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Detailed measured air speed distribution in four commercial buildings with ceiling fans

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ABSTRACT

The layout of ceiling fans in buildings is challenging because of the need to co-ordinate with other elements in the ceiling space, and because the resulting airflows within the occupied space interact with furniture. This study conducted detailed air speed measurements in four buildings with different room sizes, furniture configurations, ceiling fan types, and ceiling-fan-to-floor-area ratios. We measured air speeds across the occupied spaces at four heights while varying ceiling fan operation modes such as fan rotational speed, operating direction, and the number of operating fans. In total, we collected 207,080 air speed samples at 343 sites under 20 test conditions. This paper presents the magnitude and distribution of air speeds, cooling effects, and their influencing factors. The *Airspeed Coverage Index* (ACI $= \frac{\text{Fan air speed } (SF) \times \text{ Fan diameter } (D)}{\sqrt{\text{Average area served per ceiling fan } (A)}}$) describes the combined effects of multiple influencing factors on the magnitude of air speed. ACI is employed to predict the average air speed and occupant cooling effect, yielding regression confidences higher than 0.95. When designing a space to a target airspeed or cooling effect, the ACI can help to determine parameters such as fan density required for fan choices. The measured data are compared with predictions from the CBE fan tool that had been developed from laboratory tests under simplified conditions. The comparison displays the blocking effects of the furniture, lowering the average air movement in the space, as well as reducing the air movement at the ankle level while increasing it at higher heights. The blocking effect increases with the density of the furniture. We also visually present fan interactions in which triplets of fans are arranged linearly or diagonally, showing that the diagonal layout of ceiling fans increases average air speed and improves its uniformity.

1. Introduction

Ceiling fans are commonly part of the thermal comfort design strategy for buildings [1]. This is particularly true in warm climates, where ceiling fans enable higher comfortable cooling setpoint temperatures in the HVAC system [2–4]. A recent study in which 99 smart ceiling fans were integrated with HVAC thermostats at different sites in California's Central Valley found a median cooling energy savings of 15% per compressor, and average savings that were far higher [5]. Elevated air movement in warm conditions has many benefits beyond reducing HVAC cooling energy, including faster and more flexible control over the thermal environment, greater resilience to weather extremes and power curtailment, and better perceived comfort and indoor air quality [6–8]. Ceiling fans may also lower initial cost of equipment and ductwork in conventional air conditioning systems [9,10]. Many products available on the market use very modest amounts of energy – for example less than 10 W at speeds typically selected by occupants for 1.5 *m* ceiling diameter fans. The ENERGY STAR™ list of certified ceiling fans includes 20 models with 1.42–1.52 *m* diameter, all of which are rated below 284 m^3/h/W at design airflow [11].

The airflow distribution produced by ceiling fans within the occupied level of the space is important in design and operation for comfort. Comfort for a given occupant is usually addressed via whole-body heat balance models using air speeds that are averaged over the occupant's height [12, 13]. The SET (standard effective temperature) model is used in ASHRAE Standard 55 to convert the cooling effect of air movement into an equivalent temperature or PMV value. The Standard permits

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Nomenclature

A	Average area served per ceiling fan, m^2
ACI	Airspeed coverage index, m/s
AF	Fan blade swept area, m^2
CLO	Clothing insulation, clo
D	Fan diameter, m
HVAC	Heating, Ventilation, and Air Conditioning
PMV	Predicted Mean Vote
Q	Volumetric airflow rate through the fan blades, m^3/s
Q_{max}	The maximum volumetric airflow rate through the fan blades, m^3/s
N	Fan rotational speed, rpm
N_{max}	The maximum fan rotational speed, rpm
TSV	Thermal Sensation Vote
T_{air}	Air temperature, °C
T_r	Radiant temperature, °C
Vel	Air velocity, m/s
HVAC	Heating, Ventilation, and Air-Conditioning
R^2	Correlation coefficients (r) square
SET	Standard effective temperature, °C
SF	The fan air speed, representing the average air speed through the area swept by the fan blades, m/s

indoor air movement up to 0.8 m/s when no personal control is available, or over 1.6 m/s when there is personal control. This equates to a cooling effect of up to 4 °C for maintaining equal comfort in warmer temperatures (see Fig. 5.4 in ASHRAE 55–2020).

