Hygiene and Environmental Health Advances 4 (2022) 100029

Contents lists available at ScienceDirect

Hygiene and Environmental Health Advances

journal homepage: www.elsevier.com/locate/heha

Measuring students' exposure to temperature and relative humidity in various indoor environments and across seasons using personal air monitors

Ian Ryan[a], Xinlei Deng[a], George Thurston[b], Haider Khwaja[a,c], Xiaobo Romeiko[a], Wangjian Zhang[a], Tia Marks[a], Fangqun Yu[d], Shao Lin[a,e,*]

[a] Department of Environmental Health Sciences, University at Albany, State University of New York, Rensselaer, NY, USA
[b] Department of Environmental Medicine, School of Medicine, New York University, New York, NY, USA
[c] Wadsworth Center, New York State Department of Health, Albany, NY, USA
[d] Department of Atmospheric and Environmental Sciences, University at Albany, State University of New York, Albany, NY, USA
[e] Department of Epidemiology and Biostatistics, University at Albany, State University of New York, Rensselaer, NY, USA

ARTICLE INFO

Keywords:
Primary school
Indoor environment
Children's exposure
Personal monitor
Seasonal variation
Thermal conditions

ABSTRACT

Background: Thermal comfort is essential for human well-being. Consistent exposure to uncomfortable thermal conditions indoors leads to reduced academic performance and adverse health outcomes in schoolchildren. In addition, children are more sensitive to thermal conditions due to physiological differences, yet their exposure to thermal conditions has not been adequately measured.

Methods: This cross-sectional study evaluated students' exposure to temperature and relative humidity (RH) using personal air monitors. In this study, we recruited 90 students from 13 classrooms – 60 from 11 NYS primary school classrooms and 30 from two State University of New York at Albany classrooms. Each participant wore an AirBeam air monitor for 48 hours, and their data was transmitted to a cell phone provided by the researchers.

Results: Primary school students were routinely exposed to temperatures exceeding ASHRAE standards (winter: 75^{0}F, summer: 80.5^{0}F), particularly in school in the spring (max=102^{0}F, median=82^{0}F). At home, temperatures exceeded standards in the evening around dinnertime. However, primary students were routinely exposed to RH below recommended standards in classrooms during all seasons (median=29%). However, the RH was significantly lower in the winter than in any other season (median=17%). Finally, university students were exposed to slightly higher temperatures and significantly lower RH than primary schoolchildren in the spring.

Conclusion: These results suggest that students are exposed to uncomfortable thermal conditions, particularly in classrooms when attending class. Teachers should therefore be given more control over classroom ventilation and thermal conditions, while indoor temperature standards should be adjusted for school children.

1. Introduction

Thermal comfort, i.e., appropriate temperature and humidity level, is essential for human well-being (USGCRP 2016). As with most air quality markers, children are more susceptible to extreme temperatures and temperature fluctuations (Stanberry et al., 2018). Children are more sensitive to these conditions because, compared to healthy adults, they have a higher metabolic rate per kg of body weight, greater body surface-to-volume ratio, and limited adaptive opportunities (Stanberry et al., 2018, ter Mors et al., 2011, Teli et al., 2012).

Assuming slow air movement and 50% indoor RH, the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) recommends a temperature range from 68.5-75^{0}F in the winter and from 75-80.5^{0}F in the summer (NIOSH 2022). ASHRAE also recommends that RH stays below 65%, while the EPA recommends 30-60% RH to avoid mold growth and associated respiratory issues (NIOSH 2022). High temperatures have been associated with "impaired performance and learning outcomes" in temperate and mixed climates (Haverinen-Shaughnessy and Shaughnessy, 2015, Toyinbo et al., 2019). Within the range of 68-77^{0}F, a 1.8^{0}F decrease in temperature

* Corresponding author at: Department of Environmental Health Sciences, Associate Director of Global Health Research, School of Public Health, University at Albany, State University of New York, One University Place, Rm 212d, Rensselaer, NY 12144.
E-mail address: slin@albany.edu (S. Lin).

https://doi.org/10.1016/j.heha.2022.100029
Received 27 July 2022; Received in revised form 4 October 2022; Accepted 6 October 2022

has been associated with a 12–13-point increase in mean mathematics test scores in elementary school students (Haverinen-Shaughnessy and Shaughnessy, 2015). Similar but more variable results were also noted for reading and science scores (Haverinen-Shaughnessy and Shaughnessy, 2015). Other studies have shown that a student's thermal environment is closely related to the student's academic performance, perceived comfort, and health outcomes (Jiang et al., 2018). Raising air temperatures from 68-77^{0}F is significant enough to impair educational performance (Deng and Lau, 2019). RH is also an important factor when determining thermal comfort. Low indoor humidity is most commonly associated with acute irritation of the eyes and upper respiratory tract (Wolkoff, 2018). Chronic exposure to low humidity leads to further irritation of the eyes and airways and negative impacts on intellectual performance and sleep quality (Wolkoff, 2018).

Since children spend most of their time inside, including over 1,000 hours in school every year, monitoring air quality in schools may help prevent disease, promote health, and improve academic performance in this population group (Park et al., 2020). In addition, thermal conditions in classrooms will continue to be important because the global temperature is steadily rising, and the warm season is also extending (Domínguez-Amarillo et al., 2020).

Despite the established connection between thermal comfort and human flourishing, real-time exposure to and temporal temperature and humidity trends have not been adequately characterized in primary school-aged children or university classrooms. One reason for this is that measuring exposure to temperature, humidity, and air quality in general at the individual level is notoriously difficult and expensive. In addition, most temperature and humidity studies focus on a single location and limited time period. Furthermore, most school air quality studies observe students in tropical, warm, or temperate climates. Therefore, there is a shortage of studies looking at thermal comfort in colder areas (Zomorodian et al., 2016, Yang et al., 2018). In addition, very few studies track the real-time changes in thermal comfort as the subject goes about their schedule and changes locations over consecutive days. Lastly, though outdoor seasonal temperature and humidity trends are well understood, the indoor trends of the same indicators have not been well documented, particularly outside of occupational settings.

