Classroom as Laboratory: Engaging Architecture Students in Hands-on Building Science Research

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Abstract

Knowledge of building science – how buildings perform with respect to energy efficiency, durability, comfort, and health – is a key aspect of sustainable architectural design. Although most building science courses are taught in a traditional lecture format, experiential teaching methods have the potential to improve student engagement and comprehension of technical subject matter.

This paper describes a case study of experiential learning in building science education. In Spring, 2018, we conducted a thermal comfort study as part of an integrated design studio at Pratt Institute in Brooklyn, NY. We measured temperature and relative humidity in the studio space and asked students about their thermal comfort via daily point-in-time surveys.

We analyzed the sensor results using the PMV model, finding that the majority of the studio (87% of sensor locations) was within the comfort zone (PMV between -0.5 and +0.5) during the study period. Students' average reported thermal sensation over the same period (AMV, or actual mean vote) was -0.46, a result that suggested cold discomfort. The discrepancy between PMV and AMV suggests that factors not measured in this study – such as mean radiant temperature or air speed – may have negatively impacted students' comfort.

This case study suggests the potential for integrating hands-on building science investigations into technical architecture courses. Areas for improvement include tighter integration of these investigations into individual courses and the broader architecture curriculum to achieve the greatest impact on student engagement and learning

Keywords: Pedagogy, Experiential Learning, Building Performance, Thermal Comfort

Introduction

Knowledge of building science – how buildings perform with respect to energy efficiency, durability, comfort, and health – is a key aspect of sustainable architectural design. However, methods of teaching building science, which are primarily lecture-based, can fail to engage architecture students who are accustomed to the project-based pedagogy of the design studio.

This paper describes a case study of a hands-on, experiential approach to teaching building science that involves students in field studies of existing buildings. This approach invites students to discover links between design, performance, and occupant satisfaction through their own observations. In Spring, 2018, we conducted a thermal comfort study as part of an integrated design studio in the Master of Architecture program at Pratt

Institute in Brooklyn, NY. We installed a sensor network in the studio space and monitored temperature and relative humidity during the month of April. At the same time, we asked students about their perceptions of thermal comfort via daily point-in-time surveys. We analyzed the data to determine where and when the studio was comfortable, and whether students' perception of comfort matched the predictions of industry-standard comfort models. At the conclusion of the semester, we presented our results to the students so they could understand the connection between their experience as occupants and the architectural design of the space.

Our experience with this study suggests the potential for integrating hands-on building science investigations into the architecture curriculum as a way to boost student engagement and comprehension of this critical subject matter

Pedagogic Context

Experiential Learning and Building Science Education

Learning by doing – also known as experiential or haptic learning – refers to learning via physical engagement with the environment. While traditional teaching relies on aural and visual methods, research suggests that much of what we know about the world is learned through touch.[1] Haptic learning has a long history in architectural design education, where physical models are used to test and represent the physical configuration of buildings.

Building technology educators have demonstrated the potential of haptic methods in technical architectural courses, in addition to the design studio. Student feedback suggests that haptic techniques – such as analytical models or design-build projects – reinforce content from lectures and increase student engagement with technical subject matter. Students reported that hands-on lab work "made a real connection between what was taught in the lecture and the problem set" and what architects need to know in practice.[2]

Despite these benefits, most building technology courses are taught in a traditional lecture format. A 2017 survey of building technology educators found that 86% of respondents used lectures as the primary delivery method for building technology course content; fewer than 50% used hands-on methods like workshops, field trips, or design-build projects. Furthermore, 87% of educators reported that technology classes were taught as stand-alone subject matter, with fewer than 50% reporting that technology courses were integrated with each other or with design studios.[3]

Hands-on teaching methods are more likely to be found in building technology courses that address structures and construction systems – subjects that have a tangible physical presence. Common modes of inquiry include large-scale physical models, full-scale prototypes, and even complete, functioning buildings.[4] These methods aim to help students understand materials, construction systems, and assembly sequences through the physical act of building.