However, ceiling fans produce large spatial inhomogeneity of airspeeds that is influenced by fan size and layout, operation mode and furniture configuration. It is important to select the appropriate fan, layout, and operation for the space [14–16]. Horizontal variance of air movement may excessively cool occupants directly under the fans while those positioned further away experience insufficient cooling [14,15]. This is true in offices and other settings where people may have less freedom to relocate and fans may be set to serve a group rather than an individual.

The vertical variance is also considerable under fans. When one is not directly under a fan in an unfurnished room, the airflow radiating outward from the fan is strongest at ankle level. Under cool temperatures this may cause discomfort from drafts, since the feet and ankles are sensitive to being overcooled [17]. Conversely with furniture, the fan outward flow is redirected to higher levels and the ankles may receive very little flow. It has been found that in such situations, whole-body models like SET predict cooling successfully using airflow as measured only at the upper body level [12].

The airflow from ceiling fans is influenced by the nature of the fan, its placement and operation. These are summarized in a review of extant literature [18], and include (not limited to) fan rotational speed [19–21], blade shape and number [19,22,23], direction (upward or downward) [15,24,25], mount distance [19,23], ceiling height [19], multiple fans [13,26], and furniture [14,25]. Among these factors, detailed laboratory tests show that the fan speed, diameter, and direction have the largest impact on the resulting airflow within the occupied zone of a building [17]. These insights are packaged into useable design tools for practitioners that model airflow in either empty rooms or rooms with furniture and partitions [17]. Based on 78 full-scale laboratory tests [17], the CBE fan tool helps optimize the layout of ceiling fans in building designs [27] by estimating resulting air speeds (average, minimum, maximum) and spatial uniformity of the airflow.

Most studies of ceiling fans have been performed in laboratories, and there are limited field studies that determine whether the findings are applicable to actual buildings. In an earlier study [28], we performed spot air speed measurements in situ in 5 buildings. Ceiling fans were typically used infrequently at most sites, likely due to low ambient temperatures (~21 °C) and low cooling setpoints. Another field study of occupant behavior [29] found fans were turned on based on indoor temperature and off based on occupancy (e.g. when they left the space). 83% of occupants were satisfied with ceiling fans in their workspaces. Occupants reported limited dissatisfaction with papers blowing, lack of access to the fans, airspeeds too high, or visual distraction. Other field studies in office buildings report occupant preference for more air movement than what they are experiencing [30–33]. However, these studies were not accompanied with detailed measurements of air speed distributions. There is a need for detailed and comprehensive field measurements of airflow from ceiling fans in order to improve the design advice and guidelines for practitioners.

The objective of this study is to understand how ceiling fans work in buildings under varying real-world conditions, such as different space types and sizes, ceiling fan types and locations, furniture densities, and operation modes. We also characterize the effects of furniture and multiple fan interactions on airflow in the occupied zone. These results can provide general guidance on ceiling fan layout to optimize the design and operation in buildings.

2. Methods

2.1. Case buildings

We conducted field measurements of air speeds in 4 buildings with ceiling fans between May 2018 and March 2020. The buildings have different functional spaces and room sizes. There are two offices (the PAE and SMUD buildings), one seminar room (SC building), and one community center with a large activity and dining space (FC building). These four buildings are all in northern California, USA but in very different local climates. Among the California building climate zones [34], the PAE and SC buildings belong to Zone 3, SMUD and FC buildings belong to Zone 12. Table 1 summarizes the spaces and ceiling fans tested in this study. Both the SC and FC buildings have multiple fans that can be operated independently.

