Ceiling Fans in Commercial Buildings: In Situ Airspeeds & Practitioner Experience

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ABSTRACT

Ceiling fans are a traditional approach for increasing occupant comfort and are well-established in residential application in many parts of the world. However, they are infrequently included in commercial spaces even though they have the potential to bring benefits including increased occupant comfort and decreased energy use either through raised setpoints in cooling or destratification in heating. This study provides practical insights into the case of ceiling fans in commercial spaces. We conducted 13 interviews with architects, engineers, and facilities managers from California and around the country to compile common themes of experience. These professionals provided lessons learned from 20 operational projects that include ceiling fans serving a wide set of functions in commercial spaces. Understanding the challenges they faced and the lessons they learned from these projects will facilitate prioritization of research and communication efforts. We also took in situ airspeed measurements at five of the projects to provide insight into real-world conditions in commercial buildings with ceiling fans. For these, the ceiling fans' operation results in generally relatively low airspeeds, often under 0.2 m/s. We also found just 25% of the 20 projects discussed by interviewees had any type of automation in the ceiling fan controls. This study serves as a resource for designers and for the wider industry, to frame a path forward for the inclusion of ceiling fans in commercial buildings.

KEYWORDS

Ceiling fans; air movement; natural ventilation; airflow; design; case study

1. Introduction

Ceiling fans are common appliances for providing air movement for thermal comfort, and have been studied extensively regarding their cooling effect (for historical summaries, see [1] and [2]). Elevated air movement increases the rate of the body's cooling [3], and decreases perceived air temperature, causing people to feel comfortable in warmer temperatures than they would be in still air. Multiple lab studies have validated this effect in office, educational, workout, and other environment types [3][4][5][6][7]. One study found this "corrective power" to range from 1−6 °C (2 -11 °F) [8]. Others have reported comfort conditions as high as 28 °C (82 °F) [9].

ASHRAE 55 establishes thermal environmental conditions for human occupancy, yet most buildings are not currently meeting its comfort criteria [10], with cooling setpoints typically set lower than necessary to maintain comfort [11]. This means that even in still air conditions, typical set points can be raised without increasing occupant discomfort. The addition of air movement from fans allows even higher set points, and can provide an effectively instantaneous means of comfort control. The highest acceptable setpoints occur when air movement is under personal control [9], and warmer setpoints can also increase the range of climates in which passive strategies and compressor-less cooling are possible [12].

Air movement is often considered desirable separate from its cooling effect. Building occupants consistently want *more* air movement rather than *less,* even when reporting a 'neutral' thermal sensation [13][14][15]. Ceiling fans may also be incorporated into projects for benefits of increased individual control [16], alliesthesia [17], or improving perceived [18] and measured indoor air quality [19].

Modern ceiling fans use very modest amounts of energy; often less than 35 Watts even at the highest speed. The ENERGY STAR list of certified ceiling fans includes 16 models of roughly 1.5m (5 ft) diameter, all of which are rated below 350 CFM/W at design flow [20], and are much higher-performing at lower speeds due to the cubic fan power law. Building energy consumption can be reduced when ceiling fans replace for more energy-intensive cooling strategies, such as conventional air conditioners and heat pumps [21][22][23]. Simulations reveal potential for substantial cooling energy use reductions by utilizing air movement from ceiling fans or other devices, up to 65% [22][21][24][25][26]. However, this requires a two-step process. While the air movement affects people, it does not directly impact the air temperature, which is the signal a thermostat responds to. To save energy, one must increase the thermostat set point or otherwise cause the alternate cooling technology to run less [27][28]. The exception to this, where the energy savings can be more direct, is in radiant or high thermal mass cases where ceiling fans are used to enhance heat transfer between room surfaces and air [10][29] .

Ceiling fans can also be useful when buildings are in heating mode [30][31][32]. In spaces with high ceilings or with certain types of ventilation systems, the air can become thermally stratified and require an excessive amount of heating energy to maintain comfort in the lower occupied zone [33][34]. In these cases, fans can run at velocities so low they do not cool the body, but still mix the room air. This creates a more even temperature throughout the space, maintaining comfortable temperatures in the occupied zone while using less energy since the thermostats now respond to the warmer measured temperature [32][35][36][37].

Despite these benefits, limited information exists on how to appropriately design with ceiling fans, or in what cases they should be considered. A small number of laboratory studies provide some information. In one study, participants preferred 0.3m/s-0.5m/s airspeeds at 24°C (75°F) regardless of activity level [38]. In the same temperature, but for exercise conditions with correspondingly higher metabolic rates (MET), research subjects preferred airspeeds of 0.67 m/s (at 2 MET), 1.09 m/s (4 MET), and 1.79 m/s (6 MET) [5]. Another study focused on discomfort due to draft at the ankles, suggesting a range of 0.22-0.57 m/s at the lower and higher ends of the thermal neutrality range, respectively, to maintain dissatisfaction below 20% [39].

Data in field locations is especially limited. One case study with manually-controlled ceiling fans found that people turned fans *on* based on indoor temperature, but *off* based on occupancy (e.g. when they left for the day) [40]. In two other buildings, occupant satisfaction with the ceiling fans was high (83% and 100%) with the limited dissatisfaction caused by papers blowing, lack of access to the fans, airspeeds too high, or visual distraction. One of these survey buildings had a cooling setpoint of 28°C (82°F) [40].

The industry standard ASHRAE 55-2017 currently requires average airspeeds below 0.20 m/s when the temperature is below 23°C (73.4°F), increasing to 0.8 m/s based on a Standard Effective Temperature curve for temperatures over 25.5°C (77.9°F). There is no airspeed limit for cases where the airspeed is under the occupants' local control, or when the MET is above 1.3

[12]. Two standardized methods of test for measuring power and volumetric air flow for ceiling fan products exist: DOE requirements for fans under 7 ft (2.1m) in diameter [41] and AMCA 230-15 for greater diameters [42]. However, these methods do not provide the airspeeds used to calculate comfort criteria in accordance with ASHRAE 55-2017.

There is also limited information on the extent to which ceiling fans are incorporated into commercial buildings. As part of the Residential Energy Consumption Survey (RECS), the EIA found that over 80% of single-family homes and 40% of apartments had ceiling fans in 2015 [43], but ceiling fans are not included in the parallel Commercial Building Energy Consumption Survey (CBECS). One of the goals of this paper is to better understand why ceiling fans, while prevalent in residential buildings, are not more commonplace in commercial buildings.

This limited available design guidance is part of a larger feedback challenge in the building industry. Designers rarely get the opportunity to find out how their building is performing in the years following occupancy, unless something goes wrong. As published in a recent report on the state-of-the art of post-occupancy evaluation (POE), only 4 of the 13 documented protocols include airspeed measurements [44]. This could be due in part to the high cost of accurate airspeed sensors. Currently, most ceiling fan airspeed data is taken in empty rooms [45] [46] [47] [48]. While some lab studies examine the effects of furniture on ceiling fan air distribution [49], we could not find relevant field data in fully furnished and occupied spaces.

In the current study we are investigating what it takes to get ceiling fans into commercial buildings in cool, moderate, or hot/dry climates (i.e., we did not extend the study to the particularly challenging hot/humid climates), and what the airspeeds are once the ceiling fans are in place. We interview designers and managers of existing commercial buildings with ceiling fans to assess common applications, control approaches, barriers to market adoption that have been overcome, best practices, and resultant airspeeds. This work does not separate out successful from less successful applications of ceiling fans, or identify reasons why ceiling fans were left out of projects. We are strictly characterizing instances where ceiling fans have been included; therefore, barriers that proved insurmountable were possibly not captured. Additionally, we are providing a preliminary step towards feedback and field measurements in the form of a limited number of on-site spot airspeed measurements.

2. Methods

A. Interviews

We conducted interviews with architects, engineers, and building managers to gain insights from commercial buildings where ceiling fans were used. We aimed to understand the goals that led to the use of ceiling fans, the process of selecting and designing for them, and the outcomes. We asked especially about barriers to the use of ceiling fans, and best practices and lessons learned from completed projects.

To select participants, we recruited through the Center for the Built Environment's extensive network, seeking professionals who had designed or managed currently-operational commercial spaces with ceiling fans. Our interview guide (Appendix A) included 32 questions focusing on specific thematic areas: project overview, why ceiling fans, design, systems integration, operation, impact on further work, and market trends and obstacles. All interview protocols were reviewed and approved through our campus Institutional Review Board process.

We conducted 13 interviews from August-December 2017: 8 with engineers, 2 with architects, and 3 with buildings or facilities managers. Each interview lasted an average of 47 minutes and was audio-recorded with the formal consent of all parties. Researchers made transcripts of each discussion, and followed up with clarifying questions by email as needed. We analyzed the interviews looking for common themes and unique perspectives.

B. In Situ Spot Measurements

The research team conducted in situ spot measurements in selected commercial buildings varying in type and spatial layout to characterize typical airspeeds and distributions. We took measurements in typically occupied spaces, directly at workstations or conference room tables by moving the chair and replacing it with the anemometer tree (Figure 1). Additional locations included lecterns, in front of whiteboards, and in corridors, as opportunity allowed. Because the goal was to capture typically experienced airspeeds, we encouraged normal activity to continue in the surrounding areas, and measured the fan speed settings in place when we arrived. When testing in unoccupied areas with no information regarding typical fan speed settings, the research team selected settings for testing, generally bracketing a slow but perceptible airspeed with a second, faster airspeed that was still beneath the paper-blowing threshold.

Wherever possible we took airspeed measurements at three or four locations per space type per site, and two fan speed settings. We measured at a 2-second sampling rate over 3 minutes, using four omnidirectional anemometers mounted on a tree at 0.1, 0.6, 1.1, and 1.7 m heights to allow for averaged seated- and standing-height airspeed per ASHRAE 55 [12], though only the seated-average calculation is presented here. The anemometer system, manufactured by Sensor Inc., is designed for the typically low airspeeds in room flow with an accuracy of +/- 0.02 m/s or 1% of reading (0.05-5m/s).

We processed the airspeed logs per ASHRAE 55-2017, including averaging temporally across the 3-minute data acquisition period, and spatially among the three specified heights for seated (0.1, 0.6, and 1.1 m) and standing (0.1, 1.1, and 1.7 m). These averages are reported for each measured location and condition.

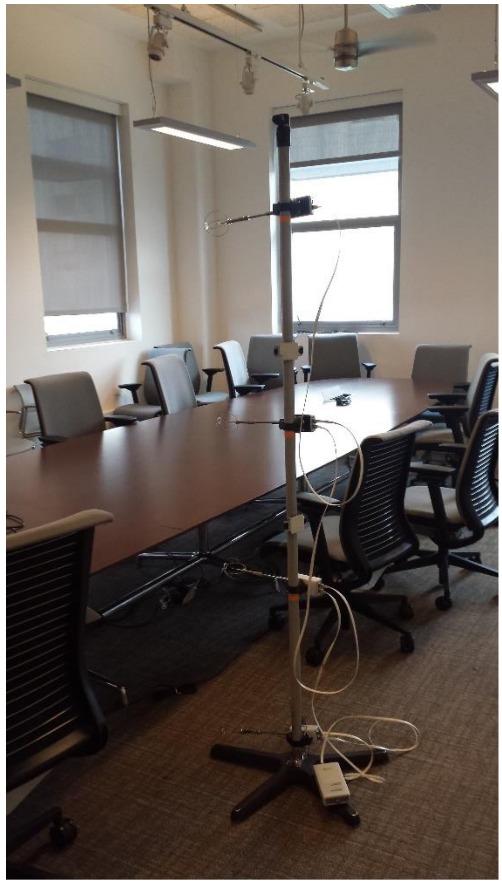


Figure 1: The anemometer tree replacing a chair at a conference table.