Less common are examples of hands-on methods in building science courses, which focus on the less tangible phenomena of building performance. A notable exception is the Vital Signs Curriculum Materials project, which began at the University of California, Berkeley in 1992 and ran until the mid-2000s.[5] This project engaged students in field studies of existing buildings. Students measured building performance ("vital signs") in areas related to building physics, energy use, and occupant health and well-being, and produced written reports ("case studies") of their observations and analysis. The project included curriculum guides, monitoring protocols, peer-to-peer training workshops, and an equipment loan program, enabling faculty to replicate the investigations at other institutions.[6]

As the founders of Vital Signs wrote, the “key to the learning process” in an investigation was “the direct experience with existing buildings, asking questions, testing hypotheses, and ultimately finding answers that [would lead] students to greater awareness and comprehension” about the impact of their design decisions for the environment and building occupants.[7]

Sensing and monitoring equipment has evolved greatly since the conclusion of the Vital Signs project. Inexpensive, off-the-shelf wireless sensor networks can log data and upload it to the cloud, where it can be viewed from anywhere, or downloaded for further analysis and visualization. The availability of large amounts of data about the built environment is reshaping the architecture profession. Data literacy – the ability to understand and communicate information with data – is becoming a core competency for architects.[8] In this context, it is an opportune time to revisit curriculum models like Vital Signs, and apply their pedagogical goals to a changing technological and professional landscape.

Building Technology Education at Pratt

Pratt’s 3-year accredited Master of Architecture program includes a 4-semester core sequence of building technology courses in the first and second year. In the first year, students take two semesters of structures, followed two building science lecture courses in the first semester of the second year (Materials and Assemblies and Environmental Control Systems [ECS]). Core building science content is delivered in ECS, which covers the fundamentals of environmental design (climate, daylighting, thermal comfort) and building systems design. Topics such as heating, cooling, lighting, and electrical service are introduced in the context of the 3rd semester design studio project, and the ECS final project is a simplified study of these systems applied to students’ third semester studio project.

In the fourth semester, content from the design and building technology courses is synthesized in an integrated studio project, comprised of two studio courses taken simultaneously: the capstone design studio (CAP), and the capstone technical studio, Integrated Building Systems (IBS). Students work in teams on a medium-sized institutional project, which they develop with input from design faculty and a team of technical instructors who are practicing structural engineers, mechanical engineers, and facade specialists. In 2016, the CAP/IBS curriculum was cited by the NAAB accreditation committee as an exemplary model of integrated design and technical education.[9]

The thermal comfort study described in this paper was conducted by IBS studio faculty in the context of this capstone technical studio. The classroom monitoring and thermal comfort surveys happened in parallel to the studio activities. Although independent of the class content, these activities reinforced concepts introduced in the ECS lecture course, and influenced discussions with the IBS technical instructors about environmental design and control systems for the CAP/IBS studio projects.

Methods

Building Context

Our investigation took place in an architecture studio on the top floor of Higgins Hall, an uninsulated mass masonry building built in 1868 on Pratt’s campus in Brooklyn, NY. The 4,000 sf space had exposures on the north, east, and south, with six operable double-hung, single-pane wood windows on the north and south walls, and two windows on the east wall (Figure 1). The room was cooled by two ceiling-mounted fan coil units, each with its own thermostat. Heating was provided by a

Figure 1 Interior of studio space

perimeter hydronic fin-tube radiator installed at the base of the three exterior walls. Heating and cooling were controlled by the campus BMS system, with a cooling setpoint of 74°F for occupied hours between 7:00 am and 10:00 pm, Monday through Sunday.

Occupants

The studio was occupied by 59 architecture graduate students. Students were between 20 and 30 years old; 46% were female and 54% were male. The students had unlimited 24-hour access to the studio space. Student desks were arranged in an open office layout. Each student had their own desk, where they did the majority of their work during the semester.