2.2. Air speed measurements

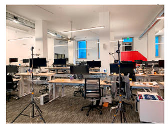
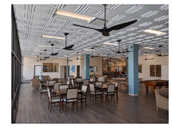
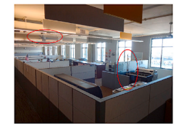
We measured air speeds at each building with different fan operation modes depending on the capabilities of the existing fan control system. The varying conditions were fan operating direction (downward and upward), fan speed (high, medium, and off), and the number of operating fans; Table 2 summarizes these test conditions. Measurement grids traversed each room, with measurement locations within each grid cell selected based on a typically occupied location. The distance between grid cells was typically 0.6–0.9 *m*. The number of measurements sites (69 in PEA, 101 in SC, 158 in FC, and 15 in SMUD) varied depending on the room size, furniture configuration, and other factors. The allotted time on site at the SMUD building did not permit grid traversing so measurements were made at workstations and areas where occupants were like to located. Appendix A shows floor plans, fan locations, and measurement sites.

We measured air speeds at four heights (e.g. 0.1 *m*, 0.6 *m*, 1.1 *m*, and 1.7 *m*) using stands with four omni-directional anemometers (5100SF, Sensor Electronics, Poland) with an accuracy of ±0.02 m/s, in accordance with ASHRAE 55–2020 [12]. We used a 2-s sampling interval over a 3-min measurement time for air speed and air temperature after an initial 30 s stabilization period, based on existing recommendations [35]. We conducted measurements at the weekend so that the spaces were not occupied.

2.3. Data processing

Measurements were exported from the anemometers as text docu-

Table 1
Case building information.

Buildings (abbreviation)		San Francisco PAE engineering office (PAE)	Santa Cruz biology seminar room (SC)	Franco Community Center (FC)	Sacramento Municipal Utility District office (SMUD)[a]
Field scene					
Total floor area, m^2/ft^2		227/2441	156/1681	367/3968	344/3700
Fan diameter (D), m/ft		2.44/8	2.44/8	1.52/5	1.52/5
Fan type (brand)		ESSENCE	ESSENCE	HAIKU	INDUSTRIAL
Maximum fan rotational speed (N_{max}), rpm		158	158	200	247
Maximum airflow through the fan blades (Q_{max}), m^3/s/cfm		16.6/35,112	16.6/35,112	4.1/8629	4.5/9602
Fan blade swept area (AF), m^2/ft^2		4.7/50.3	4.7/50.3	1.8/19.6	1.8/19.6
Number of running fans	All on	1	4	26	7
	1/2 on[b]	–	2	14	–
	1/3 on[b]	–	–	9	–
Average area served by each fan (A), m^2/ft^2	All on	226.8/2441	39.1/420.4	14.2/152.8	49.1/528.5
	1/2 on	–	78.1/840.7	26.3/283.1	–
	1/3 on	–	–	41.0/441.3	–

[a] The SMUD building results have already been reported in Ref. [26], and its measurement sensor density was lower than the other three buildings, as such, we did not include it in the detailed analysis for individual buildings. However, it is included later when combining data.
[b] The locations of the fans in operation are presented in Appendix A.

Table 2
Test conditions for each case building.

	Fan direction	Operating level	Number of fans	PAE	SC	FC	SMUD
Fan rotating speed	Down	High	All on	134 (rpm)	155 (rpm)	95 (rpm)	237 (rpm)
			1/2 on	–	155 (rpm)	95 (rpm)	–
			1/3 on	–	–	95	–
		Medium	All on	90 (rpm)	87 (rpm)	70 (rpm)	155 (rpm)
			1/2 on	–	–	70	–
			1/3 on	–	–	70	–
	Up	High	All on	140 (rpm)	156 (rpm)	–	237 (rpm)
			1/2 on	–	156 (rpm)	–	–
			1/3 on	–	–	–	–
		Medium	All on	94 (rpm)	84 (rpm)	–	155 (rpm)
			1/2 on	–	–	–	–
			1/3 on	–	–	–	–
Number of sites				69	101	158	15
Multiple fan interaction				–	–	2 fans and 3 fans interactions	–

