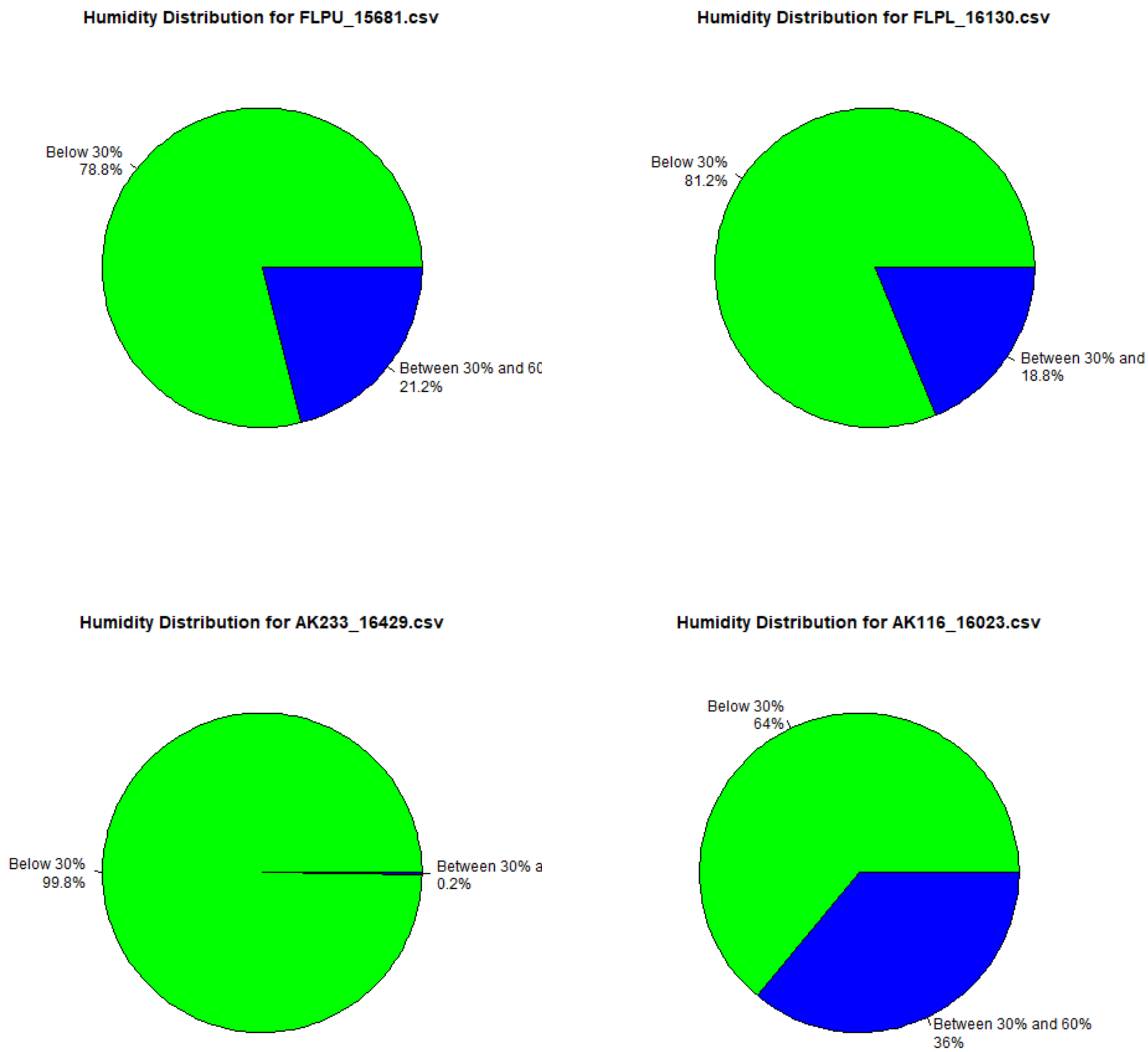


Figure 16: Comparative Distribution of Daily Room Humidity

4.3 Air Quality (CO_2, TVOCs, PM2.5)

According to Figure 17 and Figure 18, when there are people in the classroom, there is a significant increase in the amount of CO2. Most classrooms have an average of 600 ppm CO2, but it is important to note that the CO2 level is surprisingly unstable. We found that a number of them were at extremely high values. We considered that data from empty classrooms could have been accidentally recorded due to weekends or holidays. Therefore, the average CO2 level would be expected to become even higher, higher than 750 ppm, when students are using the classrooms, and even in some classrooms, it can reach 1000 ppm. Also, we find a positive relationship between occupied time and CO2. The amount of CO2 continues to increase with time until it reaches the peak, which is always above 1000 ppm. Then, as the classroom empties, the CO2 levels drop and return to healthy levels (Figure 19).