Our study addresses existing knowledge gaps in student thermal comfort research by conducting real-time measurements of a sample population of primary school children and university students' exposure to ambient temperature and relative humidity (RH) for 48 hours. In addition, this study takes place in New York State (NYS), which has a variable climate, and measurements were performed across seasons. This design allowed us to capture important temporal trends in children's exposure to thermal discomfort.

2. Materials and methods

2.1. School and classroom selection

This cross-sectional study was part of the School Health and Physical Environment (SHAPE) project. The SHAPE project was conducted from August 2017 to May 2019 and included ten NYS primary schools in the capital region. Schools with fourth-grade enrollment were selected from public school districts within the four greater Capital District Board of Cooperative Educational Services (BOCES) regions. We obtained a representative sample by selecting schools based on socio-economic status (SES) and urbanicity. School SES was measured using the percent of students eligible for a free lunch, proportions of race/ethnicity, and urbanicity of school locations from 2005 NYS Education Department (NYSED) data and checked against 2008 NYSED data. Districts with schools in the highest and lowest tertiles of SES and different urbanicity (i.e., including both urban and rural areas) were selected to obtain a geographically representative sample and increase the number of candidates. From a pool of 162 schools in 83 primary school districts, 65 schools in 41 districts were selected. A stratified random sampling method was used to choose which schools to contact first, and recruitment letters were sent to the corresponding district superintendents. The next school on the list was contacted if a school refused to participate or did not respond after three follow-ups.

Finally, nine schools agreed to participate in the SHAPE project. Unfortunately, three schools withdrew from the study before we took air quality measurements, leaving us with six primary schools – three representing low SES urban/suburban areas, two representing low SES rural areas, and one representing low SES rural areas. The researchers worked with the principals of each participating school to select teachers and classrooms to participate in the study. No other inclusion or exclusion criteria were used to select classrooms. Participating schools received \$200 gift cards to Target for school supplies. Due to our grant agreement with the US EPA, we cannot disclose identifiable information regarding school or participant names. However, we can clarify that all of the schools included in the project are within 120 miles of driving distance from Albany, NY (i.e., the NYS capital region), where the corresponding author conducts research. In this study, to serve as a comparison to the primary schools, we received approval to include two departments at SUNY Albany for a total of 13 classrooms (11 primary + 2 college). The UAlbany School of Public Health (SPH) was selected due to its proximity to a wastewater treatment plant. The UAlbany Atmospheric Sciences Research Center (ASRC) was selected to represent college students' exposure to temperature and RH on the main university campus, where they spend several hours most days.

2.2. Procedure

On average, two teachers and eight students from each participating classroom were given a personal air quality monitor for 48 consecutive hours to measure individual exposure to temperature, RH, and $PM_{2.5}$ during the week. Participants were instructed to keep the devices with them throughout the day and within ten feet of their phones to maintain the Bluetooth connection. Personal monitoring was performed in the spring and was repeated with the same students in either the fall or the winter.

2.3. Equipment description

This study utilized AirBeam personal air quality monitors (HabitatMap) to measure individual exposure to temperature and RH. The AirBeam is a hand-sized device that measures local temperature, RH, and $PM_{2.5}$ mass concentrations (HabitatMap 2021). It does so by drawing in air and using a light scattering method, which allows the monitor to determine particle mass and number in real-time (HabitatMap 2021, Mukherjee et al., 2017). AirBeams have been used in many different environments (Rabinovitch et al., 2016, Mazaheri et al., 2018, Johnston et al., 2020, Folkerth et al., 2020, Korto¸ci et al., 2021, D'Eon et al., 2021), validated against several other air monitors, and typically achieve moderate correlation and high precision with reference instruments (Mukherjee et al., 2017, Sousan et al., 2017, Borghi et al., 2018). Each participant was also given a Samsung Galaxy J3 Eclipse smartphone to record data using the AirCasting app. The data was then uploaded to our secure computers after 48 hours of continuous measurement.

2.4. Data cleaning and aggregating

Individual and in-class air monitoring data were collected for 48 consecutive hours. Each day was separated into three locations based on time, defining where the primary schoolchildren were and, therefore, their exposure windows. Location definition (home, school, or transit) was based on activity diaries that a large sample of participating SHAPE students completed ($n = 71$) and class schedules provided by the schools. Specifically, most students reported being at school from 9:00 a.m. to 3:00 p.m., at home between 3:30 p.m. and 8:30 a.m. (the next day),

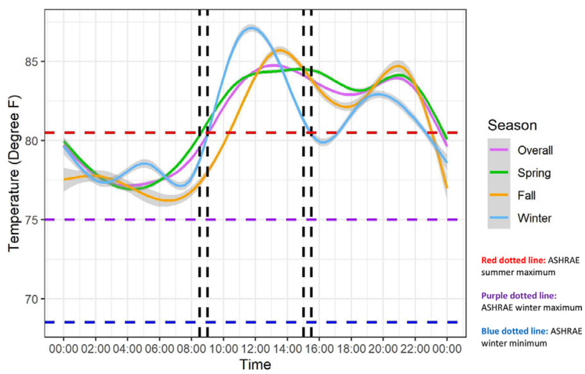


Fig. 1. Temperature trends by season in elementary school students measured by AirBeam.