ments and collated for analysis; Appendix B contains the full dataset. We used the R programming language (version R 3.6.1.) along with the 'tidyverse' and 'comf' packages [36] for data analyses and visualizations. We calculated the *cooling effect* to determine the cooling provided by ceiling fans. This is defined in Equation (1.1) as the difference between standard effective temperature (SET) at the still air case of 0.1 m/s air speed ($SET_{still\ air\ case}$) versus at the measured air speed level ($SET_{meansured\ air\ speed}$) [12]. To exclude other parameters' effects on the SET calculation, both air and mean radiant temperatures were assumed to be 28 °C[1] for the SET calculation. Other parameters were set for a standard office worker in summer (e.g. 50% relative humidity, 1.1 met for activity level, and 0.5 clo for clothing insulation).

$$Coolingeffect = SET_{still\ air\ case} - SET_{meansured\ air\ speed} \tag{1.1}$$

We used the ***Airspeed coverage Index (ACI)*** to describe the combined effects of multiple influencing factors on air speed across the measured spaces. Regression analysis is used to model the relationship between ACI and the average air speed. Equation (1.2) shows that the ACI considers several factors, including room size, ceiling fan types (diameter and the maximum airflow volume), fan rotational speed, and the number of operating fans. D is the fan diameter (m), A is the average area served per ceiling fan (m^2), and SF is the fan air speed (m/s). Equation (1.3) defines the calculation of SF, where N and N_{max} are the actual and the maximum fan rotating speeds (rpm), Q is the volumetric airflow rate through the fan blades (m^3/s) when operating at N_{max}, and AF is the fan blade swept area (m^2). The unit for ACI and SF is m/s.

[1] The 28 °C ambient temperature was chosen because it can be corrected to thermal neutrality by the elevated air speeds produced by the ceiling fans. In conditions deviating further from thermal neutrality, the cooling effects of elevated air speeds can be increased by 0–50% depending on the severity of cold or hot. But these very cold and very hot conditions are not what we expected in normal real buildings. They are, therefore, not considered in the following analysis.

$$Airspeed\ coverage\ index\ (ACI) = \frac{Fan\ air\ speed\ (SF) \times\ Fan\ diameter\ (D)}{\sqrt{Average\ area\ served\ per\ ceiling\ fan\ (A)}} \tag{1.2}$$

$$SF = \frac{N}{N_{max}} \times Q \div AF \tag{1.3}$$

3. Results and Discussion

We used the mean, median, standard deviation (SD), minimum (Min), and maximum (Max) values to summarize measured air speeds (see Table 3). These statistics are used for measurements across the space of each test condition with and without averaging by height. Air speeds averaged by heights reflect the horizontal variance across the floorplan, while air speeds without averaging show combined variance across both the floorplan and in the vertical direction. The mean air speed averaged by height varied from 0.17 to 1.83 m/s and standard deviation ranged from 0.05 to 0.58 m/s. Minimum air speeds were mostly lower than 0.2 m/s except for the SC case under 4 fans operating simultaneously; maximum air speeds were up to 3.15 m/s. Air speeds that were not averaged by height had higher maximum air speeds, lower minimum air speeds, and larger standard deviations.

Air speed distributions superimposed on floorplans with the ceiling fan layout and furniture in the four buildings are shown Fig. 1. Higher air speeds occurred under or near the downward operating ceiling fan and decreased with distance from the fans, as expected. The measured variance in air speed is the result of many factors such as fan diameter, number of fans, distance from the ceiling fan centers, fan rotational speed, and operating direction. In the following sections we will analyze and discuss these factors individually.