3. Results

A. Interviews

Project characteristics. The professionals we interviewed provided insight on a total of 20 projects that used ceiling fans as part of the building comfort system. Of these, 17 were in California and 3 were elsewhere in the U.S. All were completed within the last 10 years. The 20 buildings represented a range of different space types and ceiling fan use cases. Four incorporated ceiling fans as part of tenant improvement work, one as part of a retrofit of an existing building, and the remaining fifteen as part of new construction. Some of the described attributes are characterized in Table B1 (Appendix B). Because each interviewee had different experience, not every interview question was answered for every building.

Practical themes. While discussing best practices, lessons learned, and barriers encountered, the the most-mentioned topics by the interviewees (see Table 1) include cost and value engineering (mentioned by 8 of the 13 interviewees), aesthetics (7), ceiling coordination (6), lack of clarity over who on the design team is responsible for the ceiling fans (4), difficulty communicating and gaining trust in the benefits of the fans (4), and lack of readily available ceiling fan product information (5). These and other themes are explored below in the Discussion.

Table 1: Topics brought up by interviewees in discussing best practices, obstacles overcome, and lessons learned

	Engineers								**Facilities**			**Architects**	
Theme	*E1*	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*F1*	*F2*	*F3*	*A1*	*2 A*
<u>Best Practices</u>													
Get fans in the plan early							X					X	X
Decide and communicate purview			X	X	X							X	
Fan-by-Fan control									X			X	
Creative pitching												X	X
Dense fan coverage				X	X				X				
Space type: high met					X	X							
Space type: high ceilings			X										
Space type: radiant systems	X							X					
<u>Barriers</u>													
Fan connectivity/automation		X	X		X		X						
Perception: maintenance (malfunction, dust)					X	X		X					
Perception: paper blowing/distraction	X			X			X						
Perception: durability				X	X		X						
Communicating benefits/ Fan won't perform concerns		X	X					X				X	
Cost	X		X	X	X	X	X					X	X
Aesthetics	X		X		X	X		X				X	X
Guesswork in design/ Reliance on venders: General						X	X						X
Guesswork in design: Lack of standardized performance ratings				X	X		X						X
Guesswork in design: Red List information availability		X											
Guesswork in design: Lack of standard recommended control scheme				X									
Guesswork in design: CFD is expensive						X							
Ceilings too low						X				X			X
Ceiling coordination		X		X	X	X						X	X
Running electrical for retrofits									X		X		
Post-installation: wobbling	X											X	
Post-installation: noise or distraction							X		X			X	
Post-installation: occupant association with cooling										X			
Education							X			X	X		

Target airspeeds. Four interviewees provided the targets they used during the design process (and we compare these with in situ measurements in the Discussion). These were equivalent to:

- 0.5 – 0.8 m/s for some space types and >0.8 m/s for others
- 0.5 – 1.3 m/s
- 0.9 – 2.2 m/s
- 6000 cfm

Other interviewees stated that airspeed goals were not a driving factor in ceiling fan selection and design, saying that maximum airspeed for most ceiling fans is too high to be useful, and design drivers instead included aesthetics, weight, mounting options, etc.

In the spaces where fans had automated controls, speeds were set using a variety of methods. In two cases without other cooling available, the setting was selected based on temperature up to some maximum speed that is less than the fan's maximum (in one of these the manual override allows the higher speeds). In another case where there was also radiant cooling, the controls are on/off and the on speed is determined based on occupant feedback, largely related to noise. We were not able to collect controls information for the fourth.

B. In Situ Spot Measurements

Table 2 summarizes the five buildings in which we took measurements, providing a snapshot of conditions in the space on a single day, at locations and fan settings that were readily available.

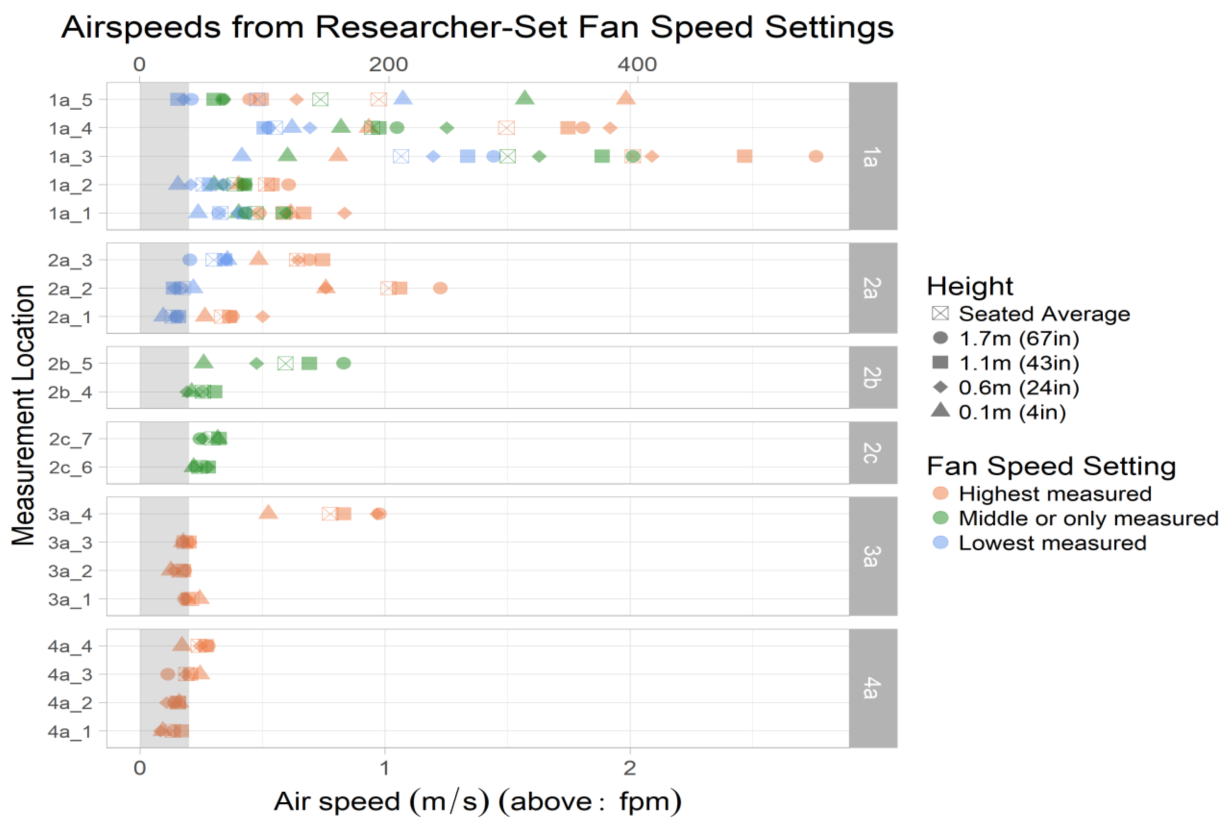
Table 2: Summary of five sites with in situ measurements

Site	Space Type	Occupancy	Fan Type	Fan Speed Settings**	Measurement Locations
1a	Meeting Room	Vacant	Traditional	FR	5
2a 2b 2c	Auditorium Meeting Room Office	Vacant	HVLS* Modern Traditional	FR	3 2 2
3a	Open Office	Partially Occupied	Traditional	AE / FR	4
4a	Open Office	Occupied	HVLS	AE / FR	4
5a 5b 5c 5d	Open Office Open Office Open Office Open Office	Occupied	Traditional	AE	4 2 3 2

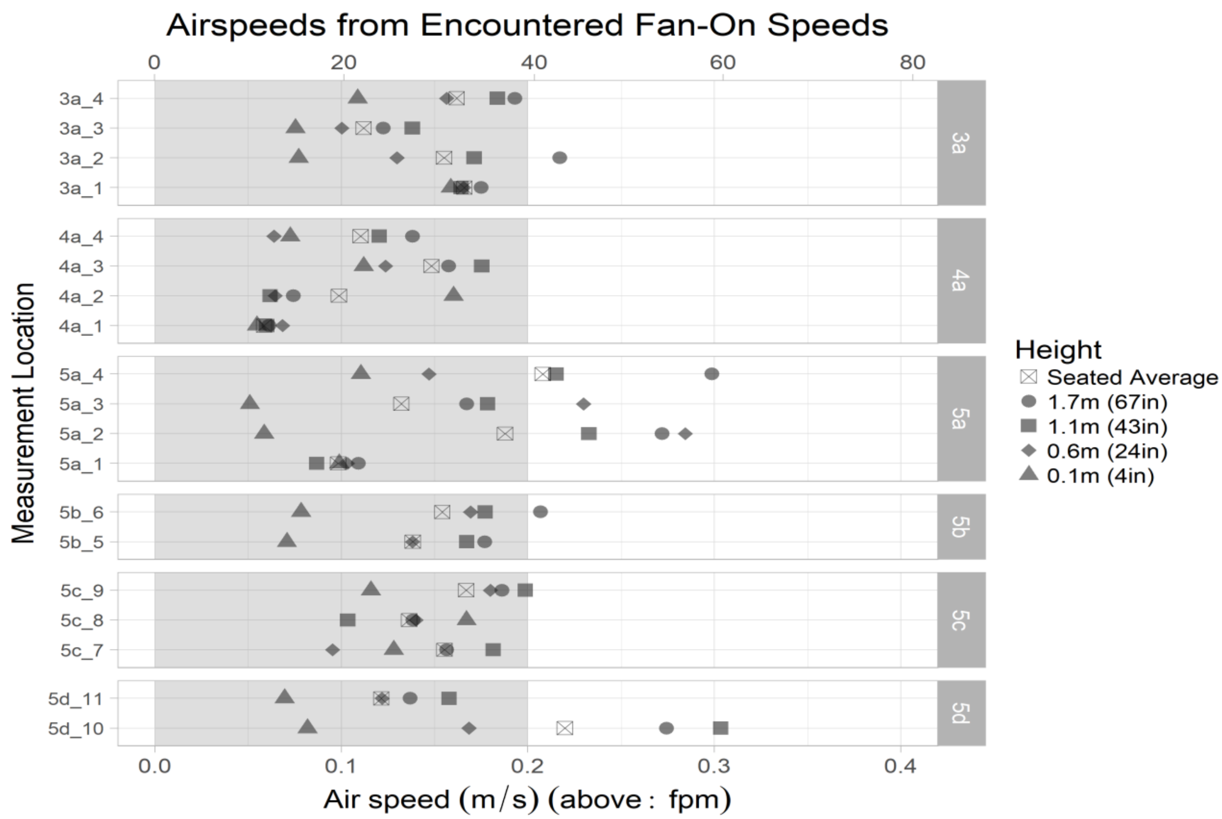
*HVLS is high volume low speed, these tend to be larger fans that rotate slowly but move a lot of air
** FR (set by Field Researcher); AE (As Encountered)

Figure 2 shows all of the in situ airspeed measurements, separated by those taken at speeds set by the researchers (Fig 2a), or the building occupants/operators (Fig 2b), or with the fans off (Fig 2c). All measurement locations are shown on the y-axis, indicated as XY_Z, where X is the site number (1-5), Y is the space (a-d), and Z is the measurement location within the space. At each location, we measured airspeed at four heights, which Figure 2 shows alongside the seated-average airspeed. The shaded regions represent airspeeds below what ASHRAE 55-2017 characterizes as “elevated” (i.e., 0.2 m/s (40 fpm)).