Sensor Hardware and Software

The study period ran from April 7 to May 7, 2018. During that time, a roof-mounted weather station recorded data about outdoor conditions every 5 minutes. The weather station (WS-1400 Observer manufactured by Ambient Weather) measured environmental conditions including temperature, relative humidity, wind speed, wind direction, precipitation, and solar radiation. Inside, a network of 52 temperature sensors and 2 relative humidity sensors measured and recorded indoor conditions every 5 minutes. The sensor network was a beta version of the Pointelist wireless sensor network developed by KT Innovations, an affiliate of the Philadelphia-based architecture firm Kieran Timberlake.[10] Sensors were arranged on a 6 ft x 15 ft grid, with each student workstation about 3 feet away from the closest sensor (Figure 2). Sensors were installed 43 inches[11] above the floor and shielded from direct light exposure with protective plastic tubing. Sensor locations were adjusted to avoid proximity to desktop items that could influence temperature readings, such as computer monitors, 3D printers, and electric kettles. Our study did not measure other environmental factors affecting thermal comfort, such as mean radiant temperature and indoor air speed.[12]

Thermal Comfort Surveys

During the study period, students received a daily thermal comfort survey via email. The survey software was a beta version of the Roast survey application, also developed by KT Innovations.[13] The survey was sent at 9:00 am and 9:00 pm. Students could answer once every 12 hours,

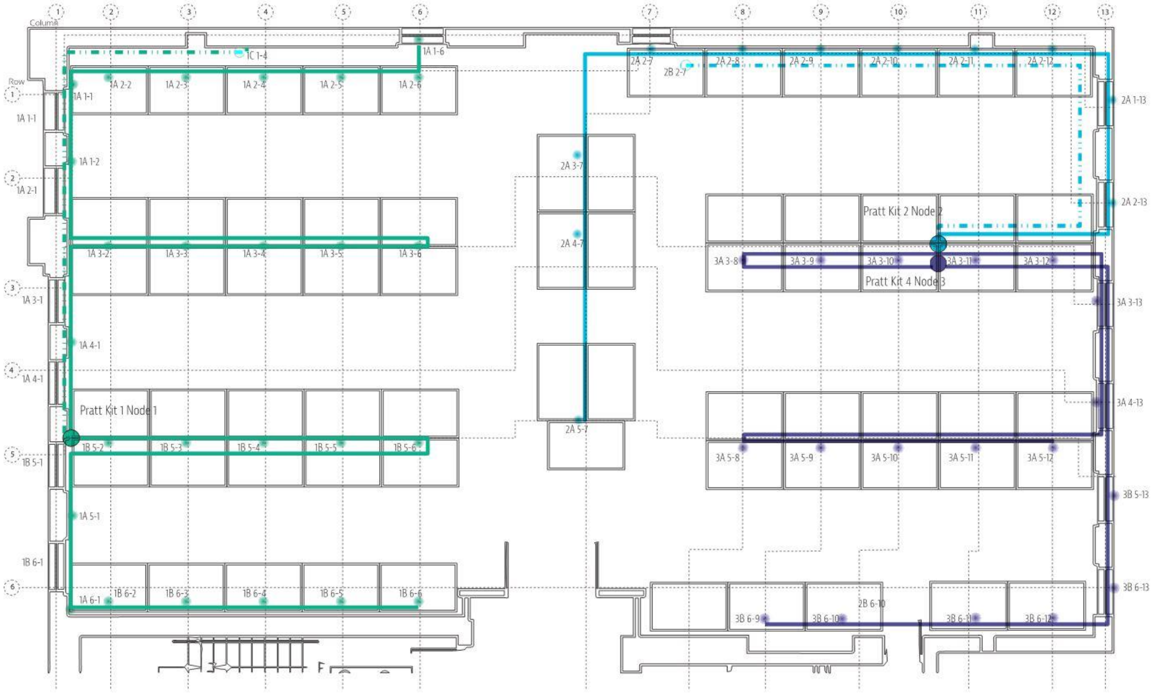

Figure 2 Sensor layout

and their responses were timestamped. The survey asked students to specify their location in the room, clothing, and activity level, and to describe their perceptions of thermal comfort, humidity, air speed, and productivity at that point in time. Responses were quantified on a 7-point scale from -3 to +3, with 0 being the neutral sensation. Descriptions of clothing insulation and activity level were converted to clo and met values using tables from established thermal comfort standards.[14] To incentivize students to participate in the survey, we offered gift cards to the three students with the highest response rate at the conclusion of the study. We conducted follow-up interviews with seven students who were frequent survey participants to better understand the factors affecting their comfort in the studio.