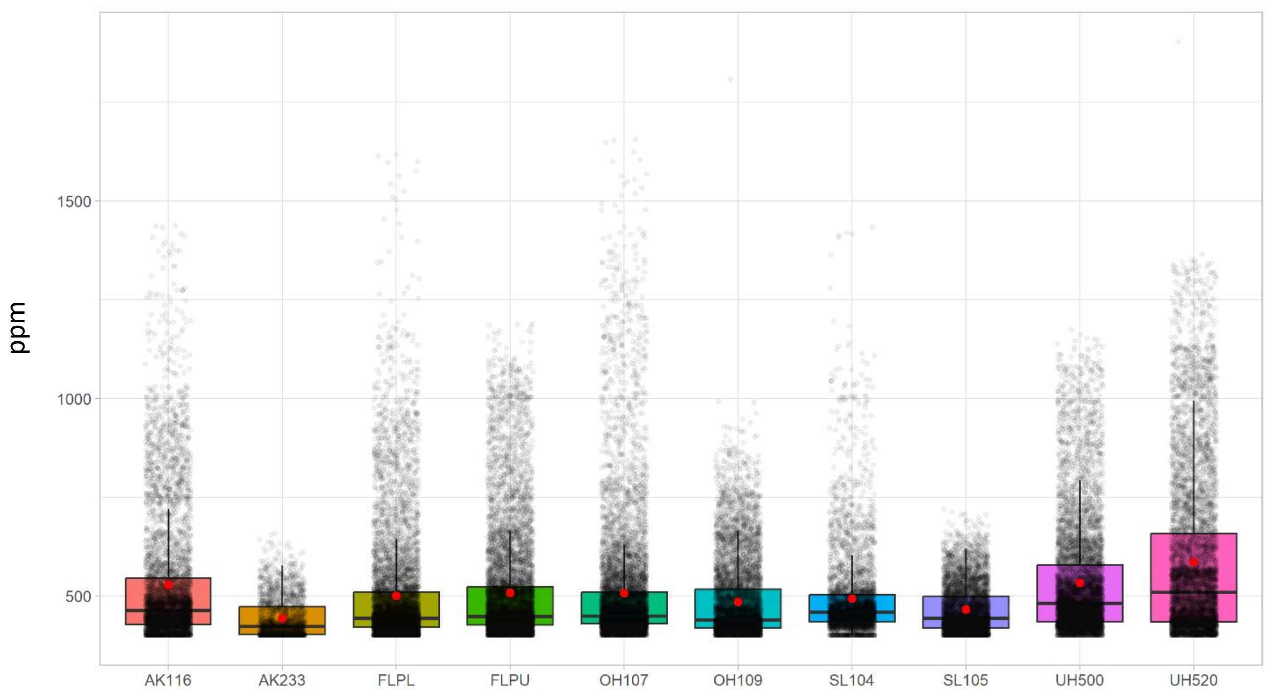


Figure 17: Distribution of Daily CO2 Over 28 days in Various Classrooms (both occupied and unoccupied periods)

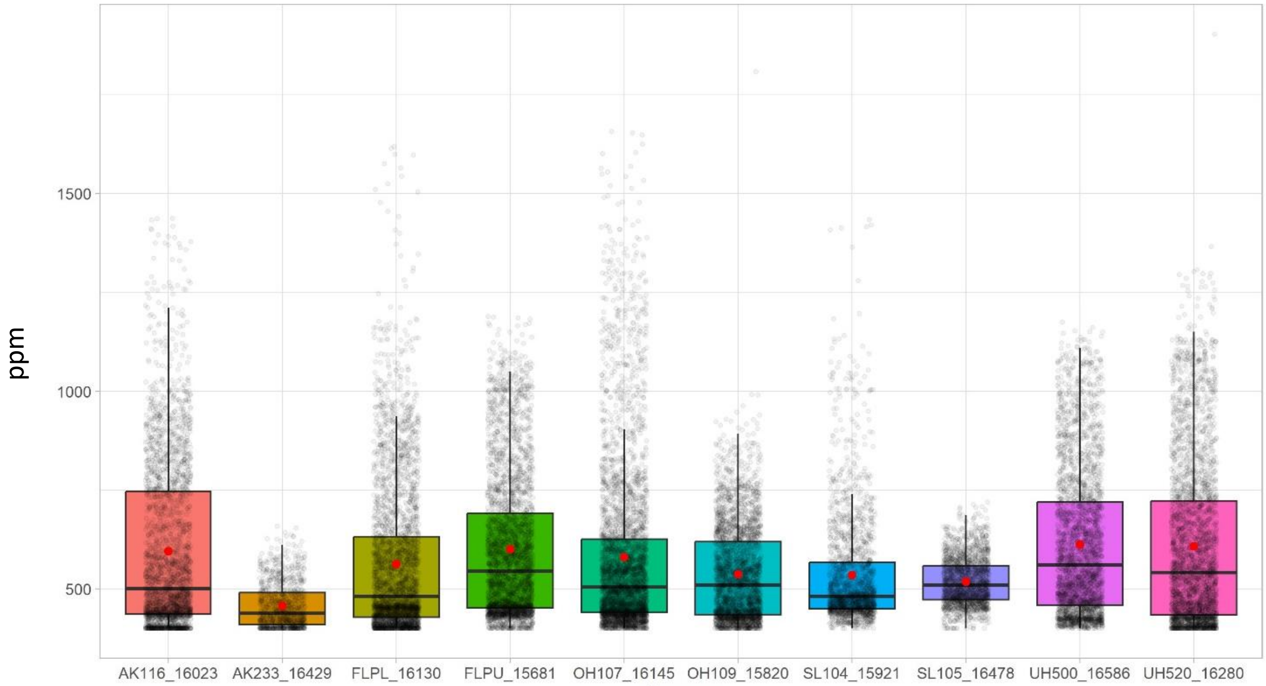


Figure 18: Distribution of Daily CO2 Over 28 days in Various Classrooms when the Room was occupied

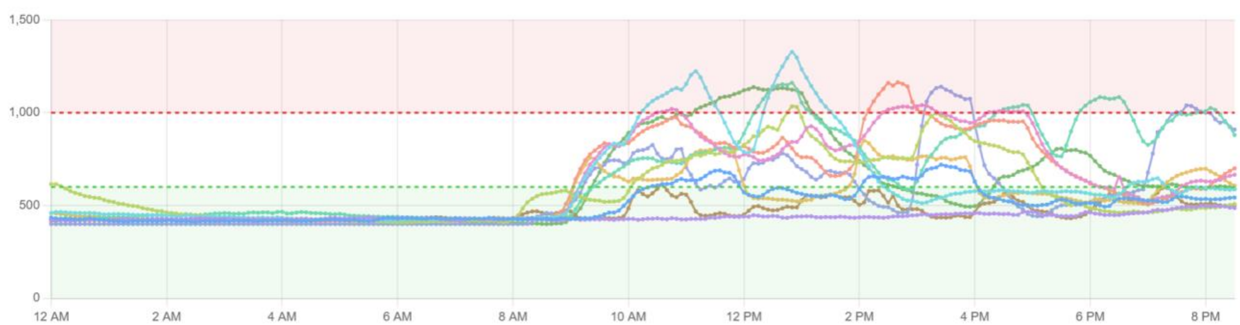


Figure 19: Hourly CO2 Profile for all classrooms February 20, 2024

In most classrooms, levels of TVOCs and PM2.5 are within safe and healthy limits, except in rare cases. Our investigations show that extreme numbers may come from poor sensor siting. This is because both higher TVOCs and PM2.5 occur only sporadically and show irregularities in the timing of their occurrence. This suggests several other factors affecting the sensors, such as dust raised by employees cleaning, dust from chalk near the blackboard, or sensor problems. However, it cannot be ruled out that there is a problem of inferior air quality in the Fuller Laboratories Upper Perreault. We need further research to rule out these external factors and get the most accurate picture of this room.