The median, lower quartile, and upper quartile of all seated-average airspeeds from encountered fan speed settings (sites 3, 4, and 5) were 0.15 m/s, 0.12 m/s, and 0.16 m/s, respectively. For measurements taken with the fans off (sites 1, 2, and 3), these corresponding numbers were 0.10 m/s, 0.05 m/s, and 0.19 m/s. The remainder of this section goes through these results site by site.



(a)



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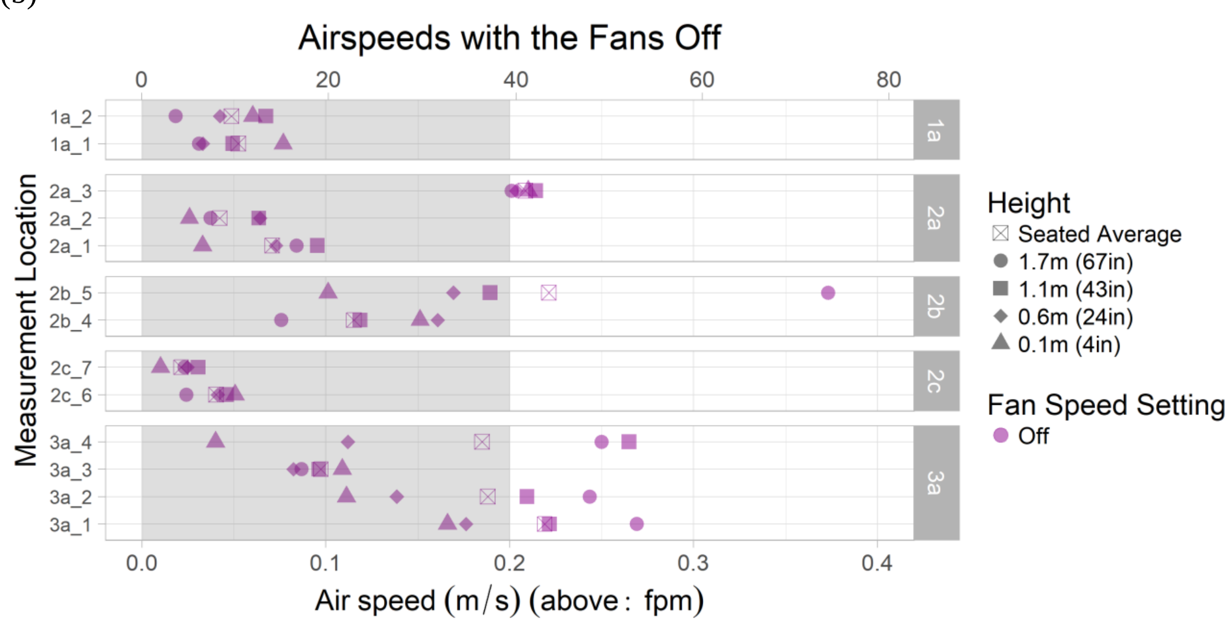


(c)

Figure 2: Overview of in situ measurement results grouped by (a) fans on at speeds the researchers set themselves, (b) fans at speeds encountered on site, and (c) fans off. The grey shaded region indicates airspeeds below the ASHRAE 55-2017 threshold for "elevated airspeed".

Site 1: Unoccupied conference room with three fans and a central table (Figure 3)

The characteristics of the space and measurements were:

- Conference room with a single large table
- Unoccupied room; no guidance available regarding typical fan speed settings
- Three ceiling fans above table (model unknown, approximately 1.5 m (4-5 ft) diameter, 3m (9 ft) mounting height.
- Air temperature approximately 21 °C (69 °F).
- Measurements at five locations:
  - (1a_1) chair along the table
  - (1a_2) just in front of the white board on the long side of the room
  - (1a_3-5) three horizontal distances below the ceiling fan not above the table: directly under, half a meter out, and one meter out from the fan, respectively
- Measurements at all three fan speed settings available on the wall controller, in addition to the fan off at two of the locations.

Figure 3 shows that all seated-average airspeeds are above 0.25 m/s whenever the fans are on. The lowest measurement height has the slowest or near-average airspeed of the four heights at locations 1a_1 and 1a_2, which were nearer obstructions, and fastest of the four heights at 1a_5, which was the least obstructed with furniture and walls.

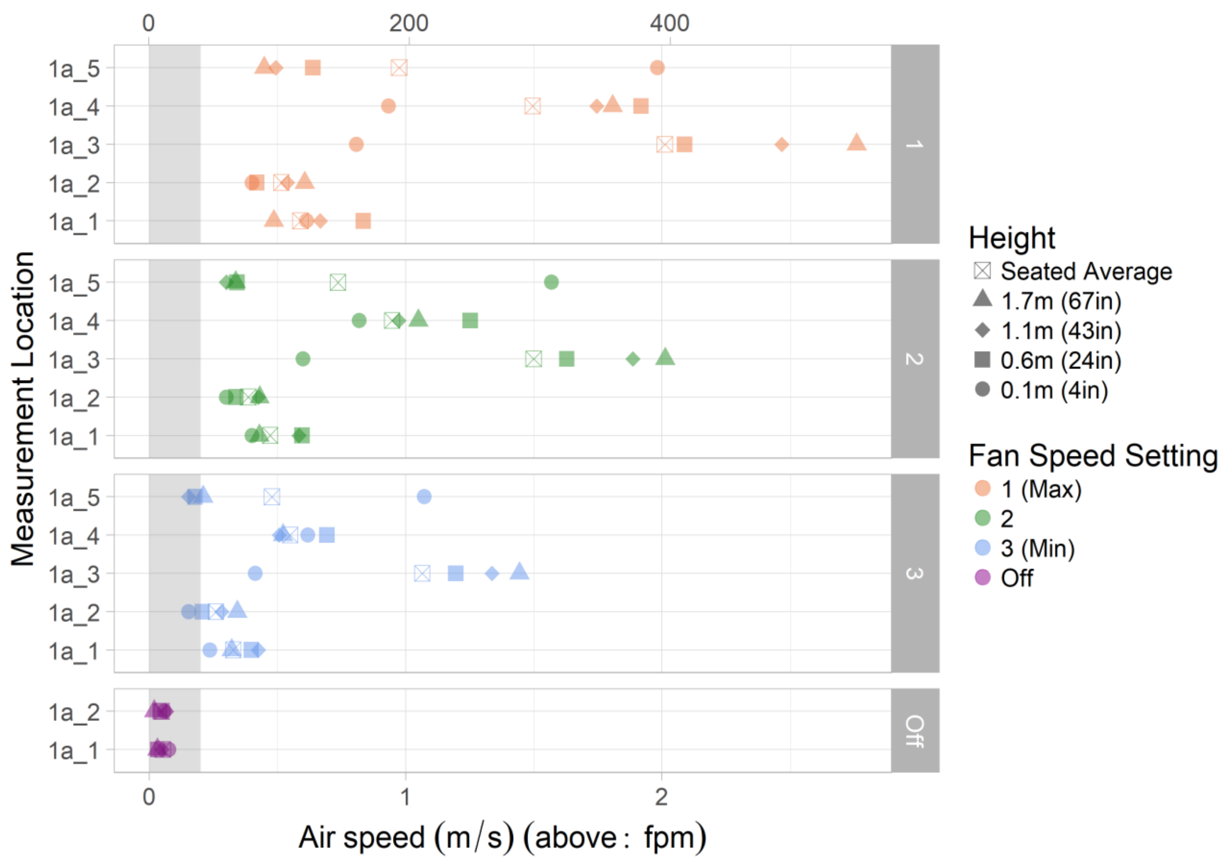


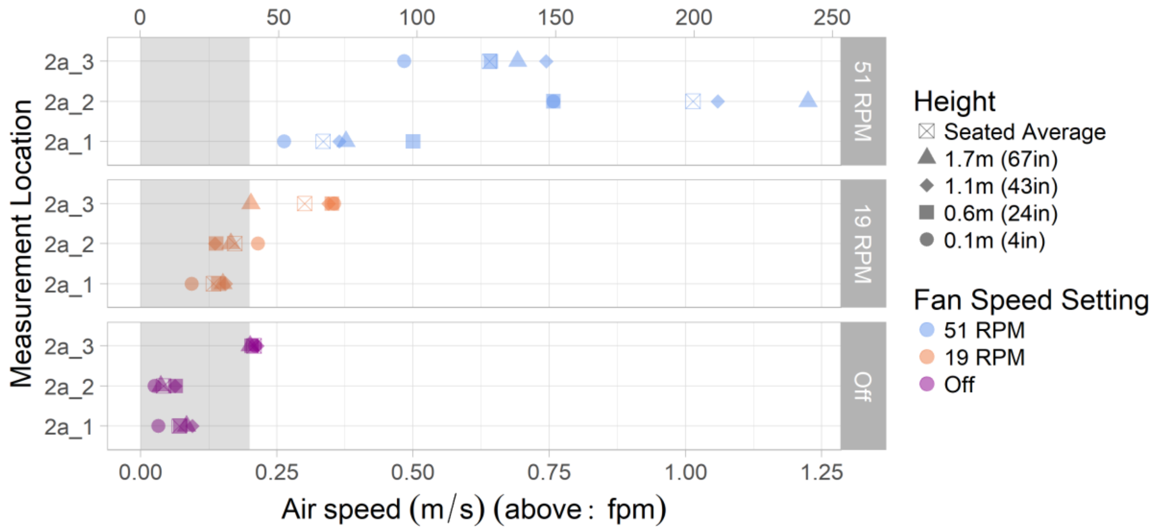
Figure 3: Site 1 airspeed measurement results by fan speed setting. All fan speeds selected by research team.

Site 2: Large lecture room with HVLS fans; conference room with two fans: and two-person office with one fan (Figure 4)

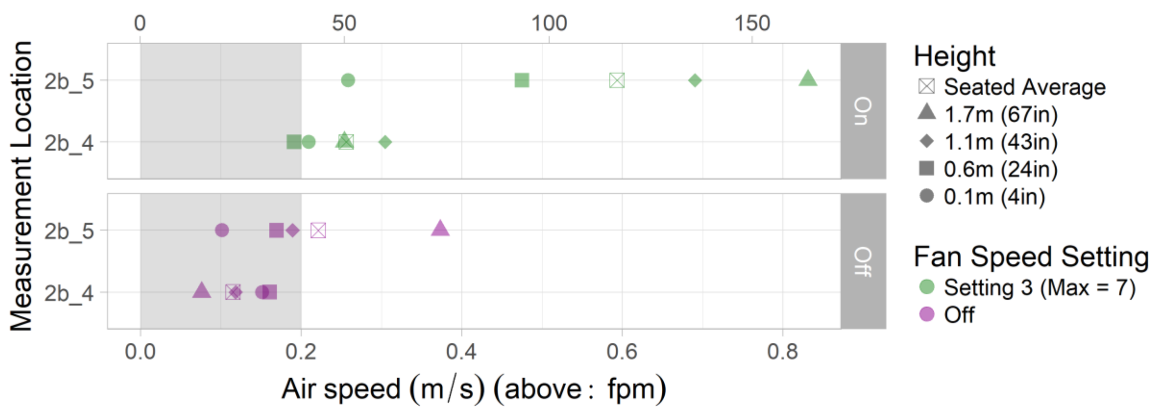
The characteristics of the space and measurements were:

- Newly-constructed site, occupied less than a month
- Three unoccupied spaces; no guidance available regarding typical fan speed settings
- Air temperature approximately 22°C (72°F).
- Space 2a:
    - Large meeting space, can seat approximately 70 people lecture-style, podium and rows of long tables and chairs.
    - Four Big Ass Fans (BAF) Essence 2.4m (8 ft) diameter HVLS fans laid out in a grid at approximately 3.5-4.5m (12-15 ft) mounting height.
    - Measurements at three locations:
        - (2a_1) chair near the center of the room, not under the fan
        - (2a_2) chair under one of the fans
        - (2a_3) behind the podium at the front of the room.
    - Measurements with the fans off and at two speeds, approximately 19 and 51 RPM (although this fan model is capable of up to 158 RPM).
- Space 2b:
    - Conference room with a table layout that seats 22, and a sloped ceiling
    - Two BAF Haiku fans, 1.5 m (5 ft) in diameter, mounted at approximately 2.7-3.7m (9-12 ft) in height.
    - Measurements at two locations:
        - (2b_5) a chair at the center of the conference table
        - (2b_6) by the whiteboard.
    - Measurements with the fans off and at speed 3 (of 7, where 7 is the fastest).
- Space 2c:
    - Office set up to be shared by two people
    - Single Hampton Industrial 1.5m (5 ft) diameter ceiling fan in the center mounted at approximately 2.1-2.7 m (7-9 ft).
    - Measurements at the two chair locations
    - Measurements with the fan off and at the second of four available speeds.