Results

Over the course of one month, we generated approximately 37,000 hourly sensor measurements and 359 survey responses. The dense sensor grid enabled us to characterize thermal comfort in the studio with a high degree of spatial resolution. The dense grid also enabled us to match survey responses with simultaneous sensor measurements to compare students' perceived thermal comfort with comfort predictions (PMV model) for the same conditions.

Indoor and Outdoor Environmental Conditions

Outdoor temperatures during the study period ranged from 32°F to 91°F, with an average of 54°F. Diurnal outdoor temperature swings ranged from 9°F to 16°F per day. Outdoor relative humidity averaged 56%, and dewpoint averaged 37°F. Indoor temperatures were relatively steady during the same period, ranging from 69°F to 81°F with an average of 75°F. Diurnal indoor temperature swings ranged from 1°F to 8°F per day. Indoor relative humidity ranged from 14% to 61% with an average of 32% (Figure 3).

Plotting average temperatures from each sensor on their location in the studio revealed local thermal anomalies, particularly at the perimeter of the room. Cold

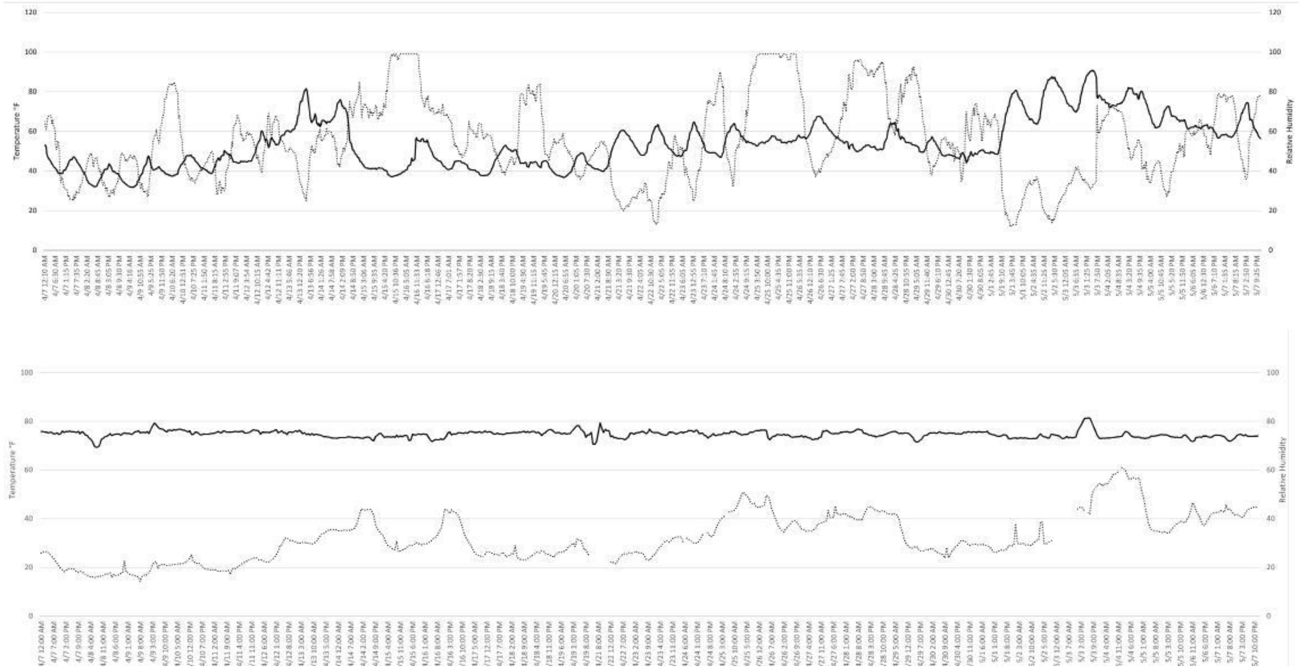

Figure 3 Outdoor (above) and indoor (below) temperature (black line) and relative humidity (gray line)