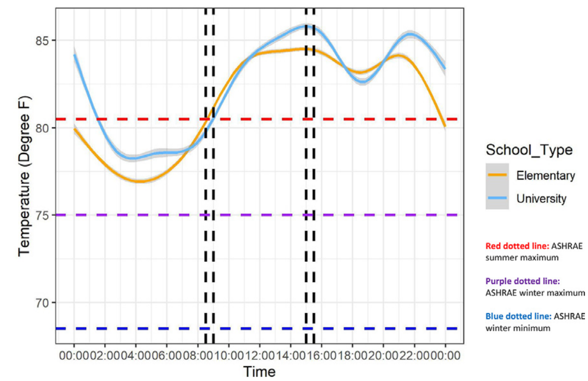


Fig. 2. AirBeam temperature trends in the spring by school type.

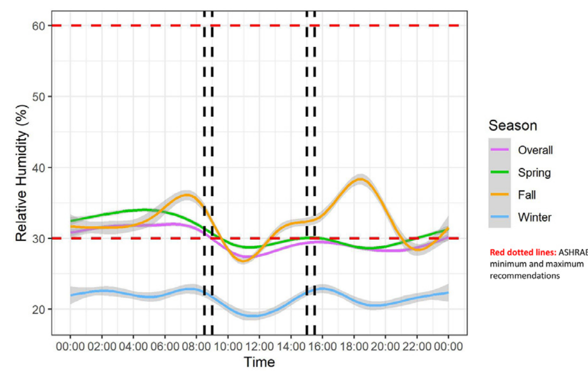


Fig. 3. Primary schoolchildren AirBeam relative humidity trends by season.

and in transit from 8:30-9:00 a.m. and 3:00-3:30 p.m.. As thermal condition data were collected every minute, we used measurements from the closest timeslot to impute any missing values to help maintain data integrity. Unfortunately, due to user error (not charging phone, disconnecting Bluetooth between phone and AirBeam, leaving AirBeam away from their person) and smartphone malfunctions (freezing, crashing), data from 12 of the 60 primary schoolchildren (20%) and 1 of the 30 college students (3.33%) was unusable. All AirBeam data was then stripped of identifying information, both individual and school, and aggregated according to calendar date and time. Thermal conditions retrieved from AirBeam data were then plotted using the smooth() function of the "ggplot2" package in R statistical software. This function smooths the mean temperature and RH trends and removes the influence of extreme spikes. Aggregation and smoothing of data also allowed us to assess the overall seasonal trend of climate exposure for NYS capital region students and helped reduce the impact of missing data in this study. We used R 4.1.2 statistical software and the "data.table" package to clean, average, and aggregate all data. We used the "ggplot2" package to create all figures.

2.5. Informed consent

The University at Albany Institutional Review Board (IRB) approved the methods used in this study (protocol number: 16-X-323-01). Each adult (college student, teacher) involved in the study and each participating child's parental guardian signed a consent form. In addition, everyone who participated in the personal monitoring component of the study received a $60 Target gift card as an incentive.

3. Results

3.1. Temperature

Fig. 1 shows that the daily temperature patterns were similar across seasons. The primary peak occurred around 3:00 p.m. in the spring, slightly earlier in the fall (1:45 p.m.), and slightly earlier in the winter (11:45 a.m.). A secondary peak formed around 7:30 p.m. in the winter and 9:00 p.m. in the spring and fall. Temperatures exceeded the ASHRAE recommended indoor maximum of 80.5^{0}F from 9:00 a.m. (the beginning of the school classes) to 10:30 p.m. in the winter, from 9:00 a.m. to 12:00 a.m. in the spring, and from 10:30 a.m. to 11:00 p.m. in the fall. Temperatures also ranged significantly within each season (Appendix A). The largest temperature range overall was recorded in the spring (max=102^{0}F, min=64^{0}F), while the maximum in the winter and fall were 95^{0}F (min=59^{0}F) and 91^{0}F (min=64^{0}F), respectively. A more detailed breakdown of the seasonal and microenvironmental temperature distributions is available in Appendix B. A comparison between temperature and RH trends is available in Appendix F.

In Fig. 2, we compared daily temperature trends in elementary schools to those observed in two university classrooms in the spring. Spring temperature trends were similar for both school types, with primary peaks occurring at 3:00 p.m. and secondary peaks occurring at 9:30 p.m.. Temperatures exceeded the recommended maximum of 80.5^{0}F from 8:30 a.m. to 11:45 p.m. for elementary school students and from 9:00 a.m. to 1:30 a.m. for university students. The range of temperatures recorded in university classrooms was slightly larger compared to elementary school classrooms, though not statistically significant.

3.2. Relative humidity

Fig. 3 shows RH in elementary school classrooms, distributed by season. RH in the winter was consistently and significantly lower than any other season and never breached the minimum recommendation of 30% RH (NIOSH 2022). In the fall, RH fell below the minimum recommendation from 9:30 a.m. to 12:30 p.m. and 9:00 p.m. to 11:15 p.m.. In the spring, RH was below the minimum recommendation from 8:30 a.m. to 10:45 p.m. RH peaked at different times in each season: 6:30 p.m. in the fall (secondary at 7:30 a.m.), 4:00 a.m. in the spring, and 7:45 a.m. as well as 4:00 p.m. in the winter. Importantly, RH dipped during school hours (9:00 a.m.-3:00 p.m.) during all seasons, even during the winter, which is the driest season. RH also ranged significantly within each season (Appendix A). The largest RH range was recorded in the spring (max=76%, min=11%), while the maximum in the fall and winter were 75% (min=7%) and 57% (min=7%), respectively. A more detailed breakdown of the seasonal and microenvironmental RH distributions is available in Appendix C. A comparison between RH and temperature trends is available in Appendix F.