Figure 4 shows that at the 19 RPM setting, the 0.1 m height has the fastest air velocities in the 2a space, but at the 51 RPM setting it has the slowest airspeed.



(a)



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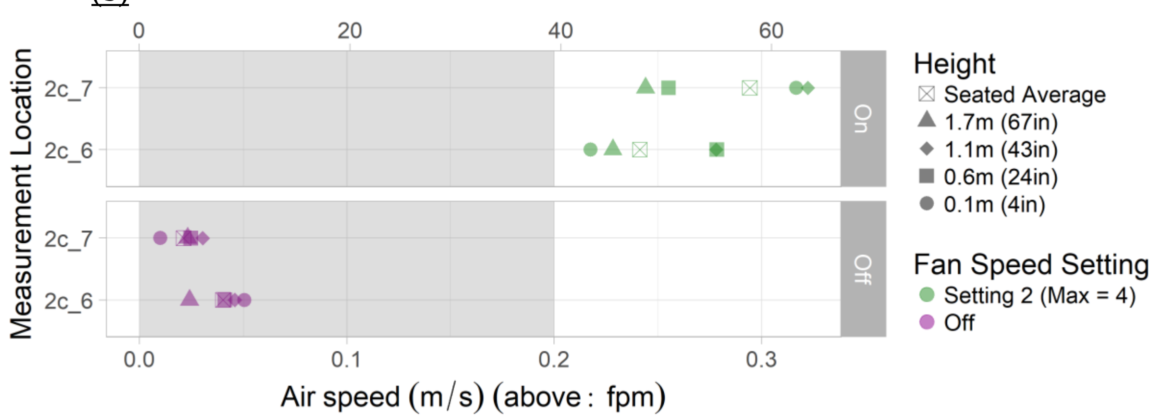

(c)

Figure 4: Site 2 airspeed measurement results in (a) the 70-person lecture room, (b) the conference room, and (c) the two-person office. All fan speed settings selected by research team.

Site 3: Open office with multiple small fans (Figure 5)

The characteristics of the space and measurements were:

- Large open office area with very high ceilings
- Fans of roughly 1.5 m (5 ft) diameter, model unknown, located at 7 m (23 ft) height and spaced 6 m x 9 m (20 ft x 30 ft) on center. There is one fan for every set of 16 (4 by 4) desks.
- Air temperature approximately 23 °C (74 °F).
- Measurements at four unoccupied chair locations (other nearby chairs were occupied at the time) at the following distances from the center of the nearest fan:
    - (3a_1) 5.8m (19 ft)
    - (3a_2) 6.1m (20 ft)
    - (3a_3) 4.0m (13 ft)
    - (3a_4) within the fan diameter, about 0.6m (2 ft) from the center.
- The fan control was a slider with an off and three other positions. The first non-off position (not measured) caused roughly half of the fans to slowly rotate and did not obviously affect the other half. The other two fan-on speed settings were measured.

Figure 5 show that there is no notable air movement (or, correspondingly, cooling effect) from the ceiling fans at the locations measured, at any fan speed setting, except for at the maximum fan setting at location 3a_4, which is directly under a fan. This lack of a measurable increase in air speed in most locations is likely due to the exceptionally high ceilings in this space, the fan mount height (7 m), and the relatively large spacing between fans. The higher fan settings are generally associated with a smaller spread in the airspeeds at different heights, but the seated-average airspeeds are not meaningfully faster at higher fan settings, or faster at all in some cases. The uniformity is also very uneven. At the max speed, some occupants would experience seated-average airspeeds below 0.2 m/s, and others would experience above 0.75 m/s. It is possible that these ceiling fans, though not useful for cooling, are useful in air mixing, destratification, or other purposes which we did not examine. Across all measurements with the fans on, the 0.1 m height has the most consistent and slowest airspeeds.

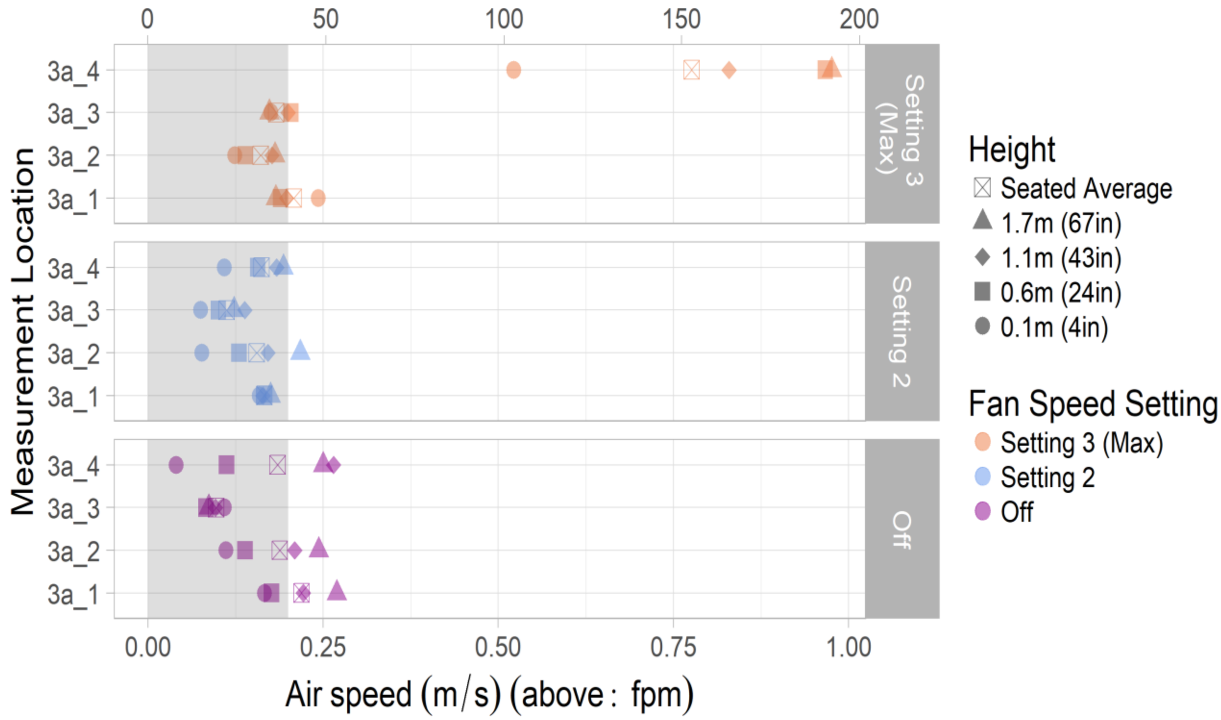

Figure 5: Site 3 airspeed measurement results grouped by fan speed setting. Setting 2 was encountered, other settings selected by research team.

Site 4: Open office with a central HVLS fan moving slowly (Figure 6)

The characteristics of the space and measurements were:

- Occupied open office with a relatively high ceiling
- Single centrally-located 2.4 m (8 ft) diameter BAF Essence HVLS fan mounted at approximately 3.5 m (12 ft). This is the same fan model as in site 2a, with a maximum RPM of 158.
- Air temperature approximately 23 °C (74 °F).
- Measurements at four locations:
  - Three at desks in the open office:
    - (4a_1) not in the same row as the fan, roughly 3.4 m (11 ft) from the fan center
    - (4a_2) near the row at the center of the fan, roughly 5.5 m (18 ft) from the fan center and near a wall
    - (4a_3) in the same row as the fan, roughly 2.3 m (7.5 ft) from the fan center
  - (4a_4) in a walkway and within fan diameter, roughly 0.8 m (2.75 ft) from the center
- Measurements at 11 RPM (encountered when the researchers arrived, minimum fan speed setting available) and also 18 RPM (11% of the maximum available, as a second speed slow enough not to risk distracting the occupants seated directly underneath the fan.)

Figure 6 shows that all seated-average airspeeds are below 0.25 m/s, though faster at every measurement location at the 18 RPM speed than the 11 RPM speed. Additionally, although the temperature was above the 23°C (73.4°F) ASHRAE threshold for elevated air movement, the measured airspeeds were not technically elevated – all of the seated-average airspeed measurements taken at 11 RPM and all except one of the 18 RPM measurements are at or below 0.20 m/s and would not be classified as elevated airspeeds by ASHRAE 55-2017.

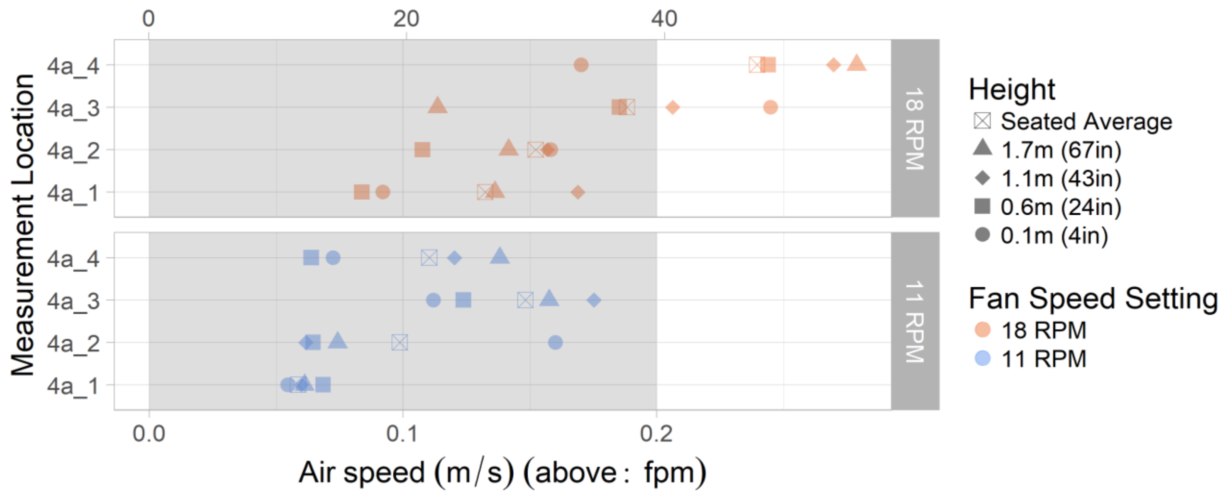

Figure 6: Site 4 in situ airspeed measurement results grouped by fan speed setting. The 11 RPM speed was encountered and the 18 RPM was selected by the research team.