microclimates may have been caused by air infiltration from drafty windows or low surface temperatures at windows and exterior walls. Warm microclimates were likely caused by heat from the perimeter radiator. Hotspots may have been exacerbated by the furniture layout. Cold microclimates in the middle of the room were located under registers for the HVAC system (Figure 4).

Predicted Thermal Comfort

Predicted Mean Vote (PMV) is a widely used thermal comfort metric for mechanically conditioned spaces.[15] The PMV equation takes into account six factors: two personal factors (clothing and activity level) and four environmental factors (air temperature, mean radiant temperature [MRT], air speed, and relative humidity).[16] To characterize thermal comfort in the studio, we calculated PMV for each measured combination of temperature and relative humidity. We used standard clothing and activity levels for office environments, and assumed negligible effects from radiant temperatures and air speed.[17]

PMV is expressed on a 7-point scale ranging from -3 (cold discomfort) to +3 (warm discomfort). PMV values of -0.5 to +0.5 define the comfort zone, with a PMV of 0 representing a neutral thermal sensation (optimum comfort). Average PMV values for each sensor indicate that that majority of locations (45 of 52 sensors, or 87%) were within the comfort zone (-0.5 < PMV < 0.5) during the study period. Seven sensors (13%) had an average PMV greater than 0.5; all were located at the perimeter of the room (Figure 5).

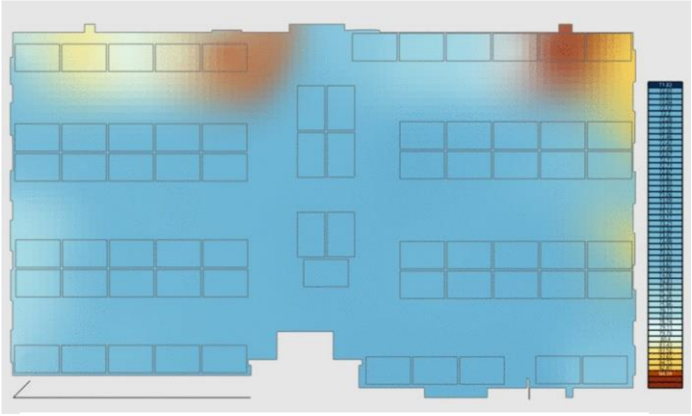

Figure 4 Thermal microclimates (May 1st, 2018 12:00 am)