3.1. Ceiling fan operation modes and the room air speeds

Among all the factors influencing room air speed from ceiling fans, the fan *operation mode* involves fan operating direction, the number of operating fans, and the fan rotational speed. There are other factors affecting air speeds in the occupied zone from ceiling fans, such as fan diameter, room size, furniture configuration, and so on [17], but they are not operating characteristics; they are inherent features of the rooms and the fans as they are currently designed. We explored three factors of fan operation mode in following analysis. For other factors, we encourage those interested to use the measured air speed data in Appendix B.

3.1.1. Fan operating direction

Ceiling fans operating in the downward direction produced significantly higher air speeds with larger variance than the upward direction (Fig. 2). When blowing downwards, air speeds varied from ~0.2 m/s in PAE and FC at low speed to ~1.8 m/s in SC with 4 fans at high speed. Lower air speeds averaging ~0.25 m/s were measured when fans were blowing upwards, except in SC when operating at the maximum speed. The distribution of air speeds demonstrates the more uniform flow within the occupied zone when fans are blowing upwards. In most cases, the standard deviation was less than 0.15 m/s (see Table 3) when blowing upwards compared to 0.28 m/s ~ 0.58 m/s when blowing downwards depending on fan diameter, size of the space, and the number of fans operating.

A comparison of vertical air speed distributions at the four measurement heights is shown in Fig. 3. Air speeds in the downwards operating direction exhibiting a bimodal or multimodal distribution regardless of fan rotating speed, indicating inhomogeneity across sites. The vertical air speed gradient reverses when the fans operate in either the downwards or upwards direction. Generally, fans operating downwards create negative vertical gradients (air speeds are fastest at the ankle height and slowest at the head height of occupants), and a positive gradient only when located directly under the fan. In contrast, fans operating upwards create positive vertical gradients (air speeds at the head height of occupants are higher than those at ankle level) throughout the space, with a negative gradient only when located in the return air path (e.g. near walls, or at the confluence of airflows from two or more fans). The vertical air speed variance may affect occupants' overall comfort given that the ankles are more sensitive to draft [37]. However, often ankles are covered by shoes and socks, which reduces the risk of draft in ankles. Natural temperature gradients across the body mean that cooling in warm conditions is best targeted at the head level rather than the feet. This is in line with the idea of thermal pleasure arising from cool stimuli applied to warm body sites described by the spatial alliesthesia hypothesis by Parkinson and de Dear [38].

Priority should be given to downward-blowing operation if design requirements are to maximize the cooling effect of ceiling fans, or to minimize fan energy consumption for a given cooling effect. Similarly, the additional variability in conditions from blowing downwards can be beneficial in many applications, such as those where occupants within the same space are likely to have different thermal comfort needs (e.g. gymnasiums, lobbies, etc.) and can freely and easily move around within the space. In contrast, ceiling fans blowing upwards have better air speed uniformity both horizontally and vertically but with a lower cooling effect. This uniformity occurs regardless of fan type or the number of fans operating. As such, ceiling fans blowing upwards are more suitable for spaces requiring uniformly distributed air speeds and low cooling effect [39]. Note also that for high performance fans such as those studied here, the blade design typically has an airfoil component to optimize performance for the downwards direction. However, these designs then generate far less airflow when blowing upwards than downwards, all else being equal. Thus, if the intent is to operate the fan blowing upwards, fan types with a symmetrical blade geometry or types that have blades which can be attached inverted (so that the fan operates in the direction the blade design was optimized for) will likely generate higher air speeds than seen in this dataset. Laboratory testing demonstrated this effect [17], measuring a 52% increase in measured average airspeeds in the occupied zone between a fan blowing upwards with and without inverted blades, other test conditions being approximately equal.

3.1.2. The number of fans

As described before, FC and SC allow us to control fans on/off in different groups. Therefore, we tested air speed distributions with different numbers of fans operating in these two buildings. The relationship between mean air speeds and the number of fans operating in the FC and SC buildings (see the Fig. 1 in Supplementary Materials file) is proportional to the square root of the number of operating fans. For the FC building, mean air speeds when half (14 fans) and one third (9 fans) of the fans were operating were 75–85% and 54%~71% of that when all (26 fans) were on. However, uniformity of air speeds in the space decreased substantially for the test conditions with fewer operating fans. For the SC building, operating half (2 fans) of the downward blowing fans yielded a mean air speed of 68% of the value when operating all 4 fans.