Site 5: An open office with automatically-controlled ceiling fans blowing upward (Figure 7)

The characteristics of the space and measurements were:

- Open office space, large total floor area >9000 m2 (100,000 ft2).
- Hampton Bay 526012 ceiling fans, 5' diameter, 2.7 m (9 ft) mounting height, spaced at 6m (20 ft) intervals
- Fans blow upwards (only project of the 20 to have the fans blowing upwards for cooling goals.)
- Automated ceiling fans in most zones, controlled through the building management system (BMS). Control is solely on/off, and each zone has its own fan speed setting used for all fans in that zone whenever they are on.
- Speeds and upward direction were established by facility managers over time based on anecdotally collected occupant feedback related to noise and comfort.
- Air temperature approximately 24°C (75°F)
- Measurements in four different zones (a-d)
- Measurements at each zone's established fan speed setting (not identical across spaces).

Figure 7 shows that most of these seated-average airspeeds are in the 0.15–0.20 m/s range and are not characterized as elevated by ASHRAE 55-2017. The 0.1 m height has much slower comparative airspeeds than in the other locations. It is the slowest airspeed in 8 of the 11 locations across Site 5, in many cases by over 0.05 m/s.

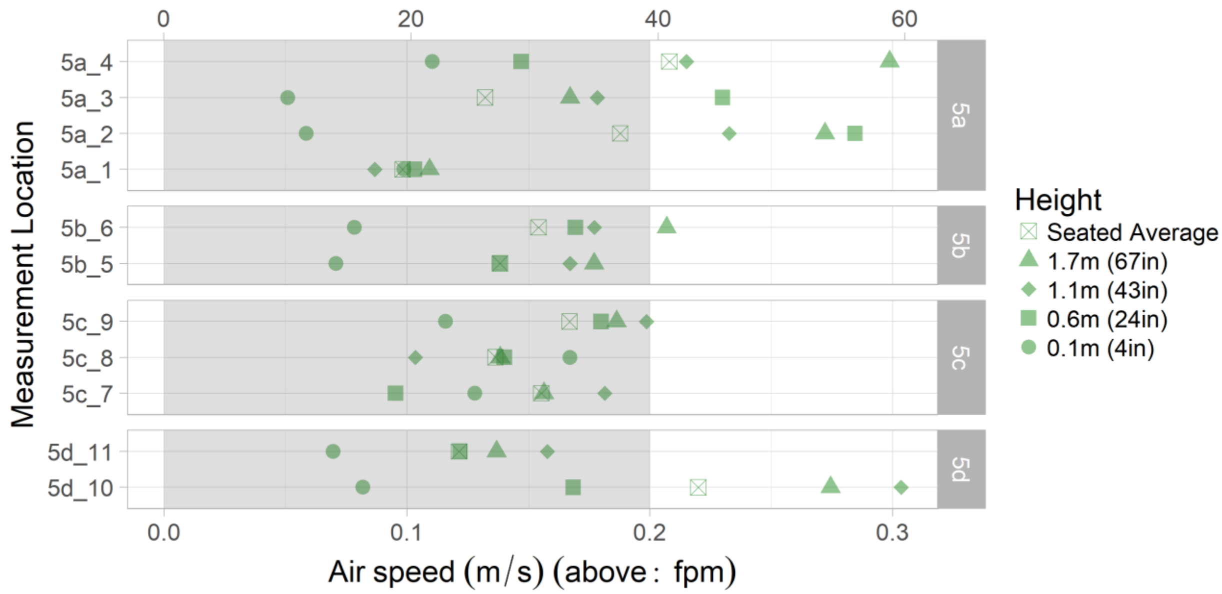

Figure 7: Site 5 in situ airspeed measurement results. Fan speeds were as encountered in each zone. Note that the encountered fan speeds varied between zones and that the fans blow upwards in this space.

4. Discussion

A. Ceiling Fan Applications and Motivations

Applications. Interviewees were most likely to use ceiling fans in a few specific types of designs. The first are designs that do not use traditional cooling systems. This includes buildings with radiant systems, whose heat transfer effects are enhanced by ceiling fan air movement **[10]**. It also includes buildings without mechanical cooling (i.e., no refrigerant cycle), such as those that use economizer-only cooling, natural ventilation (daytime or thermal mass with night flush), or no cooling besides the ceiling fans. Ceiling fans might be implemented to make up the small difference needed to provide comfort on the hottest days of the year, or to provide the first few degrees of comfort cooling before other systems switch on, or to be operated manually independent of other cooling systems. Several interviewees discussed the value of ceiling fans in school districts in milder climates that expressly prohibit the use of compressor-based cooling in classrooms. The second are spaces with higher metabolic rate activities, such as gyms and dance studios, where there are fewer concerns about nuisance issues such as noise or blowing papers. Higher airspeeds are generally welcomed in these types of spaces, allowing greater adaptability to different activity levels. The third are spaces with high ceilings, where ceiling fans are popular for use in air mixing and destratification in heating mode.

Motivations. The reasons designers used ceiling fans in commercial spaces varied. Most cited goals such as comfort cooling or air mixing for destratification. Another recurring theme was a desire to increase occupant control, with one common example being to give teachers more individual control over their classrooms when they may not have thermostats. One interviewee noted that personal USB-powered fans can be a better option in open office type settings, where ceiling fans will affect multiple people. The research team believes personal desk fans may also be a useful supplement to ceiling fans in shared spaces. Air movement was also reported as its own goal without thermal considerations, perhaps for reasons of improved perceived or measured air quality in the breathing zone or alliesthesia (thermal delight associated with temporal or spatial variability).

Aesthetics were also a recurring theme, with many stating that for ceiling fans to be incorporated at all they need to be beautiful. Aesthetic motivations either referred to liking the look of the ceiling fans, or that ceiling fans eliminated the need for visible ducts. The ceiling fans mixed the ventilation air, thus reducing the number of diffusers needed and removing the need for any ducts in the space. A similar exists through increased design cooling setpoint, reducing the required cooling airflow to the point where side wall diffusers are sufficient, without requiring ducts or diffusers in the space itself.

B. Automatic versus manual control

There was considerable discussion about whether automated or manual control is preferable. Only four of the 20 projects have primarily automatic controls, with one having easily-accessible manual overrides. One additional project has manual control with occupancy sensors that turn fans off when the office is empty, and then back on to the previous speed when re-occupied. The other 15 projects have manual control only.

Manual control has the benefit of giving occupants a direct say in ceiling fan operation. Several interviewees said that manual control is their preference whenever possible and that this approach works best when one person had clear agency in a space, such as in a private office or for the teacher in a K-12 classroom. Even with manual controls, interviewees thought it would be nice to have automatic control as a back-up (e.g. with an occupancy sensor).

The interviews revealed two main challenges associated with manual control. The first occurs when it's hard to establish ownership over the fans, such as spaces with transient occupancy or shared open office plans. People's individual preferences can vary significantly, and airspeeds can vary spatially throughout the zone, so negotiating control can be challenging. The second is that many occupants do not understand stratification or how ceiling fans help with heating. When an occupant is chilly, and sees that the fan is on, the first response is often to turn it off regardless of the speed or the ceiling height, thus eliminating the effectiveness of ceiling fans for destratification. Several designers planned trainings or placards for occupants, but reported that these had mixed success.

Automatic control of the ceiling fans can solve some of these issues, but with its own concerns. The primary challenge is that most ceiling fans are not readily controlled by the BMS, requiring custom solutions in most cases. Four interviewees named difficulties with ceiling fan connectivity as a barrier to ceiling fan use.

Site 5 offered the greatest information about automated control over fans intended only for comfort cooling, not destratification. This building had a large number of fans and active on-site facilities management who were able to adjust the fan speed settings manually or control when the fans switch on using the BAS. Figure 8 describes the fan control algorithm they have established over several years. In each zone the ceiling fans are either off, or on at a designated speed that has been set for that particular zone taking noise and occupant preferences into account. The ceiling fans run in 'reverse', blowing upward, and the spatial variation of airspeeds in the occupied zone is far less than in cases where the fans were blowing downwards.

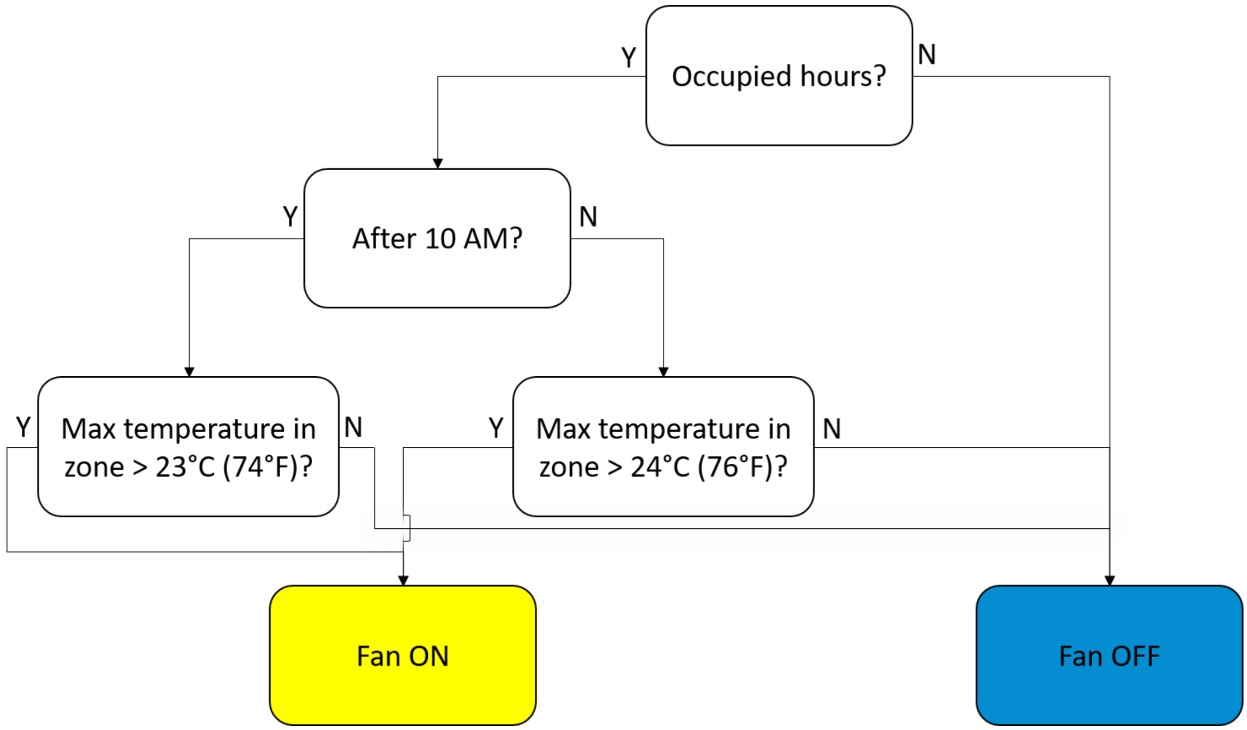

Figure 8: An on/off control sequence for automated ceiling fans established over time for Site 5

C. Best Practices and Lessons Learned

Incorporate fans in the plan early. Three interviewees felt that early consideration meant that ceiling fans were more likely to be appreciated as an integral part of the system, and less likely to be removed from the project at a later stage or to create issues.

Have a coordination plan. Four interviewees mentioned that there was confusion or excessive time spent establishing who was in charge of the specification, design, drawings, and eventual installation of the ceiling fans. The architect could address how fans are a component of the aesthetics of the space; the lighting and electrical team need to integrate the fans into the ceiling design and power distribution; or the mechanical team needs to consider fans as part of the thermal comfort system. Whatever is right for a specific project, the decision should be made early and communicated clearly.