Fig. 4 shows that RH was significantly and consistently lower for university students compared to their primary school counterparts. For elementary school students, RH peaked at 5:00 a.m., with a secondary peak at 3:15 p.m. For university students, RH peaked at 2:45 a.m., with

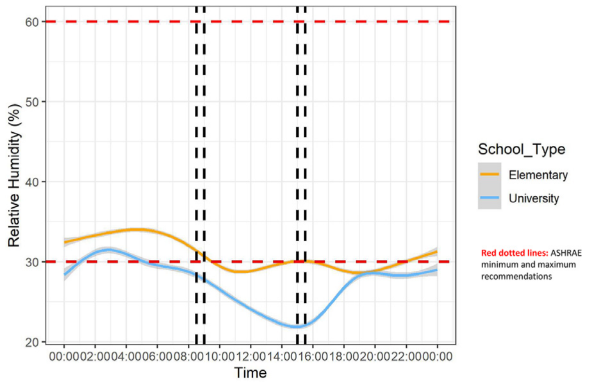


Fig. 4. AirBeam relative humidity trends in the spring by school type.

a secondary peak at 7:30 p.m. Most students spent most of the day in drier-than-ideal conditions, particularly during school hours.

4. Discussion

4.1. Temperature temporal variation

4.1.1. Daily variation

From midnight to 8:00 a.m., primary schoolchildren experienced relatively comfortable temperatures. However, temperatures elevate beyond the recommendation for comfort as soon as the children enter the school classroom at 9:00 a.m.. Importantly, the temperature remains elevated throughout the school day and in the evening when the child returns home. Hot thermal conditions are implicated in a host of learning and health problems in children (Mendell et al., 2013, Mendell et al., 2015, Haverinen-Shaughnessy et al., 2015), while elevated temperatures at home indicate no relief from the heat. A second daily temperature peak occurred between 7:30 and 09:30 p.m., coinciding with primary peaks of in-home $PM_{2.5}$ concentrations reported in another manuscript. Based on this timing, the secondary peak is likely due to cooking activities. These data also suggest that homes, like classrooms, may have inadequate temperature regulation (Lin et al., 2017, Lu et al., 2018, Lawrence et al., 2020). To the authors' knowledge, this is the first study to analyze daily temperature trends for primary school children across locations and seasons. Therefore, there is little research with which to compare our results.

4.1.2. Seasonal variation

Across all seasons, the temperature only remained below the indoor summer recommendation of 80.5^{0}F overnight. In the spring and winter, classroom temperatures remained above recommendations for the entire day. The highest classroom temperatures were observed in the winter (87.0^{0}F), suggesting that NYS elementary school classrooms have insufficient ventilation and/or the teacher has limited ability to control thermal comfort within the classroom, particularly in the colder months. Importantly, the indoor temperature recommendation during the winter is 75^{0}F, making this elevated measurement more worrisome. Our findings are consistent with results from other research studies. For example, a study conducted in primary schools in Venice, Italy, found that classroom temperatures in the spring ranged from 68.5-78.6^{0}F (De Giuli et al., 2012). This study also found that teachers' preferences were the most significant factor determining classroom thermal conditions, indicating that these conditions are likely not ideal for children. Another study conducted in 43 primary school classrooms in Southampton, UK, found that most of them were too warm for students' comfort, particularly during the summer (Teli et al., 2017). This study also mentioned that this problem will be compounded due to climate change, especially in areas where overheating has not typically been a problem (ex., the northeast US) (Teli et al., 2017). Finally, a largescale study conducted in 70 5th grade classrooms in the Southwest US found that students were typically exposed to comfortable temperatures (mean: 73^{0}F) (Haverinen-Shaughnessy et al., 2015). These studies suggest that areas which experience extremely hot conditions (southwest US) ensure that their schools are properly thermally regulated. In contrast, schools in relatively cool areas (northeast US) are underprepared for such conditions.

4.2. Temperature Geographic Variation

4.2.1. Home, school, and transit

Temperatures remained under the ASHRAE recommendations almost exclusively overnight. In the fall, recorded temperatures exceeded indoor guidelines from 10:00 a.m.-11:00 p.m. In the spring and winter, temperatures remained elevated for an additional hour on each side of that range (9:00 a.m.-12:00 a.m.). This trend indicates that participants in this study were personally exposed to uncomfortable thermal conditions for most of their day, on average. These findings are consistent with several similar studies. A largescale study conducted in Australian primary and secondary schools found that students generally preferred cooler thermal conditions (Kim and de Dear, 2018). "The students' preferred temperature was found to be between 2 and 3 K cooler than recommended by ASHRAE's adaptive comfort standard for adults in naturally ventilated buildings" (Kim and de Dear, 2018). A study conducted on primary school children in the Netherlands, which has a very moderate climate, also suggests that current standards are too warm for students (ter Mors et al., 2011). Finally, a study conducted in primary school classrooms in China showed that the ideal temperature, as indicated by academic performance, was when students felt "cool" or "slightly cool," at approximately 57.2 ^{0}F (Jiang et al., 2018). Based on previous research, ASHRAE's thermal recommendations are too high for children's comfort. Unfortunately, NYS primary schools do not even meet this standard.

4.2.2. Elementary schoolchildren vs. college students

Compared with elementary school students, college students were exposed, for even longer periods, to elevated temperatures (9:00 a.m.-1:30 a.m.) in the spring. In addition, they were exposed to larger spikes in temperature (86 vs. 85^{0}F respectively), though the daily temperature trends were similar.