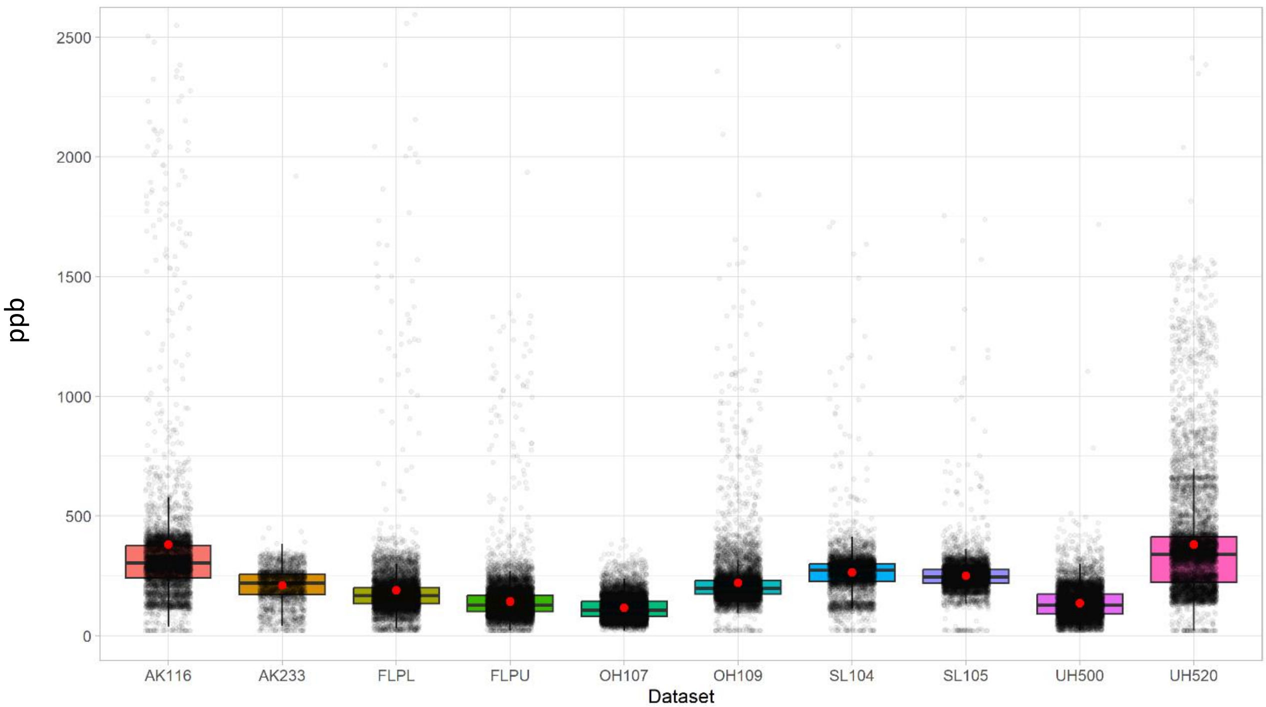


Figure 20: Distribution of Daily TVOCs Over 28 days in Various Classrooms (both occupied and unoccupied periods)

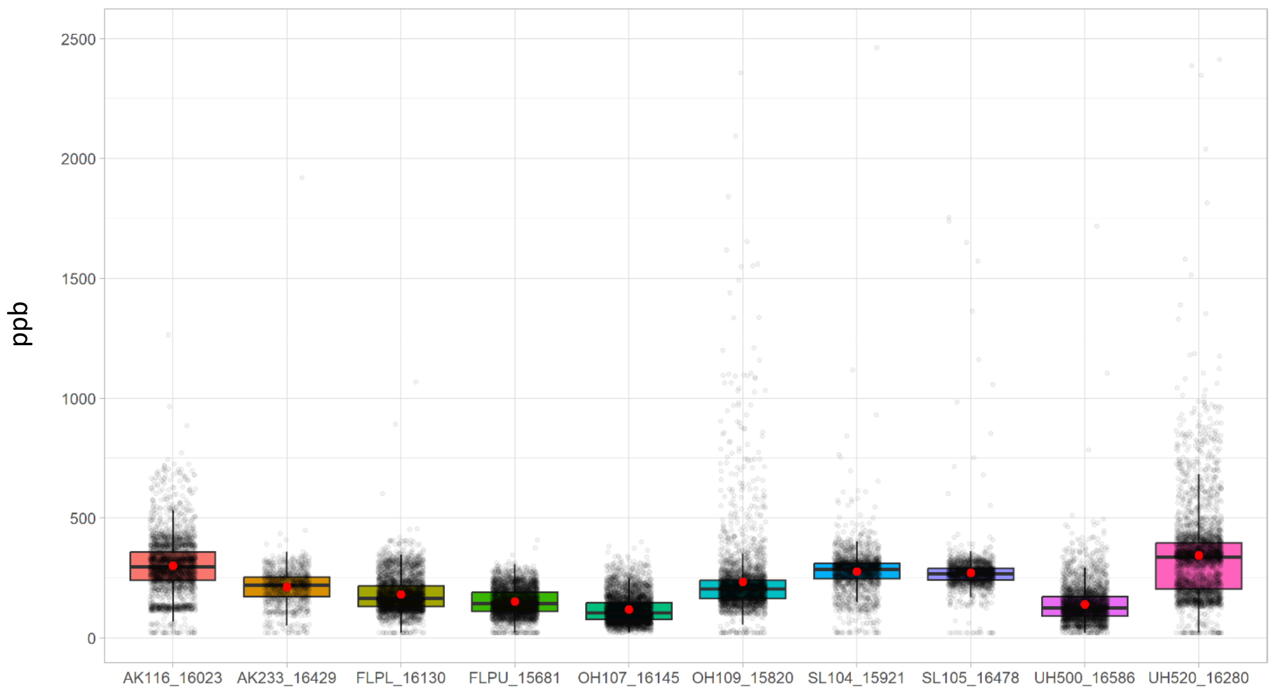


Figure 21: Distribution of Daily TVOCs Over 28 days in Various Classrooms when the Room was occupied