Fan-by-fan control. Two interviewees explained that their projects only allowed for multiple ceiling fans to be controlled together, and if done again they would have included a mechanism for each fan to be controlled individually.

Pitch creatively. Both interviewed architects had developed strategies for pitching ceiling fans to clients, including focusing on comfort and individual control, or bundling the ceiling fans into a larger package of solutions such as efficient envelope strategies. Several other interviewees also noted that ceiling fans were less likely to be cut late in the process if they were being relied on as a critical part of the cooling, ventilation-mixing, or other comfort systems.

Dense coverage. Three interviewees reported that projects required fairly dense ceiling fan coverage to get appropriate air movement throughout the space. In at least one case, the number of fans was value engineered down and the result was less satisfactory.

D. Barriers to Ceiling Fans in Commercial Buildings

Some barriers encountered were very minimal and easily overcome, while others created much more substantial obstacles. Below are eleven the research team feels are worth calling out. Because we intentionally limited our interviews to designers and operators of commercial buildings with ceiling fans, all of these obstacles were evidently overcome in at least some of the projects. Conversely, because we did not ask questions about projects in which ceiling fans were *not* implemented, we recognize that there may be additional, more prohibitive, obstacles that were not necessarily identified.

Perceived Concerns. Our interviewees often had to deal with concerns from other architects and engineers, building owners, and facilities teams. These often included the ceiling fans being noisy or causing maintenance issues, air movement causing papers to blow, or that the fans would not have the necessary durability. For example, in a classroom setting, blowing papers became an issue at lower airspeeds than anticipated because student worksheets were often extremely lightweight. In other examples, a facilities manager and multiple engineers made adjustments to ceiling fans or even replaced some to address noise issues. However, the general opinion was that perceived concerns about maintenance, durability, and other practical considerations have not been problems in the (admittedly short) lifetime of these projects.

Communicating benefits. Four interviewees told us they struggled to effectively communicate the benefits of ceiling fans to others during the design process, and they lacked a set of commonly-understood terminology. As one architect put it, "…you can't say 'perceived comfort' or 'perceived temperature' because that's not a real thing for many engineers." Or an engineer said "It's always a bit of a challenge to try to educate and explain the benefits of ceiling fans, that you can have two spaces exactly the same temperature but you can markedly improve the thermal comfort of one space by increasing air movement."

Cost. Over half of the interviewees mentioned cost as a barrier, more than any other single theme, centered on three points. 1) The installed cost for an existing space is often much higher than the ceiling fan itself and can be prohibitive. 2) The difference in cost between a basic fan and a larger or modern engineered fan of the same diameter can be an order of magnitude or more, which can be difficult to justify, or can be at risk for swap-out by contractors. 3) The most prevalent comment was about ceiling fans being seen as a 'bonus' or 'amenity', making them a prime target for being value engineered out of the project, or reduced in number below what designers would prefer, especially in projects where large numbers of fans are called for.

Aesthetics. Interviewees emphasized that ceiling fans form part of the visual impression of the space, and they are only going to incorporate fans that work aesthetically with the overall design of a space. One interviewee added that some desired aesthetic elements, such as “clean, uncluttered” open ceilings or uplighting, are at odds with most ceiling fans.

Guesswork in design and reliance on vendors. Multiple interviewees stated that designing with ceiling fans continues to be a matter of trial and error or guesswork. They find CFD modeling too expensive, and a lack of available design tools and guidelines, and therefore either use their own educated guesswork or rely on manufacturers’ assistance. Only a few interviewees reported being able to easily find the performance information they wanted. Multiple interviewees expressed the desire for more standardized performance information in addition to independent design resources.

Ceilings too low. Three interviewees explained that even in spaces that are otherwise good candidates for ceiling fans, ceiling height limitations can prohibit or limit their use. One interviewee told us that he has found this to be an issue in some fitness spaces, since the extra height added by people standing on exercise equipment can make ceiling fans a safety hazard.

Ceiling coordination. Almost half of interviewees mentioned the challenges of coordinating the ceiling fans with lighting or other equipment so that they did not interfere with each other in terms of their physical placement, allowing each to serve its purpose unobstructed without flicker or sway. Along these lines, other ceiling components must also be taken into consideration, including ventilation and fire sprinklers. Ceiling fans, especially larger ones with splay wires, greatly increases the effort required.

Furniture. No interviewee reported having an established furniture layout prior to designing for the ceiling fans that was *not* changed later in the process. For example, certain activity areas might get different spacings of fans, or fans would be centered over walkways rather than desks. Those areas then ultimately may or may not end up being set up in that layout.

Running electrical for retrofits. Several building managers mentioned that adding additional ceiling fans would be a prohibitive task due to the need to run electrical service through existing ceilings. In one case, this was an issue primarily due to the location being a public education facility with limited funding available. In another, it was due to a radiant slab ceiling.

Post-installation challenges. Relatively few of our interviewees were significantly involved with the projects after occupancy. Those that were cited several specific challenges, especially related to noise or wobbling, but these were generally addressed soon after occupancy by either replacing the fan with another of the same model or using fan settings to limit the maximum operational speed.

Education. Several interviewees discussed steps to educate building occupants on the best practices for using the ceiling fans in their spaces. At least two projects provided placards or informational sheets either mounted near the controls or given to each employee. In another case, design team members gave a presentation to the employees at the time of occupancy. Building occupants generally associate ceiling fans with cooling, and there can be challenges getting the fans to be used appropriately for destratification or air mixing in heating.

E. In Situ Spot Measurements

Encountered airspeeds. The seated-average encountered airspeed measurements from Sites 4 and 5 ranged from 0.07 - 0.23 m/s, well below the target airspeed ranges reported by interviewees for several other sites. This was not necessarily a detriment to comfort, however, given that the buildings were operating around 23 24°C (74-75°F), warm enough that ASHRAE 55-2017 permits elevated airspeeds but considered thermally comfortable regardless of added air movement. This indicates a potential opportunity to reduce HVAC energy consumption by increasing zone cooling setpoints and using the ceiling fans for the first stage of comfort cooling.

Comparing our measurements at the 1.1 m (3 ft 6 in) height to some found in the literature, our measured range of 0.06-0.3 m/s was noticeably slower than the 0.3-0.4 m/s preferred airspeed reported by Zhai et al for office activity at 24° C (75°F) [38]**.** Yet they were more comparable to the 0.15 m/s and 0.25 m/s measured at 1.09 m in Rohles' classic paper [50] (Figure 9). Rohles reports that even a 0.15 m/s airspeed measured with the fans on showed significant impacts in thermal sensation over a 0.06 m/s airspeed measured with the fans off. Rohles refers to this 0.15 m/s speed as "extremely low" and "probably...unable to be perceived". He suggested that the benefit may have been a placebo effect, but we believe it is also possible that there are air quality or alliesthesia factors to consider. Whatever the cause, even with minimal cooling effect, the building occupants in both Site 4 and Site 5 had elected to have the fans on, indicating they found some benefit (psychological, air quality, thermal comfort, or otherwise) present even at these low airspeeds. Note that site 5 has a large number of occupants, zones and fans, and as such is not a small sample size. Note also that the encountered fan speed in site 4 was very low (7% of maximum fan speed).

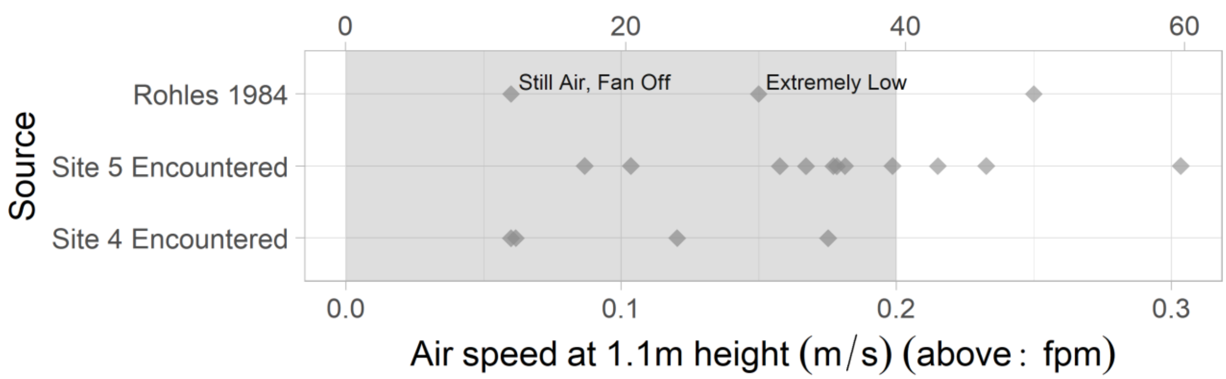

Figure 9: Comparison of Site 4 and 5 Encountered seated-average airspeeds with the three lower airspeeds from Rohles 1984.

Uniformity in the Space. The range of encountered airspeeds was smaller for Site 5 (multiple fans blowing upward) than for Site 4 ((single HVLS fan blowing down). The proposed standard ASHRAE 216P contains a uniformity metric of $\boldsymbol{U_{Seated} = 1 - \frac{V_1 - V_2}{V_1}}$ where $\boldsymbol{V_1}$ is the second highest seated-average air velocity in a space and $\boldsymbol{V_2}$ is the second lowest. Because this is designed for much larger sets of airspeeds, we will use the same approach but with the fastest and slowest seated-average airspeeds in each space, for each fan speed setting measured.

While we took different numbers of measurements in each space, and at different distances from the fan, measurements are still roughly comparable across fan settings at the same site (Figure 10). The spatial uniformities are somewhat consistent in spaces 1a, 2a, and 4a across multiple fan speed settings, indicating that uniformity may not be strongly dependent on fan speed setting. Space 3a is an outlier, likely due to the exceptionally high ceiling and fan mount height; the air movement was perceptible only at the medium speed and directly under the fans.

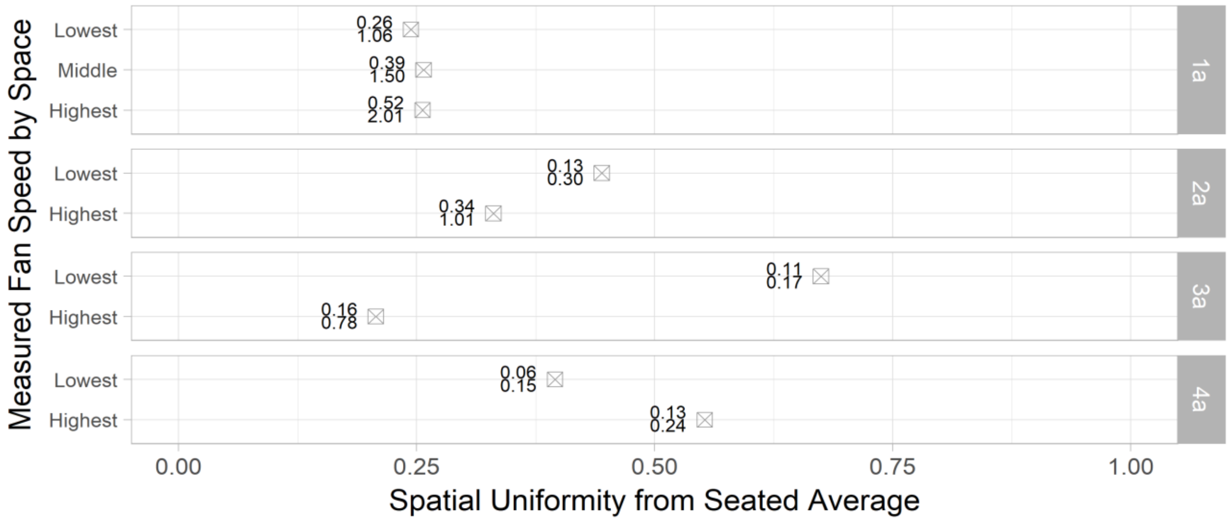

Figure 10: Spatial uniformity calculations from spot measurements, annotated with the minimum and maximum seated-average airspeed in m/s.