3.1.3. Fan rotational speed

Simplified regression models based on the number of fans, vertical heights, and operating directions in the Fig. 2 of Supplementary Materials file show how air speeds in the occupied zone vary with fan rotational speeds. The small differences in regression lines between the number of fans operating and the four vertical heights in the FC building shows suggests a consistent relationship at different heights. Regression models from measurements in PAE, SC, FC, and SMUD buildings show a linear relationship between air speed and fan rotational speed for both downward and upward-blowing directions. These results are consistent with the modeling approach used by Raftery et al. [17].

Table 3
Summary statistics across all sites and test conditions.

				Air speed (m/s) averaged by heights/Not averaged by height					
Cases	Direction	Fan rotating speed	Number of fans	Mean	Median	SD	Min	Max	Space
PAE, 2.44 *m* fan	Down	134 rpm	1 fan	0.61/0.55	0.40/0.33	0.51/0.61	0.10/0.01	2.38/4.06	Office room
		90 rpm		0.35/0.32	0.22/0.20	0.28/0.34	0.08/0.01	1.23/2.21	
	Up	140 rpm		0.28/0.28	0.26/0.27	0.10/0.12	0.14/0.01	0.61/0.74	
		94 rpm		0.19/0.20	0.19/0.19	0.06/0.08	0.09/0.01	0.37/0.49	
SMUD, 1.52 *m* fan	Down	237 rpm	7 fans	0.76/0.76	0.80/0.64	0.30/0.50	0.21/0.16	1.20/2.35	Office room
		155 rpm		0.46/0.46	0.47/0.39	0.17/0.28	0.13/0.11	0.70/1.45	
	Up	237 rpm		0.30/0.30	0.29/0.28	0.07/0.11	0.17/0.07	0.43/0.66	
		155 rpm		0.20/0.20	0.21/0.20	0.05/0.07	0.12/0.07	0.27/0.39	
SC, 2.44 *m* fan	Down	155 rpm	4 fans	1.83/1.76	1.80/1.61	0.53/0.81	0.47/0.15	3.15/5.15	Seminar room
			2 fans	1.25/1.20	1.05/0.93	0.58/0.82	0.39/0.15	2.78/5.46	
		86 rpm	4 fans	1.03/1.01	0.98/0.95	0.21/0.40	0.67/0.06	1.56/2.95	
	Up	157 rpm	4 fans	0.54/0.55	0.55/0.54	0.16/0.24	0.20/0.08	0.82/1.81	
			2 fans	0.47/0.47	0.48/0.45	0.15/0.21	0.20/0.02	0.79/1.30	
		84 rpm	4 fans	0.30/0.31	0.29/0.29	0.08/0.14	0.09/0.04	0.48/1.07	
FC, 1.52 *m* fan	Down	70 rpm	26 fans	0.28/0.27	0.26/0.24	0.10/0.17	0.07/0.01	0.66/1.14	activity area
				0.25/0.25	0.23/0.22	0.08/0.14	0.05/0.01	0.48/0.93	dining area
			14 fans	0.24/0.23	0.22/0.18	0.10/0.16	0.04/0.01	0.64/1.06	activity area
				0.21/0.20	0.19/0.17	0.09/0.13	0.08/0.01	0.52/0.92	dining area
			9 fans	0.19/0.18	0.17/0.14	0.10/0.15	0.04/0.01	0.66/1.11	activity area
				0.17/0.16	0.15/0.13	0.09/0.13	0.05/0.01	0.51/0.89	dining area
		95 rpm	26 fans	0.47/0.46	0.46/0.42	0.16/0.25	0.12/0.04	1.13/1.94	activity area
				0.39/0.39	0.37/0.33	0.13/0.22	0.19/0.05	0.85/1.29	dining area
			14 fans	0.41/0.38	0.38/0.31	0.16/0.26	0.12/0.01	1.02/1.72	activity area
				0.31/0.29	0.27/0.24	0.13/0.2	0.15/0.02	0.83/1.24	dining area
			9 fans	0.34/0.33	0.30/0.25	0.16/0.25	0.14/0.02	1.25/1.85	activity area
				0.22/0.21	0.21/0.16	0.12/0.17	0.07/0.01	0.76/1.20	dining area