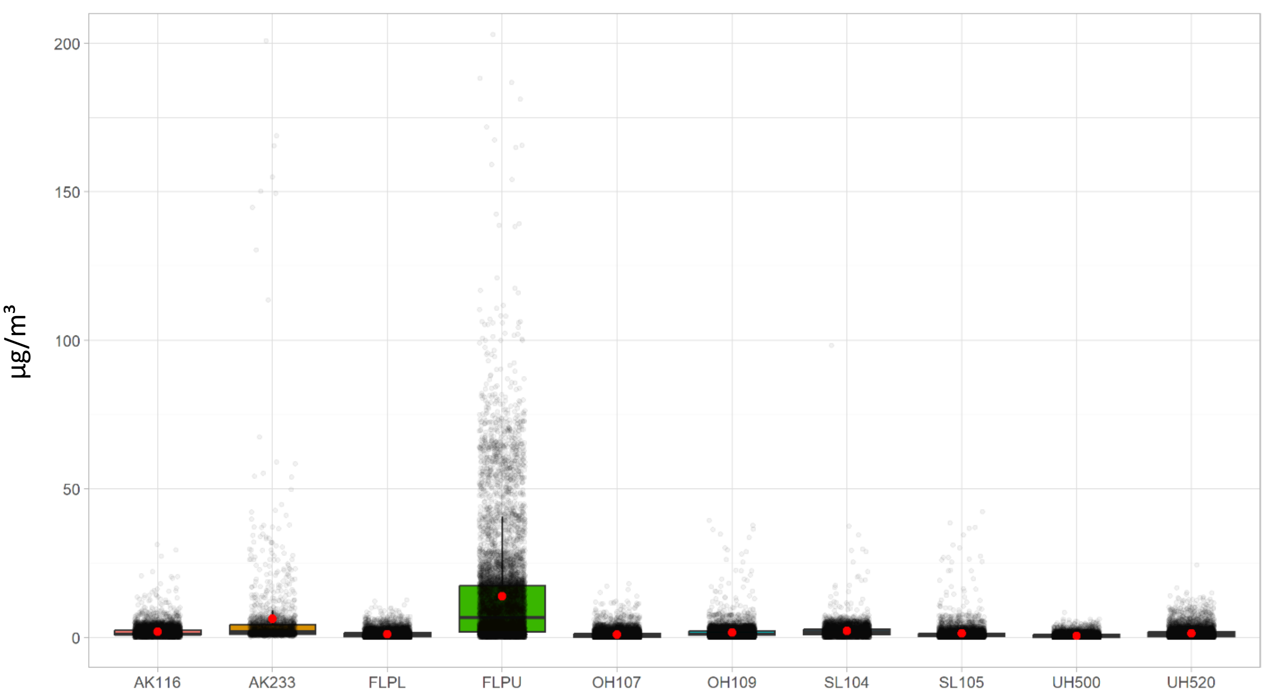


Figure 22: Distribution of Daily PM2.5 Over 28 days in Various Classrooms (both occupied and unoccupied

periods)

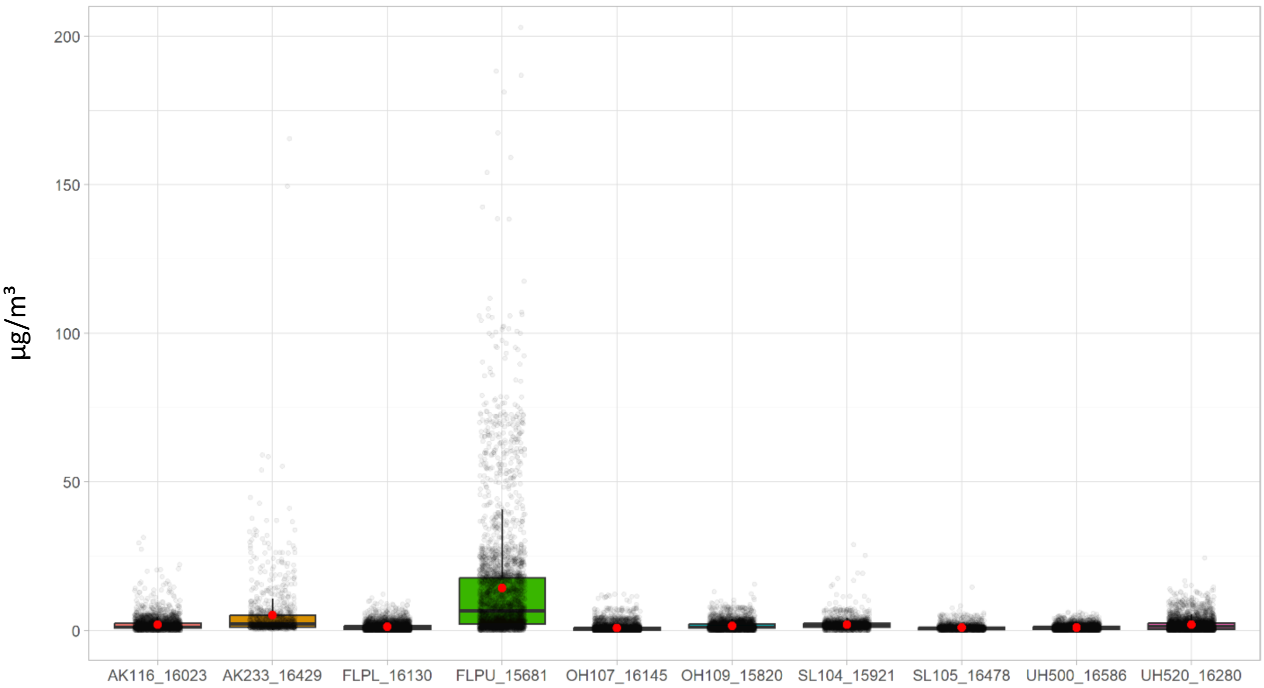


Figure 23: Distribution of Daily PM2.5 Over 28 days in Various Classrooms when the Room was occupied