Height-based variation. Of the four heights we measured, the literature suggests that the fastest airspeeds outside of the ceiling fan diameter are often at the 0.1 m height **[47][49]**. However, only six of the 65 airspeed measurement sets showed this, and in only 20 was the airspeed at the 0.1m height faster than the seated-average airspeed (Figure 11). In many more measurement cases the 0.1 m measurement had the slowest airspeed recorded. The greatest height-based difference was at site 1a_5, at the most open area, not near a workstation, table, or wall. It is possible that these result are due to disruption from our sensor support structure, or ‘tree’, which has a heavy pronged base near the center with airflow obstructions rising approximately 4 cm (1.5 in) high (Figure 12). It is also possible that the furnished, occupied environments we studied have more obstructions near the floor than the open environments from the literature.

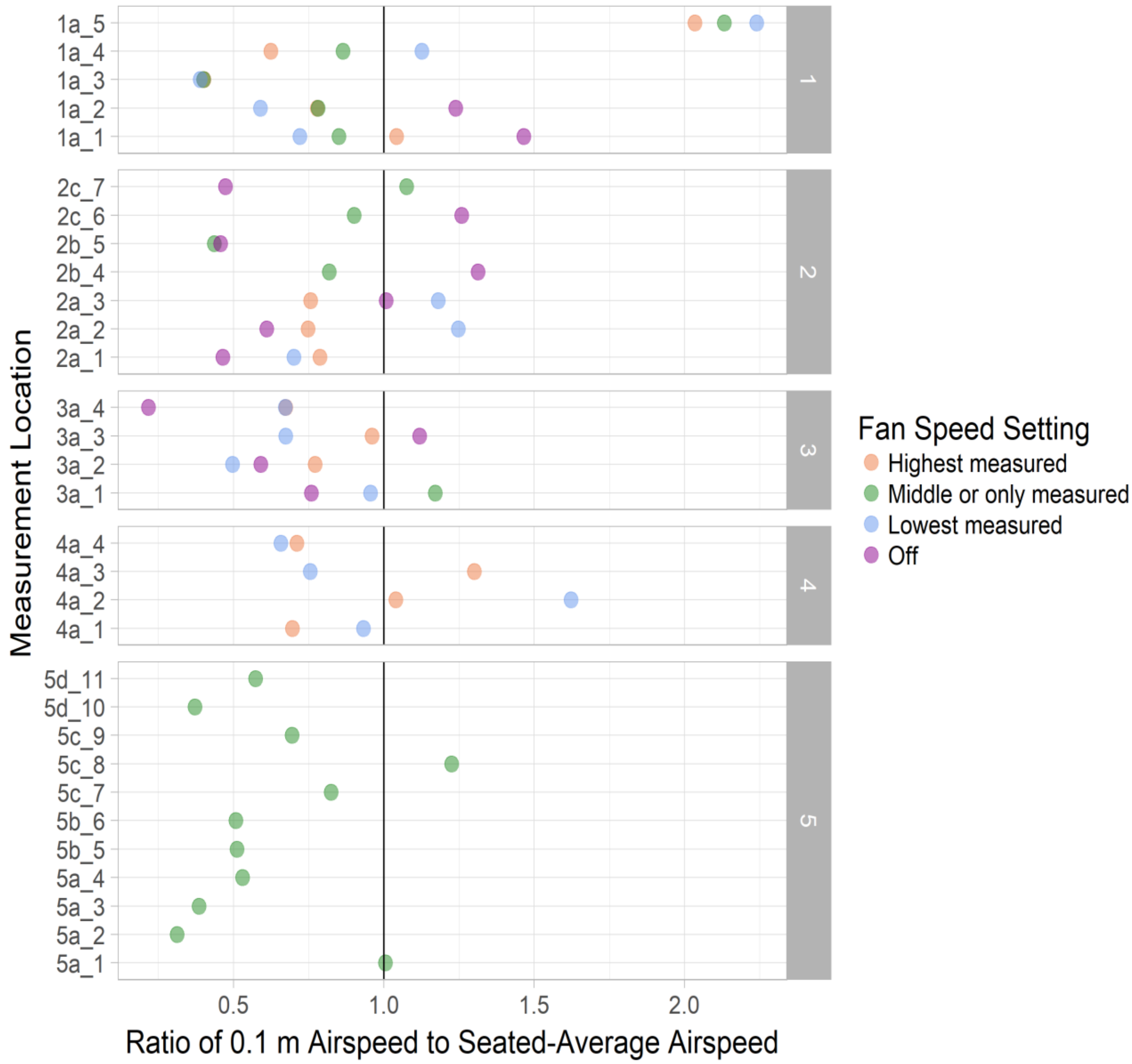

Figure 11: Ratio of airspeed at 0.1m height to seated-average airspeed at each measurement location. Points to the right (or left) of 1.0 have 0.1m airspeeds that are higher (or lower) than the seated average airspeed, respectively.

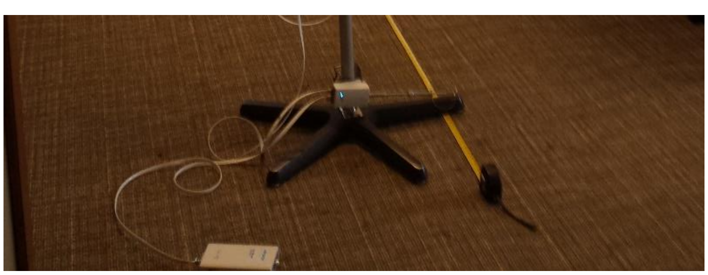

Figure 12: Base of measurement tree

Representativeness. Compared to lab studies, our field sites were more representative of real-world environments in terms of furniture layout, acoustic and lighting obstacles, ductwork, ventilation diffusers, and other physical objects in the space. The HVAC systems were also operating as they normally would. In most cases, the outdoor temperatures were not particularly warm and, according to ASHRAE 55, the indoor temperatures would have been considered comfortable even without the use of ceiling fans. At Site 5, the cooling setpoint used for controlling the HVAC in Site 5's spaces (24°C (75°F)) indicates that these zones are unlikely to get warm enough for the occupants to desire a significant cooling effect due to air movement. This suggests a lost opportunity for energy savings.

Controllers. Figure 13 shows a selection of the different ceiling fan controllers in these buildings, ranging from labeled remotes left loose in the space or mounted on the wall to unlabeled sliders on a control panel along with lighting controls. The large round controls (a and b) are for BAF HVLS fans: rotating changes speed, and pushing turns on or off. The remote (f, wall mounted or floating) is for BAF Haiku fans. Most other types of fans had vertical sliders, with or without labeling of any kind (c, d, e). Overall, the controls were not straightforward. When controls were numerically labeled, higher numbers could be either faster or slower fan speed settings. None of the controls explicitly say they are for the ceiling fan, and some of the sliders start at the fastest speed. In some cases, the controllers are located far from the fans they control or in obstructed locations.

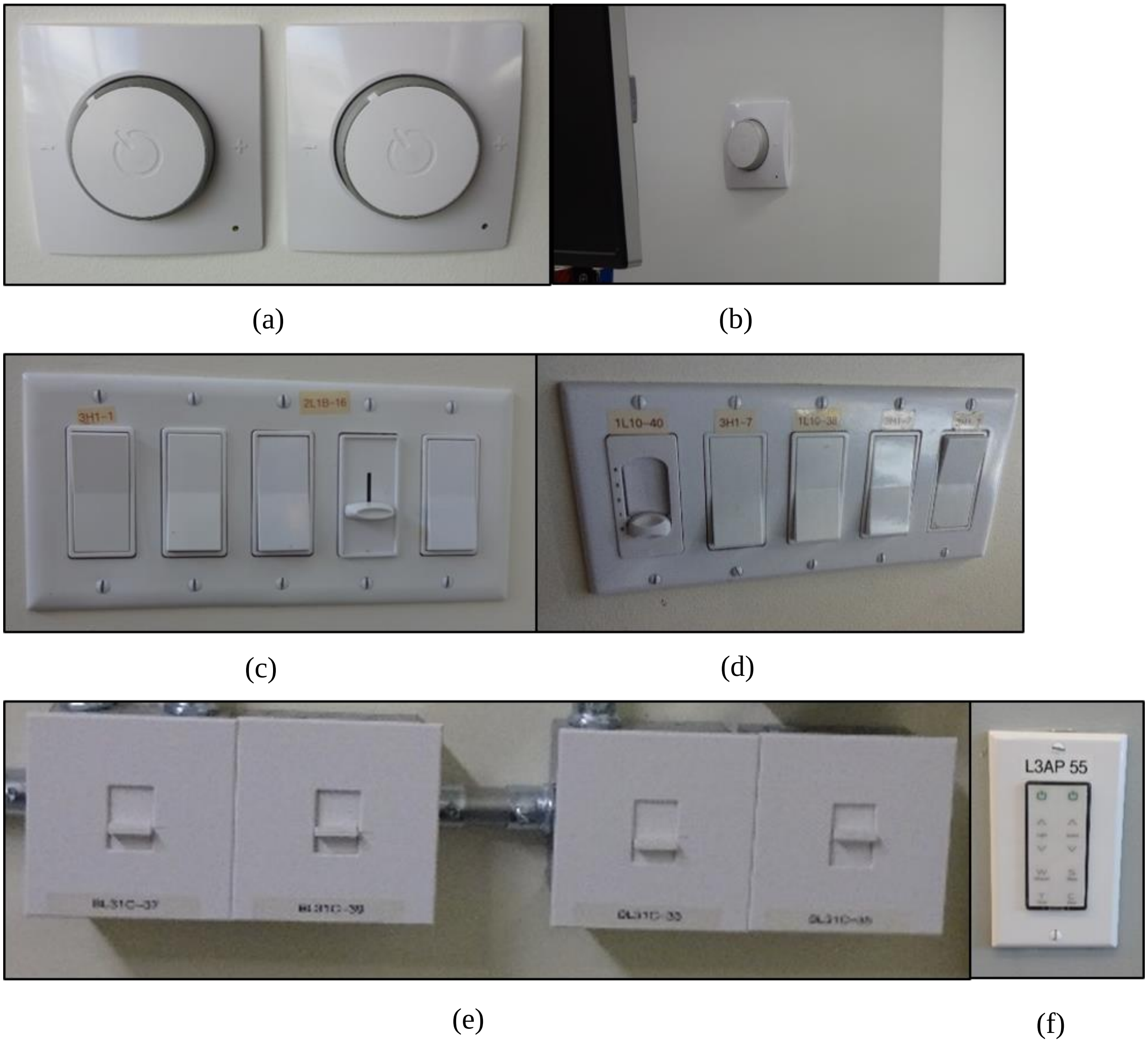

Figure 13. A selection of ceiling fan controls from in situ measurement sites.

5. Conclusion

We conducted interviews with 2 architects, 8 engineers, and 3 facilities managers focused on 20 operational commercial building projects that incorporated ceiling fans, and also took a total of 65 in situ airspeed measurements across five sites. The purpose was to better understand common motivations and applications, control strategies, barriers to market adoption, best practices, and airspeeds. Although interviewees revealed many challenges and barriers during the design process, their feedback about the fans is generally positive once installed. Occupants often choose to have the ceiling fans on even when the resulting airspeeds are too slow to create an appreciable cooling effect. This aligns with findings from the interviews, that ceiling fans provide benefits not only for comfort conditioning and energy use reduction, but also provide individual control, non-thermal benefits (such as perceived and measurable air quality), or an aesthetic choice not only in their own right, but sometimes as a way to eliminate visible ductwork.