4.3. Relative Humidity Temporal Variation

4.3.1. Daily spikes

RH remained consistently just above or below the ASHRAE indoor recommendation of 30%. Interestingly, RH only stayed above this recommendation at home before school but reliably dipped below the minimum standard at school and stayed there the entire day. RH then varied slightly before returning to baseline late at night. To the authors' knowledge, this is the first study to analyze daily RH trends for primary school children across locations and seasons. Therefore, there is little research with which to compare our results.

4.3.2. Seasonal variation

During the fall and spring, RH hovered around the indoor guideline of 30%. However, in the winter, RH was consistently below the indoor standard and averaged 22% across all measurements (median: 17%). Interestingly, RH fluctuated by approximately 11% in the fall (27-38%) but only 4-5% in the spring (27-32%) and winter (19-23%). This data suggests that school-aged children are regularly in dry environments, particularly during the winter. In addition, students and teachers are less able to control their thermal environment in the fall, as evidenced by significant RH fluctuations. Deng et al. also found that RH was highest in the fall and lowest in the winter, with several classrooms staying between 20-30% throughout the day (Deng and Lau, 2019).

4.4. Relative humidity geographic variation

4.4.1. Home, school, and transit

Across all seasons, the lowest RH was observed during school hours. In the spring and winter, the entirety of the school day (9:00 a.m.-3:00 p.m.) was the driest part of the schoolchildren's schedule and fell below the indoor recommendation of 30%. In the fall, the primary slump in RH was observed during school hours at 11:00 a.m. Interestingly, between 6:00-7:00 p.m., RH spiked significantly in the fall, fell slightly in the winter, and stayed relatively flat in the spring. These data suggest significant differences in how school and home environments change depending on the season, which may require schools to change their ventilation strategies during different seasons, further highlighting the importance for classroom occupants to manage thermal controls. These findings are unique compared to other research. For example, in a large-scale study of thermal conditions in classrooms in the Midwestern U.S., Deng et al. found that the mean classroom RH was 39.8% (26.1-50.0%), which is relatively dry but still within thermal condition recommendations (Deng and Lau, 2019). In addition, Haverinen-Shaughnessy et al. (2015b) found that the mean classroom RH was 46.6% (Haverinen-Shaughnessy et al., 2015), which is within the ASHRAE recommended comfort range (30-60%). These results suggest significant regional differences in school ventilation and thermal control. Again, this may be explained by differences between regional climates where schools in warmer locations are more prepared to deal with humid conditions.

4.4.2. Elementary schoolchildren vs. college students

College students were exposed to drier spring conditions than elementary school children. While RH remained stable in primary school classrooms during the day, RH in college classrooms continued to decrease until 3:00 p.m. At that point, the RH steadily increases until midnight but never reaches the minimum ASHRAE recommendation of 30%. Similar to the temperature trends, RH trends between different school types follow the same basic pattern.

4.5. Between school variation

Importantly, the seasonal and overall trends for temperature and RH trends are influenced by individual school characteristics. For example, although all participating schools were located in the capital region of NYS, each school exists in a unique urbanicity and socio-economic environment. Half of the primary schools were in urban/suburban regions, and the other half were in rural regions (Appendix D). Urbanicity is significant with regard to thermal conditions as the asphalt and cement utilized in cities retain far more heat than the green and blue spaces in rural areas. The urban heat island effect could be another source of extreme heat exposure in urban schools. Economically, all urban/suburban schools participating in this study were in the high need (low SES) category (Appendix D). SES is significant with regard to thermal conditions because it speaks to the school building's age, general condition, and air conditioner use.

Similarly, there are differences between the heating, ventilation, and air conditioning (HVAC) systems in the participating primary schools. Three of the five primary schools with detailed HVAC data did not possess centralized HVAC systems (Appendix E). In addition, one of the schools with a centralized HVAC system reported having a heat generating system and ventilation equipment in "unsatisfactory" condition. Crucially, no school reported any HVAC-related system to be in "excellent" condition. The nature and condition of HVAC technologies deployed in schools are crucial variables affecting classroom thermal conditions.

4.6. Humidity and viruses

Lower humidity has been associated with an increased influenza virus survival rate in grade school classrooms (Wolkoff, 2018, Koep et al., 2013). Our study found that microenvironmental parameters in primary school classrooms in upstate NY frequently fall outside the ASHRAE recommended thermal comfort levels across all seasons, particularly in the winter. RH in classrooms is, therefore, important in the context of the COVID-19 pandemic as students are excellent vectors for viruses to spread, and children have returned to school where conditions are generally dry.

4.7. Strengths and limitations

To our knowledge, this study is the first to measure temperature and RH at school and home for the same group of subjects. A strength of this study was the innovative use of personal air monitoring devices to measure real-time temperature and RH exposure among students. Unlike most previous thermal comfort research focused on exposure in one location, this study examined hourly trends of such conditions for the same individual across 48 consecutive hours. This project also compared temperature and RH exposure among students across seasons; at home, school, and transit; and between primary school children and college students. This is also one of the few studies to analyze the seasonal trends of classroom thermal conditions, which is a significant innovation.

On the other hand, one potential limitation of this study was the relatively small sample size and the geographical area we looked at due to the funding and resource restrictions. This study collected monitoring data from 77 individuals in 13 classrooms in upstate NY, which may have limited the study's power to detect significant differences. However, we did find some significant temporal and spatial differences even with this small sample size. We also computed and assured an adequate study power of over 80% based on the 77 participants. Another concern is selection bias, i.e., whether the participating schools represent our target population of primary schools in upstate NY. To address this concern, we purposely sampled schools representing different socio-demographics to represent our target population accurately. Therefore, selection bias should not be a major issue in this study.