4.4 Noise and Light

Overall, each classroom's noise and light level did not show any pattern. For noise, all data is between 85db and 20db, like the sound of a loud truck and breathing. We need to mention that the location of deployed sensors and the structure of the classroom has a strong effect on noise detection. For OH107, we noticed that it had a significantly low noise level, and after the investigation, we discovered that our sensor is deployed at the back of the classroom, making it hard to receive sound waves. On the other hand, some sensors deployed near the platform or speaker show a significantly larger noise level, like UH500 and UH520. For the light level, because we try to minimize the influence of sensors on students, we deployed sensors at the corner of the classroom, and it highly affected the light data collection. Each classroom would have its single measurement standard, and we cannot use it to do any analysis because of inaccurate data.

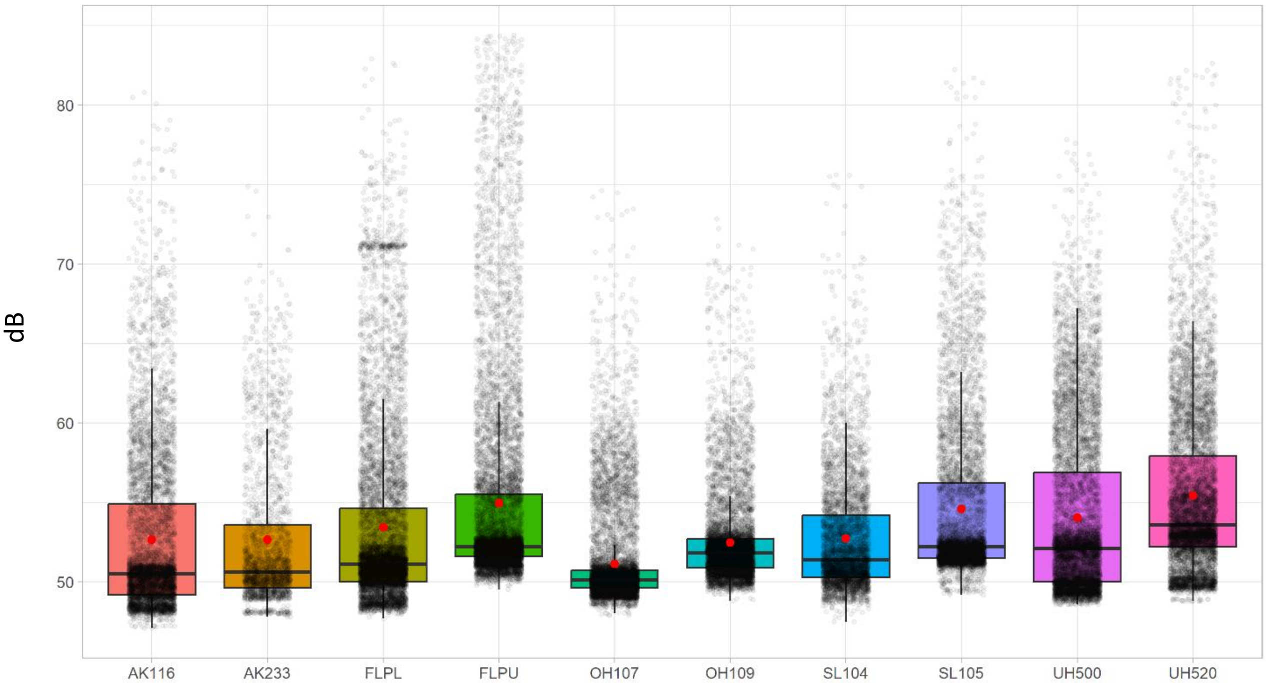


Figure 24: Distribution of Daily Noise Over 28 days in Various Classrooms (both occupied and unoccupied periods)