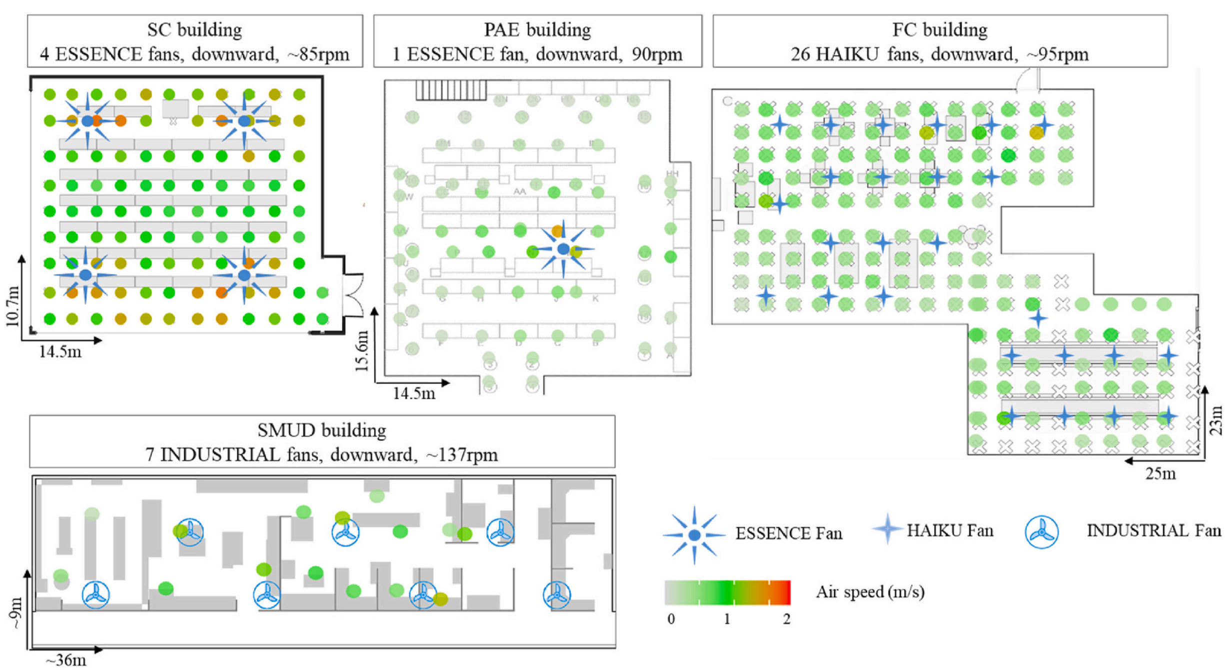


Fig. 1. Floorplan and air speed distributions in the four buildings. The color of the circles represents the magnitude of air speed at each site averaged by heights. The background is the floorplan showing the furniture (grey squares) and ceiling fans (stars), both to scale.

3.2. *Cooling effects of ceiling fans*

The purpose of introducing ceiling fans into buildings is to provide controllable cooling effects via elevated air speed. By using the SET (standard effective temperature), the cooling effect from air movement can be converted to an equivalent temperature, which is more straightforward when interpreting the benefits of ceiling fans and in setting space temperatures.