The use of ceiling fans in commercial spaces that have mechanical ventilation and/or cooling systems is still a relatively uncommon practice. We believe that the benefits of fans in commercial spaces will be adopted more widely in the coming years as we better understand best practices. Furthermore, though the encountered-on-site fan settings and resulting airspeeds were low, it is important to note that these zones were already operating within ASHRAE 55 comfort conditions in the absence of air movement. Higher airspeeds would have overcooled the occupants unless increased the zone temperature. This indicates a potential opportunity to reduce HVAC energy consumption by increasing zone cooling setpoints and running ceiling fans faster to provide the first stage of comfort cooling.

Among the projects we studied, there were few applications of automatic control, and interviewees did not offer a consensus about whether manual or automated control was preferable, seeing pros and cons of each. We believe that a viable option is that of occupancy- and temperature-responsive automated controls that can be configured and temporarily overridden by occupants— similar to current best practice in the lighting industry.

As with many strategies that aim to improve building performance, best practices start with an integrated design process where different stakeholders communicate early in the process and coordinate decision making. This would facilitate overcoming many of the identified barriers to implementing ceiling fans, such as perceived concerns about noise, maintenance, or papers blowing; ability to clearly explain the benefits of fans to building owners or other design team members; cost tradeoffs; and lack of design guidelines. It's also important that the process doesn't end with design but is maintained through occupant education so that users fully understand the range of performance characteristics of ceiling fans (i.e., cooling vs. destratification), so the benefits are fully realized.

This study found substantial uncertainty around designing with ceiling fans despite the significant potential benefits. Lack of design guidance and measured performance is a significant barrier to downsizing HVAC equipment based on ceiling fan inclusion. Designers would benefit from outside support, such as from industry, government, or academia. The most significant support would be in the form of design guidance, backed by laboratory testing, CFD, and field studies, for commercial spaces with ceiling fans. This would make designers less reliant exclusively on manufacturers' guidance, and improve communication regarding the abilities and design goals of ceiling fans, and make the designers more confident that their designs would perform as intended. Another need is an expansion of the set of available standardized product test specifications, which would allow designers to more directly compare ceiling fan products. This will require industry effort; though ASHRAE is currently working on Standard 216, *Methods of Test for Determining Application Data of Overhead Circulator Fans*, which would meet most of this need. Industry could also better support ceiling fan products that can easily communicate with building automation systems or, ideally, that are BACNET-capable. In general, a more standardized design process would reduce several of the barriers to implementation. Members of the research team are continuing to work to better understand the needs of the design community in regard to designing with ceiling fans and intend to create a publicly-accessible design tool in the next two years.

Acknowledgements

This work was supported by the California Energy Commission (CEC) Electric Program Investment Charge (EPIC) Grant Award # 031322-022 and the Center for the Built Environment. Elaina Present holds a Career Development Grant from AAUW. Thank you to Therese Peffer for her help in preparing the manuscript and to Arfa Aijazi and Carlos Duarte for their feedback on some of the figures.

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Appendix A: Interview Guide

Project Overview

- Was this a new or retrofit project?
- What was your role on the project?
- Over what time period were you involved on the project?

Why Ceiling Fans/Getting Ceiling Fans on the Table

- Why did you choose ceiling fans on this project? (Comfort? Energy savings? Destratification?)
- What led to the decision to move forward with ceiling fans? What alternatives were considered?
- What types of HVAC systems are in the areas where fans are used? Setpoints?
- Why did you choose the ceiling fan and controls technologies that were installed? Did you consider any other options?
- What, if any, barriers were there to specifying or installing ceiling fans on this project?

Design

- What resources assisted you in specifying fans on this project – guides, tools, performance specifications, standards, etc.?
- Was adequate performance information available for you to choose a fan? What information was unavailable (or difficult to find)?
- Did you have specific airspeed targets?
- Was fan power consumption or efficiency a consideration in the selection process?
- How did you determine the locations for the fan(s) within the space?
- Was the furniture layout fixed at the time when you finalized the fan selection/design? If not, were there multiple options on the table, or was there simply no information at that point in time?

The System

- How many ceiling fans were used, in what types of spaces and with what spacing? How was this decided?
- How are the ceiling fans controlled? Who has control of the ceiling fans? What is the hierarchy of control?

Operation

- How long has the ceiling fan system been in operation? Have any changes or updates been made?

- How well are the fans and controls working? Are they achieving the intended effect? What is working well? What is not working well? Have there been any surprises?
- What has the response from occupants been? (Do they like the fans, or have there been complaints? How have any complaints been addressed?)
- Has there been a difference in the responses of those with more versus less control?
- Have there been any issues with maintenance (perceived concerns, or actual failures) of the fans since install?
- Have you noticed whether or not the occupants have used the fans as intended? Have the fans been moved or adjusted in any way since installation?
- Adjustment to set points?

Impact on Further Work

- Have you considered/specified/installed ceiling fans in any subsequent projects? Why or why not?
- What lessons learned from this project have you applied to subsequent projects?

Market Trends and Obstacles

- In your experience, has the number of ceiling fan products on the market increased or decreased?
- How have costs for ceiling fans and ceiling fan controls changed over time?
- Are there any specific design or control strategies you would recommend?
- Are there specific products you would recommend over others, either hardware, controls systems, or design or specifying resources?
- What, if any, improvements to the products or control strategies would you like to see?
- What kinds of product or control changes would encourage you specify or install more fans in the future?
- What, if any, barriers are there to specifying or installing ceiling fans on future projects?

Wrap-Up

- What should we have asked that we did not ask?

Appendix B: Project Characteristics

Table B1: Project characteristics

Project/ Site #	Location	Space type with Ceiling Fans	Ceiling fan Goals	Cooling in Ceiling Fan Spaces	Interviewee(s)	Controls	# Ceiling fans	Ceiling fan spacing	Fan diameter (Approx.)
1	Berkeley, CA	Conference rooms Common areas Open offices Private offices	Energy savings LEED certification	Other compressor-based	Building manager	Manual (mostly grouped)	Varies	Varies	NA
2	Santa Cruz, CA	Large seminar room (SR) Conference rooms (CR) Private and shared offices (O)	Cooling Destratification (SR) Occupant control (O) Aesthetics (SR - no ducts)	Operable windows No compressor cooling VAV central air handler with no cooling coil, economizer cooling only	Mechanical engineer	Manual (SR) Manual (proprietary remotes) (CR) Manual with occupancy (O)	1 per office 4 in SR 1-2 in CR	NA	HVLS 2.4m (8 ft) (SR) 1.5m (5 ft) (CR) 1.5m (5 ft) (O)
3	Emeryville, CA	Open Office	Destratification Air movement Cooling	Other compressor-based	Architect, Facilities	Manual	Array	6m (20 ft) on center x 9m (30 ft) on center	1.5m (5 ft)
4	San Francisco, CA	Open office	Destratification Air movement Aesthetics	VRF fan coil units	Tenant Engineering Consultant	Manual (wall)	1	~Centered	HVLS 24m (8 ft)

Project/ Site #	**Location**	**Space type with Ceiling Fans**	**Ceiling fan Goals**	**Cooling in Ceiling Fan Spaces**	**Interviewee(s)**	**Controls**	**# Ceiling fans**	**Ceiling fan spacing**	**Fan diameter (Approx.)**
5	Sacramento, CA	Open office	Comfort cooling Air movement	Radiant cooling Night pre-cooling	Building manager/ Controls implementer	Automatic	10/open office zone	6m (20 ft) on center	1.5m (5 ft)
6	Woodside, CA	Maker space (MS) Preschool	Occupant control Comfort	NA	Architect	Manual	1 HVLS in MS Array in preschool	Varies	NA
7	Finland, MN	Housing common area	Destratification Cooling on warmest days	Whole-house fan No compressor cooling	Mechanical engineer	Manual (proprietary remote)	1	~Centered	1.3m (52 in)
8	Saratoga, CA	Maintenance shops	Cooling on warmest days	No compressor cooling	Mechanical engineer	Manual	6 (1 per shop)	NA	HVLS 2.4m (8 ft)
9	Watsonville, CA	Lab spaces Conference room Offices (private & open)	Occupant control Enhance radiant	Radiant cooling	Architect	Manual	NA	Varies	1.5 m (5 ft)
10	Santa Rosa, CA?	Multi-use spaces Offices (private) Classrooms Kitchen Specialty Areas	Comfort User control Destratification Flexibility Enhance randiant	Radiant cooling	Architect	Manual	12 in dining room 1 per office Other: varies	Varies	Varies (some HVLS)
11	Menlo Park, CA	Open office Private office Dining rooms	Extend comfort cooling range Enable/enhance radiant (Comfort and efficiency)	Radiant cooling Chilled sails/fan coils Operable windows	Mechanical engineer	Manual (wall)	~60 1 per office Arrays elsewhere	3.7-4.6m (12-15 ft) on center	1.2m (4 ft)
12	Atherton, CA	Classrooms Library	Occupant control Cooling Eliminate AC	Other compressor-based	Architect	Manual (grouped)	12 in library 1 per classroom?	Varies	1.5m (5 ft)

Project/ Site #	Location	Space type with Ceiling Fans	Ceiling fan Goals	Cooling in Ceiling Fan Spaces	Interviewee(s)	Controls	# Ceiling fans	Ceiling fan spacing	Fan diameter (Approx.)
13	Basalt, CO	Open office Kitchen Atrium Convening room	Comfort cooling Air movement	No compressor cooling	Architect	Automatic	Array	6m (20 ft) on center	1.2m (4 ft)
14	Seattle, WA	Open office Conference room	Added air movement Thermal comfort improvement	Radiant cooling Natural ventilation Operable windows Thermal mass	Mechanical engineer	Occupant control (proprietary remotes)	8 in open office 2 in conference room	every structural bay (~6m (20 ft) on center)	1.5m (5 ft)
15	Oakland, CA	Classrooms (C) Assembly area (A) Indoor courtyard (IC) Private offices (O)	Cooling Air mixing Destratification Assist with night pre-cool	Thermal mass Night pre-cooling	Project engineer, Mechanical engineer/ Commissioning agent	Automatic Manual override	1 /(C) 1 /(O) 2/(IC, A)	~Centered	HVLS 5.5m (18 ft) (A, IC) HVLS 3.7m (12 ft) (C) HVLS 1.8m (6 ft) (O) 1.5m (5 ft) (O, Phase II)
16	Newport Beach, CA	Semi-enclosed, semi-exterior lounge space	Cooling on warmest days	No compressor cooling	Mechanical engineer	Automatic (temperature - based)	2	NA	HVLS 2.4m (8 ft)
17	San Jose, CA	Open office	Destratification Air movement	Water source heat pumps	Mechanical engineer	Manual (touchscreen, grouped)	4	NA	HVLS 1.8m (6 ft)
18	Sacramento, CA	Open office	Destratification Air movement	Packaged unit	Mechanical engineer	Manual	1 HVLS 3 smaller	NA	HVLS 2.4 m (8 ft) 1.3m (52 in)
19	Northridge, CA	Fitness rooms Gym area	Comfort cooling	Campus VAV	Mechanical engineer	Manual	30	NA	1.2m (4 ft)
20	Pomona, CA	Fitness studios Gym area	Occupant control Comfort cooling	Campus VAV	Mechanical engineer	Manual	30	NA	1.3m (52 in)