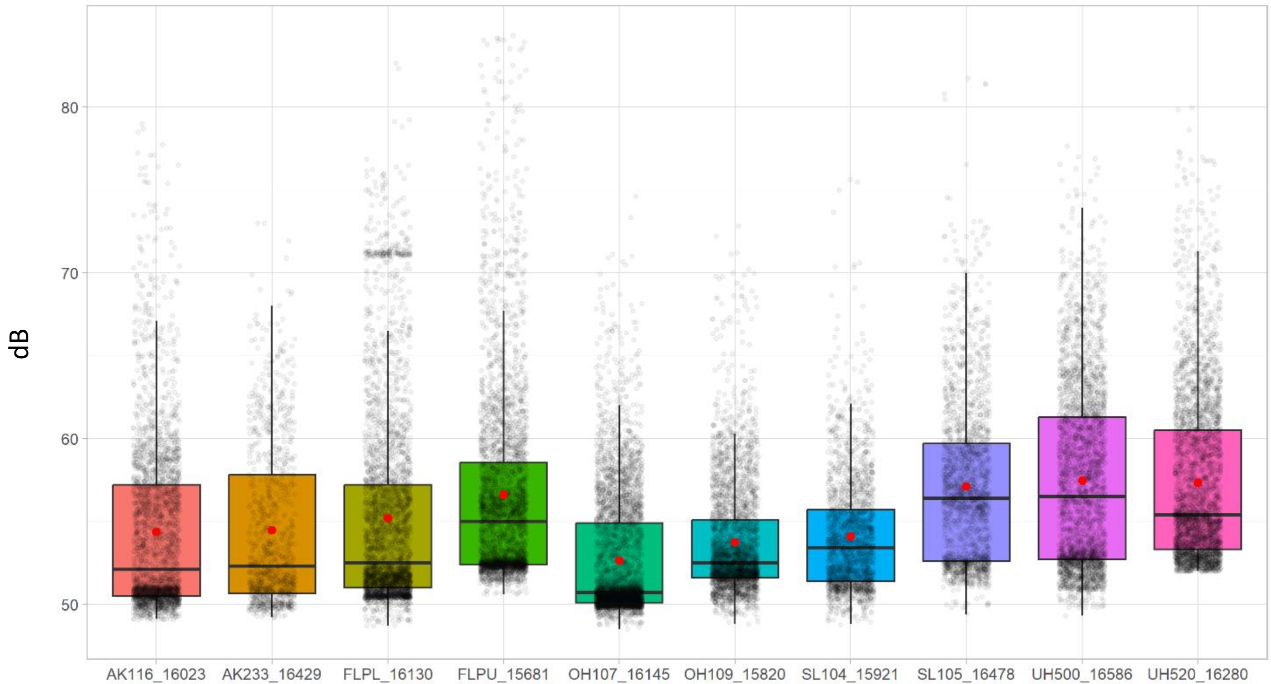


Figure 25: Distribution of Daily Noise Over 28 days in Various Classrooms when the Room was occupied

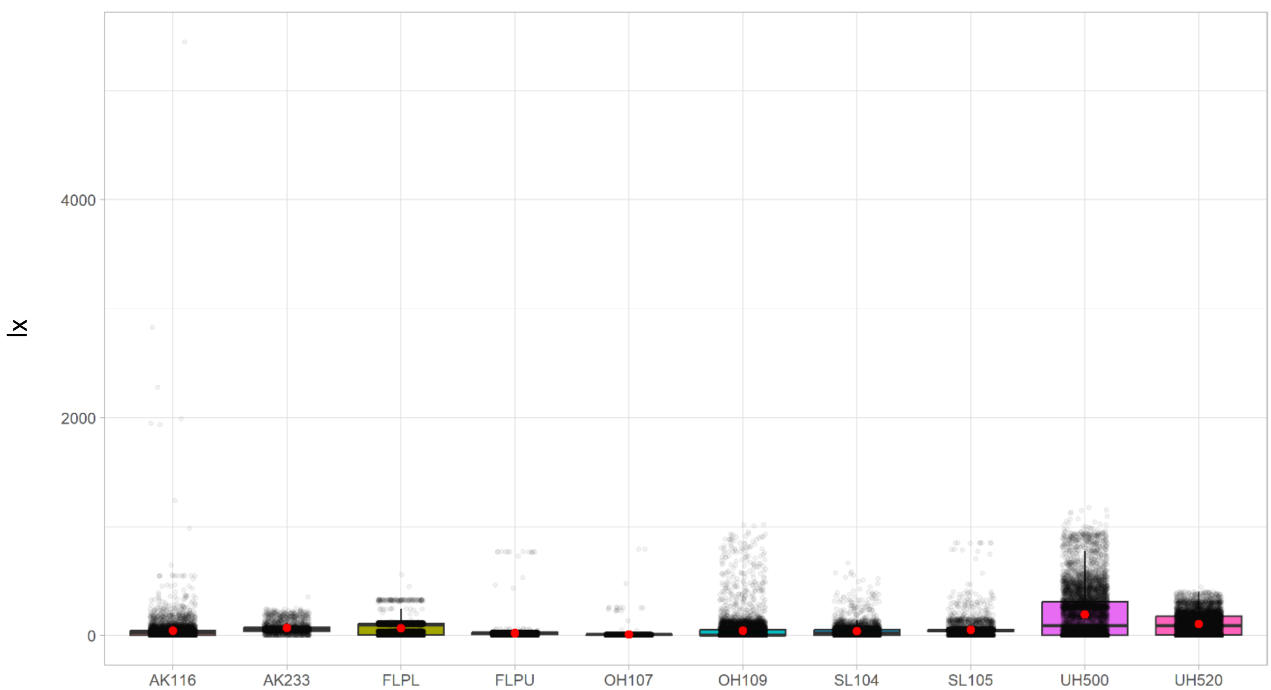


Figure 26: Distribution of Daily Light Over 28 days in Various Classrooms (both occupied and unoccupied

periods)