Regarding QA/QC, we have already developed a comprehensive and lengthy plan based on this project's funding agency, the U.S. EPA. All detailed procedures regarding sampling method, equipment calibration, and temperature/RH measurement recording have been standardized. In addition, all field staff involved in this project were systematically trained by Dr. Thurston and Dr. Khwaja, Co-Investigators, to ensure the quality and normal functioning of AirBeam and other equipment before each field trip.

4.8. Future research

Several factors make research into thermal comfort a complex and difficult task. First, there is no established standard. Considering all the factors that affect temperature preferences – age, gender, geography, climate, clothing, etc. – it is unreasonable to expect a straightforward standard to exist. Participants report significantly different ranges of thermal comfort throughout this entire area of research, suggesting that a more comprehensive framework is needed to understand the relationship between thermal perception, preference, and adaptation (Rodriguez et al., 2019). While most studies focus on 2 – 5 parameters, a study conducted in classrooms at Columbia suggests that 49 different parameters should be evaluated to provide the most comprehensive picture of school thermal conditions (Rodriguez et al., 2019). In addition, the instructor's preference seems to be a critical factor in determining classroom thermal conditions, even though these preferences may not be ideal for student academic performance.

5. Conclusion

Overall, classroom temperature and humidity fell outside NIOSH workplace recommendations for thermal comfort. Students in our study were consistently exposed to excessively warm temperatures and dry conditions, particularly during school hours. Ventilation and thermal comfort in classrooms were not adequately controlled, as temperature and humidity regularly fall outside indoor guidelines during the school day. In addition, students were exposed to the driest conditions and largest temperature fluctuations in the winter. Finally, there is an urgent need to analyze and compare thermal conditions in different climates and geographic regions. The differences between these areas demand unique strategies to cope with unique thermal problems, especially in the face of accelerating climate change. Policy change to update school classrooms' infrastructure may potentially improve health and academic performance for millions of students annually.(Appendix A, B, C, D, E, Appendix F)

Declaration of Competing Interest

None.

Acknowledgments

The authors thank the previous researchers who conducted the in-school field sampling and measurements. In addition, we extend our sincerest gratitude to the teachers, principals, and superintendents in the primary schools and university departments that participated in the study. Lastly, we extend gratitude to the US Environmental Protection Agency for funding this vital project. This work will help protect children's health in the future, and we could not have done it without this help.

Appendix A

Appendix A
Thermal conditions among primary school children by season, 2017-–2019 (AirBeam).

Statistic	Temperature (°F)				Relative Humidity (%)			
Season	Overall	Winter	Spring	Fall	Overall	Winter	Spring	Fall
Maximum	102	95	102	91	76	57	76	75
Minimum	53	59	53	64	7	7	11	7
Median	82	80	82	82	29	17	30	29
Mean	82	81	82	81	30	22	31	31
25th Percentile	78	77	78	77	21	14	23	24
75th Percentile	86	84	86	86	38	28	39	39
IQR	8	7	8	9	17	14	16	15
Total Measurements	56,768	7435	41,764	7569	55,189	7320	40,536	7333
Measurements >75^{0}F/<30%	49,669	6659	36,683	6327	29,477	5732	19,917	3828

Appendix B
Temperature (°F) among primary school children by microenvironment and season, 2017–2019 (AirBeam).

Statistic	In-School				Transportation				Home			
Season	Overall	Winter	Spring	Fall	Overall	Winter	Spring	Fall	Overall	Winter	Spring	Fall
Max	93	91	93	91	91	91	91	91	102	95	102	91
Min	53	59	53	64	69	73	69	73	62	69	62	68
Median	80	78	80	78	84	84	82	87	82	80	82	84
Mean	80	80	80	79	82	83	81	85	82	81	82	83
25th Percentile	77	77	78	75	78	77	78	80	78	78	78	80
75th Percentile	84	84	84	82	86	87	86	89	86	84	86	86
IQR	7	7	6	7	8	10	8	9	8	6	8	6
Total Measurements	14,570	1659	10,146	2765	2221	297	1671	253	39,977	5479	29,947	4551
Measurements >75^{0}F	11,774	1308	8628	1838	1893	237	1432	224	36,002	5114	26,623	4265

Appendix C
Relative humidity (%) among primary school children by microenvironment and season, 2017–2019 (AirBeam).

Statistic	In-School				Transportation				Home			
Season	Overall	Winter	Spring	Fall	Overall	Winter	Spring	Fall	Overall	Winter	Spring	Fall
Max	75	53	70	75	64	40	64	53	76	57	76	71
Min	11	11	11	15	12	12	16	17	7	7	13	7
Median	29	17	31	26	27	15	29	27	29	17	29	31
Mean	30	22	31	30	29	21	30	30	29	22	30	32
25th Percentile	22	14	24	22	19	14	23	22	21	14	22	26
75th Percentile	39	28	39	37	38	27	39	34	38	28	39	39
IQR	17	14	15	15	19	13	16	12	17	14	17	13
Total Measurements	14,251	1643	9932	2676	2163	297	1599	267	38,775	5380	29,005	4390
Measurements <30%	7410	1284	4373	1753	1222	238	833	151	20,935	4210	14,735	1990

Appendix D

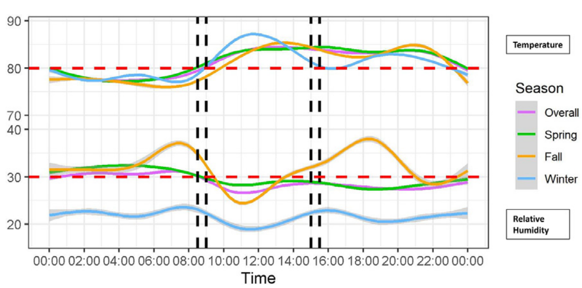
Description and list of school, classroom, and student inclusion characteristics.