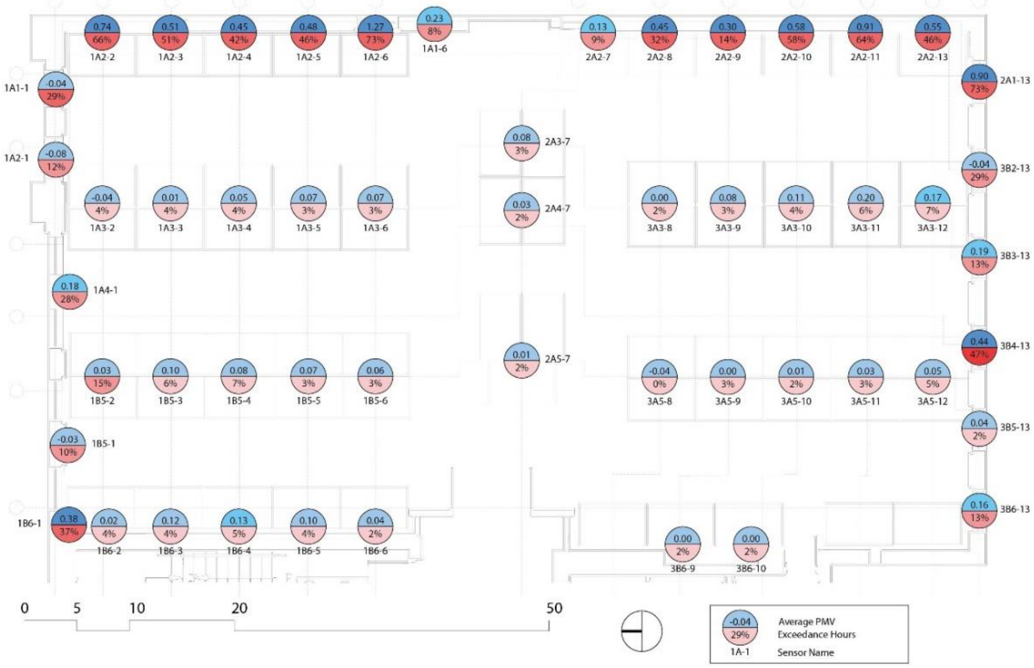

Figure 5 Average PMV and Exceedance Hours for each sensor

Thermal discomfort can also be expressed as exceedance hours: the number of hours in a given time period in which conditions are outside the comfort zone. While ASHRAE-55 does not prescribe minimum standards for exceedance hours, we observed that 33 sensors (63%) had exceedance hours of less than 10% over the study period. The remaining sensors had exceedance hours of 10% or greater, with a maximum of 73%. Sensors with high percentages of exceedance hours were located at room perimeter (Figure 5).

Survey Analysis

We sent 3540 surveys over the study period and received 359 survey responses, a response rate of 10%. Of the 59 students in the class, 33 students (56%) responded to the survey at least once. Of these, 11 students (33%) responded only once, and 12 students (36%) responded 10 or more times. ASHRAE-55 does not prescribe a statistically significant response rate for point-in-time surveys.[18] However, a majority of students (37 students, or 63%) did not answer the survey at all, or answered only once, raising the possibility that the survey results may not be representative of the overall student group. Survey responses averaged 15 per day. Most surveys were answered between 8am and 5pm, with the majority (92 surveys, or 26%) answered at 1 pm, just prior to the start of the 2 pm studio (Figure 6).

The average clothing insulation (clo) value over the study period was 0.87 (median: 0.73); this reflects clothing insulation between summer (0.5) and winter (1.0) levels, as would be expected for the month of April. The average activity level over the study period was 1.11 met (median: 1.0), which reflects typical office activities like reading (1.0) and typing (1.1). The average thermal sensation over the study period was -0.46 (median: 0), which suggests that, while many of the students were comfortable, some were uncomfortably cold (Figure 7). Average perceptions of humidity (-0.25, median: 0) and air movement (0.19, median: 0) were more neutral across the student population.