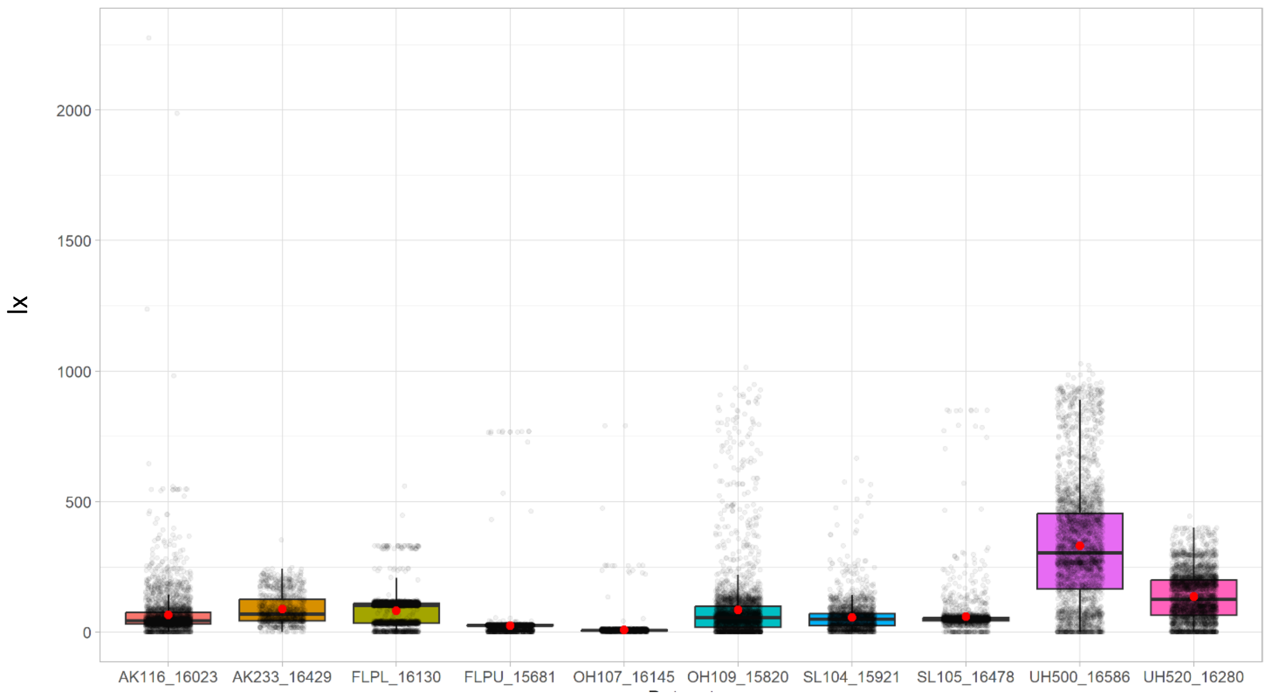


Figure 27: Distribution of Daily Light Over 28 days in Various Classrooms when the Room was occupied

4.5 Survey

As of March 20th, we have received four valid surveys. Only one student expressed dissatisfaction with the air quality in SL105, while the rest showed satisfaction with various indoor environmental factors. We believe that we need to change our questionnaire strategy to increase student participation.

5. Conclusions & Recommendations

Overall, the indoor environments of the ten classrooms we observed were within acceptable limits. However, temperature, humidity, and CO_2 are not within the range of the most appropriate environments for student learning.

1. Optimal learning performance is noted within a temperature range of 20°C to 24°C (68°F to 75.2°F). However, three classrooms (AK233, AK116, and OH107) were frequently outside the optimal temperature range, with AK116 failing to reach the optimal temperature 89.5% of the time, indicating poor temperature control influenced by external temperatures.
2. Most classrooms displayed lower humidity levels than desired, under 30%. Low humidity levels were linked to discomfort and reduced concentration among students.
3. Elevated CO_2 levels were observed when classrooms were occupied, exceeding the optimal level of 600 ppm and, in some cases, reaching up to 1000 ppm. This suggests poor ventilation or air quality control.
4. While most classrooms maintained TVOCs and PM2.5 within safe limits, irregular high readings suggest potential issues with sensor placement or sporadic sources of pollution
5. Too few valid questionnaires were collected, reflecting potential problems with questionnaire design.

Therefore, we have made the following recommendations for improving the indoor environment of WPI classrooms.

1. Improving classroom ventilation management can significantly enhance control over temperature, humidity, and CO2 levels. Our findings indicate that classrooms on the cooler side (AK233, AK116, and OH107) are more affected by external temperatures. We recommend identifying and sealing gaps or cracks in windows, doors, and walls with weather stripping or caulk to mitigate this. Additionally, implementing a controlled ventilation system can help maintain optimal room temperature and increase fresh air intake, thereby reducing carbon dioxide levels. It is worth noting that external

conditions influence humidity levels more than temperature. Although all classrooms exhibit low humidity levels, indoor humidity increases with outdoor humidity, especially during rainy conditions.

2. Incorporating humidifiers can significantly enhance humidity control within classrooms. Currently, humidity levels are not controlled, leading to a drop below 30% during winter months, which can adversely affect student learning. Considering budgetary constraints, opting for portable humidifiers presents an affordable and effective solution to address this issue.
3. Enhancing indoor environment monitoring is essential for creating a healthy and conducive learning environment. Continuous oversight of temperature, humidity, CO2 levels, and air quality within educational facilities ensures the well-being of students and staff. At the same time, we use appropriate visualization tools to help students and staff monitor the indoor environment to ensure it is in the healthy and comfortable range.
4. Raising public awareness about the importance of indoor study environments is crucial for enhancing learning efficiency and student well-being. Our questionnaire found that students are generally not interested in the indoor environment. The indoor environment is often overlooked, but it seriously impacts students' learning efficiency. Therefore, it is necessary to raise students' awareness of the indoor environment through advertising.
5. Opting for interviews over questionnaires when assessing student satisfaction with the indoor environment will likely yield more nuanced and detailed insights. Interviews allow for deeper exploration of students' perceptions and experiences, offering a platform for them to articulate their feelings and thoughts more comprehensively. This qualitative approach facilitates a better understanding of the factors contributing to their satisfaction or dissatisfaction. Furthermore, interviews provide an opportunity for follow-up questions, enabling researchers to delve into specific areas of interest or concern that may arise during the conversation. This adaptability helps uncover aspects of the indoor environment that might not have been previously considered or are challenging to capture through standardized questionnaire responses.

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Appendix A: Indoor Environment Satisfaction Questionnaire

Consent

We value your input on the physical aspects (e.g., temperature) of the classroom environment. This survey should take approximately 1 min to complete.

You will receive $0.25 for each survey completed after a class. Please take the survey on the same day you take the class in this room. Additionally, you will be entered into a lottery with a chance to win an additional **$20.**

Your responses will remain confidential.

Proceed?

- Yes
- No

Survey

Email Address:

(Please enter your WPI email address that you will receive the Amazon e-gift card)

The classroom where you were taking class

Rate your general thermal sensation

- Cold
- Cool
- Slightly Cool
- Neutral
- Slightly Warm

○ Warm
○ Hot

How satisfied were you with the temperature?

○ Dissatisfied
○ Slightly Dissatisfied
○ Slightly Satisfied
○ Satisfied

How satisfied were you with the humidity?

○ Dissatisfied
○ Slightly Dissatisfied
○ Slightly Satisfied
○ Satisfied

How satisfied were you with the indoor air quality in the classroom?

○ Dissatisfied
○ Slightly Dissatisfied
○ Slightly Satisfied
○ Satisfied

How satisfied were you with:

	Dissatisfied	Slightly Dissatisfied	Slightly Satisfied	Satisfied
The amount of light	○	○	○	○
The visual comfort of the lighting (e.g., glare, reflections contrast)	○	○	○	○

How satisfied were you with the noise while in the classroom?

○ Dissatisfied
○ Slightly Dissatisfied
○ Slightly Satisfied

○ Satisfied

All things considered, how satisfied were you with the physical environment while in the classroom?