School	SES	Urbanicity	Classrooms (#)	Students (#)
Primary 1	High need	Urban/suburban	2	3
Primary 2	High need	Urban/suburban	3	14
Primary 3	High need	Urban/suburban	2	13
Primary 4	High need	Rural	1	9
Primary 5	Average need	Rural	1	3
Primary 6	High need	Rural	2	6
Primary 7	Average need	Rural	-	-
Primary 8	Average need	Rural	-	-
Primary 9	Average need	Urban/suburban	-	-
Primary 10	Average need	Urban/suburban	-	-
UAlbany SPH	-	-	1	22
UAlbany ASRC	-	-	1	7
Total	-	-	**13**	**77**

Appendix E

Description of heating, ventilation, and air conditioning (HVAC) systems at participating primary schools.

School	Central HVAC	Heat Generating System (Condition)	Heating Fuel/Energy System (Condition)	Cooling/AC System (Condition)	Air Handling/Ventilation Equipment (Condition)
Primary 1	No	Yes (Satisfactory)	Yes (Satisfactory)	Yes (Satisfactory)	Yes (Satisfactory)
Primary 2	Yes	Yes (Satisfactory)	Yes (Satisfactory)	Yes (Satisfactory)	Yes (Satisfactory)
Primary 3	No	Yes (Satisfactory)	Yes (Satisfactory)	Yes (Satisfactory)	Yes (Satisfactory)
Primary 4	-	-	-	-	-
Primary 5	No	Yes (Satisfactory)	Yes (Satisfactory)	Yes (Satisfactory)	Yes (Satisfactory)
Primary 6	Yes	Yes (Unsatisfactory)	No(-)	Yes (Satisfactory)	Yes (Unsatisfactory)



Appendix F. Comparison between AirBeam temperature (top) and relative humidity (bottom) trends for primary schoolchildren.

References

USGCRP, 2016. The impacts of climate change on human health in the United States: a scientific assessment. In: Crimmins, A., Balbus, J., Gamble, J.L., Beard, C.B., Bell, J.E., Dodgen, D., Eisen, R.J., Fann, N., Hawkins, M.D., Herring, S.C., Jantarasami, L., Mills, D.M., Saha, S., Sarofim, M.C., Trtanj, J., Ziska, L. (Eds.), U.S. Global Change Research Program, p. 312. doi:10.7930/J0R49NQX Washington, DC.

Stanberry, LR, Thomson, MC, James, W, 2018. Prioritizing the needs of children in a changing climate. PLoS Med. 15 (7), e1002627. doi:10.1371/journal.pmed.1002627.

ter Mors, S., Hensen, J.L.M., Loomans, M.G.L.C., Boerstra, A.C., 2011. Adaptive thermal comfort in primary school classrooms: Creating and validating PMV-based comfort charts. Build. Environ. 46 (12), 2454–2461. doi:10.1016/j.buildenv.2011.05.025.

Teli, D., Jentsch, M.F., James, P.A.B., Bahaj, A.B.S., 2012. Field study on thermal comfort in a UK primary school. In: Proceedings of 7th Windsor Conference: The Changing Context of Comfort in an Unpredictable World, 7730, pp. 12–15.

NIOSH, 2022. Indoor Environmental Quality – Temperatures and Occupancy Settings.

Haverinen-Shaughnessy, U., Shaughnessy, R.J., 2015. Effects of classroom ventilation rate and temperature on students' test scores. PLoS One 10 (8), 1–14. doi:10.1371/journal.pone.0136165.

Toyinbo, O., Phipatanakul, W., Shaughnessy, R., 2019. Haverinen-Shaughnessy DSc. Indoor Air 29 (3), 510–520. doi:10.1111/ina.12547.

Jiang, J., Wang, D., Liu, Y., Xu, Y., Liu, J., 2018. A study on pupils' learning performance and thermal comfort of primary schools in China. Build. Environ. 134 (February), 102–113. doi:10.1016/j.buildenv.2018.02.036.

Deng, S., Lau, J., 2019. Seasonal variations of indoor air quality and thermal conditions and their correlations in 220 classrooms in the Midwestern United States. Build. Environ. 157 (February), 79–88. doi:10.1016/j.buildenv.2019.04.038.

Wolkoff, P., 2018. Indoor air humidity, air quality, and health – an overview. Int. J. Hyg. Environ. Health 221 (3), 376–390. doi:10.1016/j.ijheh.2018.01.015.

Park, R.J., Goodman, J., Hurwitz, M., Smith, J., 2020. Heat and learning. Am. Econ. J. 12 (2), 306–339. doi:10.1257/pol.20180612.

Domínguez-Amarillo, S., Fernández-Agüera, J., González, M.M., Cuerdo-Vilches, T., 2020. Overheating in schools: factors determining children's perceptions of overall comfort indoors. Sustainability 12 (14), 1–20. doi:10.3390/su12145772.

Zomorodian, Z.S., Tahsildoost, M., Hafezi, M., 2016. Thermal comfort in educational buildings: a review article. Renew. Sustain. Energy Rev. 59, 895–906. doi:10.1016/j.rser.2016.01.033.

Yang, B., Olofsson, T., Wang, F., Lu, W., 2018. Thermal comfort in primary school classrooms: a case study under subarctic climate area of Sweden. Build. Environ. 135 (February), 237–245. doi:10.1016/j.buildenv.2018.03.019.

HabitatMap, 2021. AirBeam.

Mukherjee, A., Stanton, L.G., Graham, A.R., Roberts, P.T., 2017. Assessing the utility of low-cost particulate matter sensors over a 12-week period in the Cuyama valley of California. Sensors 17 (8). doi:10.3390/s17081805.