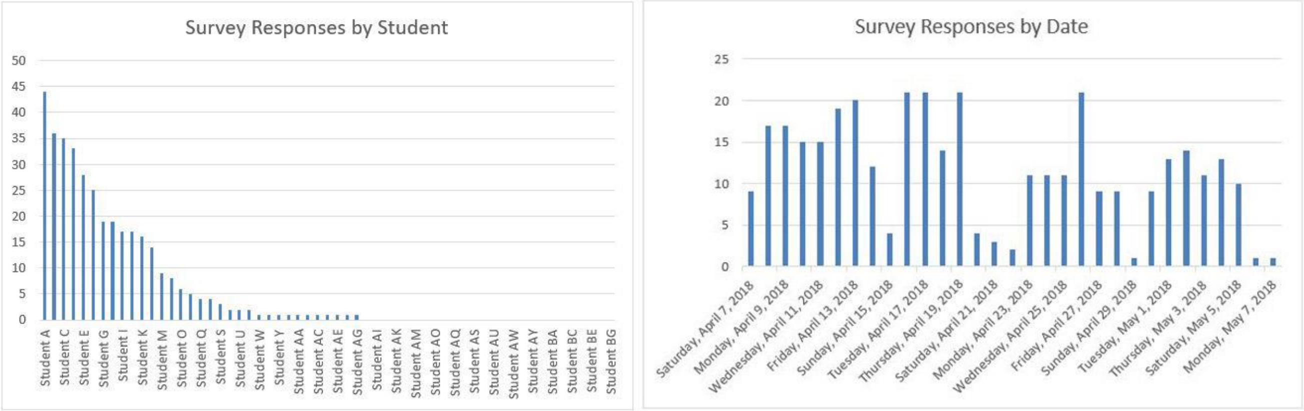

Figure 6 Survey responses by student and date

Actual vs Predicted Thermal Comfort

PMV was calculated for each survey response using the students' reported clo and met values and simultaneous temperature and relative humidity measurements from the closest sensor.[19] Average PMV for all survey responses was -0.01 (median: -0.14), suggesting that students' perceived comfort should have been neutral for the given conditions. However, the average reported thermal sensation value (actual mean vote, or AMV) was -0.46, suggesting that, on average, students were experiencing cold discomfort when PMV predicted a neutral sensation (average [PMV – AMV]: 0.44; median: 0.26).

While we may conclude from these results that PMV is over-predicting thermal comfort conditions for the studio, many studies have validated the PMV model in air-conditioned buildings.[20] The discrepancy between AMV and PMV may be related to factors that were not measured in this study. Follow-up interviews with students cited proximity to cold, drafty windows or blowing air from the HVAC units as sources of cold discomfort, particularly at night. Further study is needed to quantify these effects.

Discussion

This study suggests both the potential for integrating hands-on building science investigations into the technical architecture curriculum, and areas for improvement. Student participation in the thermal comfort survey was low. Aside from several dedicated participants, the majority of students (63%) answered the survey once, or not at all. This was likely due to a lack of effective integration of the study with the technical studio coursework. Making the survey part of a graded assignment would have increased student participation, and, by extension, student engagement with the study content. Another missed opportunity for engagement was involving students directly in analyzing the study data. For example, students could have plotted their own survey responses on the psychrometric chart, comparing its predictions to their own experience of thermal comfort.

The next phase of our work will focus on opportunities for curricular integration via the creation of a Pratt Building Science Lab. The lab will serve as a central repository of monitoring equipment for the Pratt community, and as a framework for developing hands-on STEM exercises with educators from several Institute departments and schools (including Graduate and Undergraduate Architecture, Interior Design, and Mathematics and Science).

While we see great potential for this collaboration, we recognize the challenges in developing innovative building science curriculum in architecture schools. Existing building science courses are often overloaded

Figure 7 Survey results for thermal sensation

with NAAB criteria, and instructors may be reluctant to rewrite coursebooks. Administrators may be unable to allocate funds to purchase monitoring equipment. Finally, there may be cultural or institutional barriers to foregrounding technical education in design-focused professional degree programs. It is important to build support for curricular innovation among design faculty and administrators, who may feel that more demanding technical courses divert students' energy from the design studio

Conclusion

Although architectural education prioritizes hands-on, project-based exploration in the design studio, many technical courses employ a traditional lecture-based approach. This case study suggests the potential to integrate research-based inquiry into the technical architecture curriculum. As participants in the thermal comfort study, students were asked to make connections between the content of their building science courses and their own subjective experience of comfort – potentially deepening their understanding of and engagement with the technical subject matter.

Our study suggests that such investigations must be thoughtfully integrated into the broader architecture curriculum to achieve positive effects on student engagement and learning. This integration can happen at multiple scales and intensities – from a single lab assignment to dedicated seminars or advanced studios. Beyond any one course, implementation of innovative approaches to teaching building science requires both the initiative of building science educators and broad support from other faculty and administrators to achieve the desired impact.

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