○ Dissatisfied
○ Slightly Dissatisfied
○ Slightly Satisfied
○ Satisfied

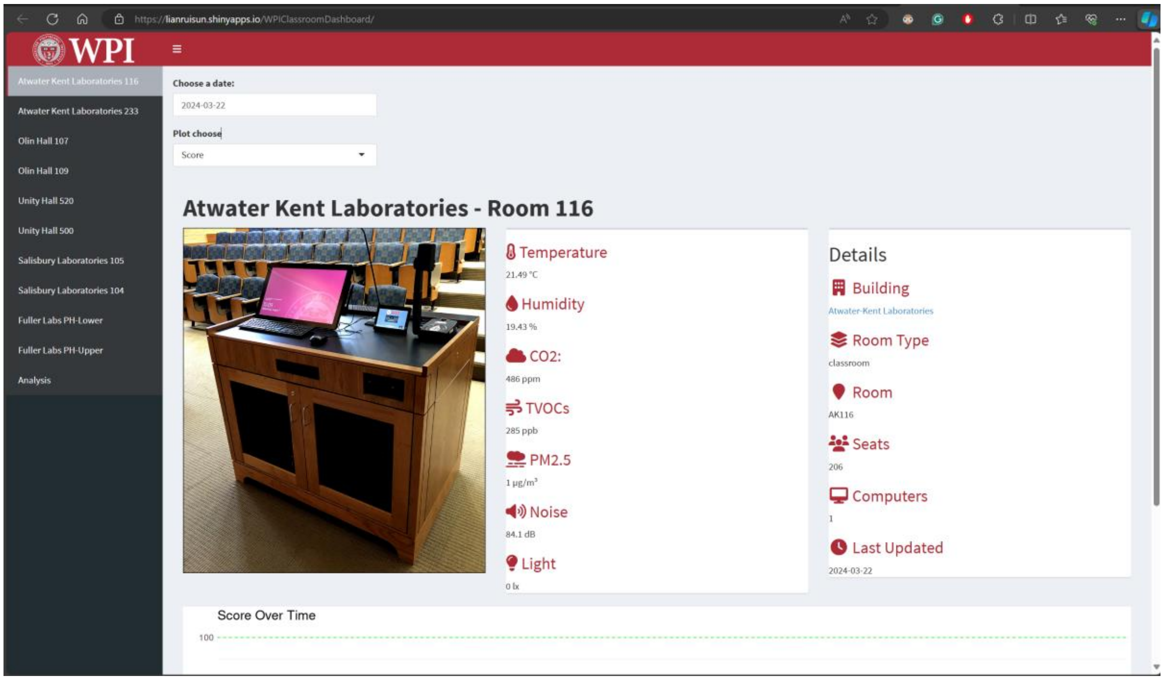
Describe your engagement in the class

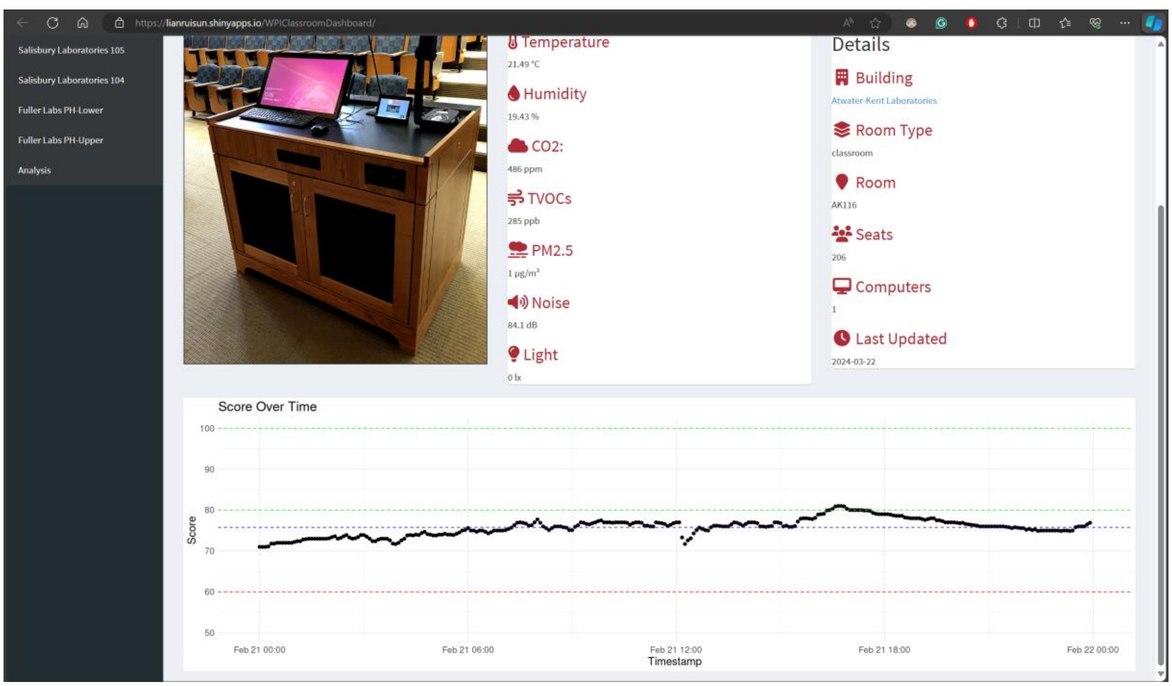
	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
I paid attention in the class	○	○	○	○	○
I pretended to participate in class not actually	○	○	○	○	○
I enjoyed learning new things in class	○	○	○	○	○
I felt discouraged when we worked on something	○	○	○	○	○
I asked myself questions to make sure I understood the class content	○	○	○	○	○

On a scale of 1 to 5, where 1 represents 'Not stressed at all' and 5 represents 'Extremely stressed,' how would you rate your overall level of stress after you take course in this classroom?

Not stressed at all			Extremely stressed	
1	2	3	4	5

Appendix B: Data Analysis and Visualization Website





https://lianruisun.shinyapps.io/WPIClassroomDashboard/

https://github.com/LianruiSun/IQP-Rating-Dashboard