Rabinovitch, N., Adams, C.D., Strand, M., Koehler, K., Volckens, J., 2016. Within-microenvironment exposure to particulate matter and health effects in children with asthma: a pilot study utilizing real-time personal monitoring with GPS interface. Environ. Health 15 (1), 1–10. doi:10.1186/s12940-016-0181-5.

Mazaheri, M., Clifford, S., Yeganeh, B., Viana, M., Rizza, V., Flament, R., Buonanno, G., Morawska, L., 2018. Investigations into factors affecting personal exposure to particles in urban microenvironments using low-cost sensors. Environ. Int. 120, 496–504. doi:10.1016/j.envint.2018.08.033.

Johnston, J.E., Juarez, Z., Navarro, S., Hernandez, A., Gutschow, W., 2020. Youth engaged participatory air monitoring: A 'day in the life' in urban environmental justice communities. Int. J. Environ. Res. Public Health 17 (1). doi:10.3390/ijerph17010093.

Folkerth, M., Adcock, K., Singler, M., Bishop, E., 2020. Citizen science: a new approach to smoke-free policy advocacy. Health Promot. Pract. 21 (1_suppl), 82S–88S. doi:10.1177/1524839919883586.

Korto¸ci, P., Motlagh, N. H., Zaidan, M. A., Fung, P. L., Varjonen, S., Rebeiro-Hargrave, A., Niemi, J. V., Nurmi, P., Hussein, T., Pet¨aj¨a, T., Kulmala, M., & Tarkoma, S. (2021). Air pollution exposure monitoring using portable low-cost air quality sensors. Smart Health, 100241. https://doi.org/10.1016/j.smhl.2021.100241

D'Eon, J.C., Stirchak, L.T., Brown, A.S., Saifuddin, Y., 2021. Project-based learning experience that uses portable air sensors to characterize indoor and outdoor air quality. J. Chem. Educ. 98 (2), 445–453. doi:10.1021/acs.jchemed.0c00222.

Sousan, S., Koehler, K., Hallett, L., Peters, T.M., 2017. Evaluation of consumer monitors to measure particulate matter. J. Aerosol Sci. 107, 123–133. doi:10.1016/j.jaerosci.2017.02.013.

Borghi, F., Spinazzè, A., Campagnolo, D., Rovelli, S., Cattaneo, A., Cavallo, D.M., 2018. Precision and accuracy of a direct-reading miniaturized monitor in PM2.5 exposure assessment. Sensors 18 (9), 1–21. doi:10.3390/s18093089.

Mendell, M., Eliseeva, E., Davies, M., Spears, M., Lobscheid, A., Fisk, W.J., Apte, M.G., 2013. Association of classroom ventilation with reduced illness absence: a prospective study in California elementary schools. Indoor Air 23 (6), 515–528. doi:10.1111/ina.12042.

Mendell, M., Eliseeva, E. Davies, M., and Lobscheid, A. (2015). Do classroom ventilation rates in California elementary schools influence standardized test scores? Results from a prospective study. 26, Issue 4 p. 546-557. https://doi.org/10.1111/ina.12241

Haverinen-Shaughnessy, U., Shaughnessy, R., Cole, E., Toyinbo, O., and Moschandreas, D. (2015b). Building and Environment. Volume 93, Part 1, 35-40. https://doi.org/10.1016/j.buildenv.2015.03.006

Lin, S., Lawrence, W.R., Lin, Z., Francois, M., Neamtiu, I.A., Lin, Q., et al., 2017. Teacher respiratory health symptoms in relation to school and home environment. Int. Arch. Occup. Environ. Health 90 (8), 725–739. doi:10.1007/s00420-017-1235-x.

Lu, Y., Lin, S., Lawrence, W.R., Lin, Z., Gurzau, E., Csobod, E., Neamtiu, I.A., 2018. Evidence from SINPHONIE project: Impact of home environmental exposures on respiratory health among school-age children in Romania. Sci. Total Environ. 621, 75–84. doi:10.1016/j.scitotenv.2017.11.157.

Lawrence, W.R., Lin, S., Lin, Z., Gurram, N., Neamtiu, I.A., Csobod, E., Gurzau, E., 2020. Interactions between dietary habits and home environmental exposures on respiratory symptoms in Romanian school children: an analysis of data from the SINPHONIE project. Environ. Sci. Pollut. Res. Int. 27 (3), 2647–2657. doi:10.1007/s11356-019-07129-z.

De Giuli, V., Da Pos, O., De Carli, M, 2012. Indoor environmental quality and pupil perception in Italian primary schools. Build. Environ. 56, 335–345. doi:10.1016/j.buildenv.2012.03.024.

Teli, D., Bourikas, L., James, P.A.B., Bahaj, A.S., 2017. Thermal performance evaluation of school buildings using a children-based adaptive comfort model. Procedia Environ. Sci. 38 (0), 844–851. doi:10.1016/j.proenv.2017.03.170.

Kim, J., de Dear, R., 2018. Thermal comfort expectations and adaptive behavioural characteristics of primary and secondary school students. Build. Environ. 127 (October 2017), 13–22. doi:10.1016/j.buildenv.2017.10.031.

Koep, T.H., Enders, F.T., Pierret, C., Ekker, S.C., Krageschmidt, D., Neff, K.L., Lipsitch, M., Shaman, J., Huskins, W.C., 2013. Predictors of indoor absolute humidity and estimated effects on influenza virus survival in grade schools. BMC Infect. Dis. 13 (1). doi:10.1186/1471-2334-13-71, 1.

Rodriguez, C.M., Coronado, M.C., Medina, J.M., 2019. Classroom-comfort-data: a method to collect comprehensive information on thermal comfort in school classrooms. MethodsX 6, 2698–2719. doi:10.1016/j.mex.2019.11.004.