Fig. 4 shows the magnitude of cooling effect for each building using Equation (1.1). Differences in cooling effect are the result of different air speeds, where higher air speeds correspond with a stronger cooling effect. In the SC and PAE buildings, upward blowing fans produced 19% ~57% lower cooling effect than blowing downwards at similar rotational speeds. A similar reduction was found in the SMUD building. As expected, the downward blowing fans provide greater cooling effects (approximately 2–4 °C) than upwards blowing fans (approximately 1–2 °C). This has important consequences if ceiling fans are selected to offset an increase in cooling setpoint temperature.

Fig. 5 shows the distribution of the cooling effect from elevated air speeds under different test conditions in the FC building. Ceiling fans

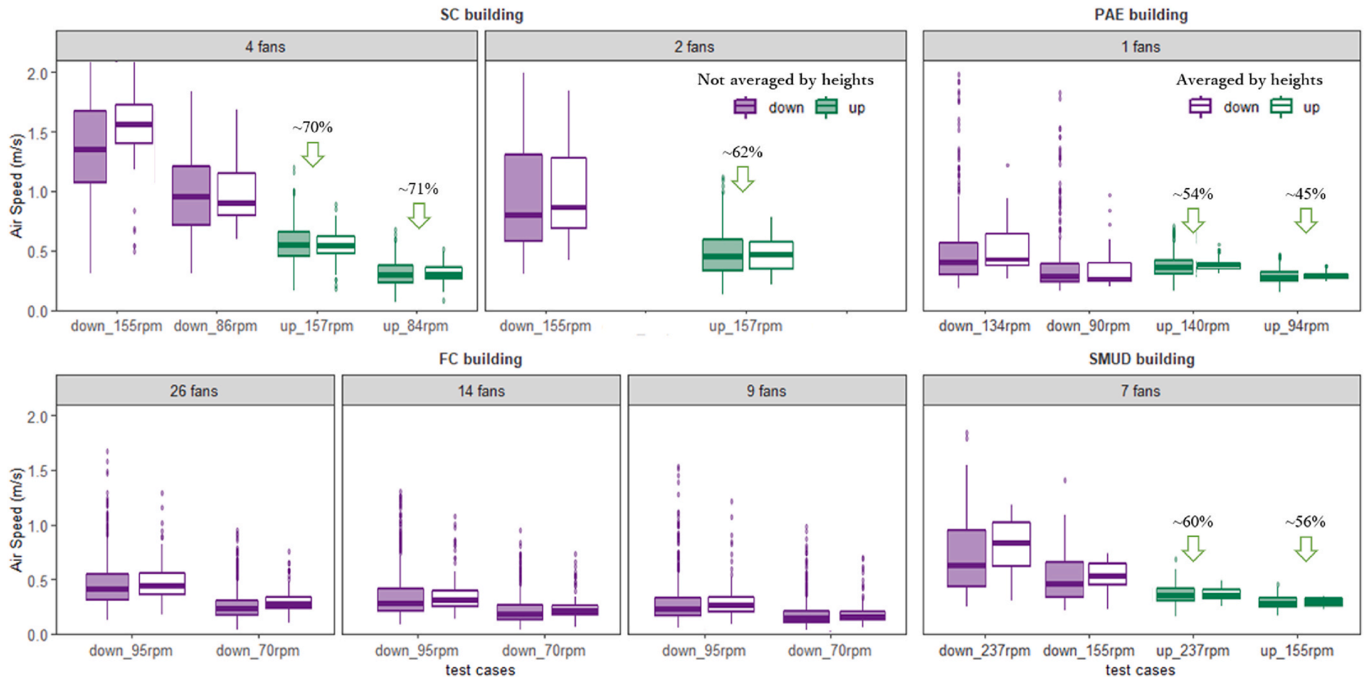


Fig. 2. Air speed distributions under downward (purple) and upward (green) operating directions at all sites and 4 measuring heights in one test condition. Each box represents represent the 25th to 75th percentile of the air speeds before (filled shape) and after (open shape) averaging by heights.

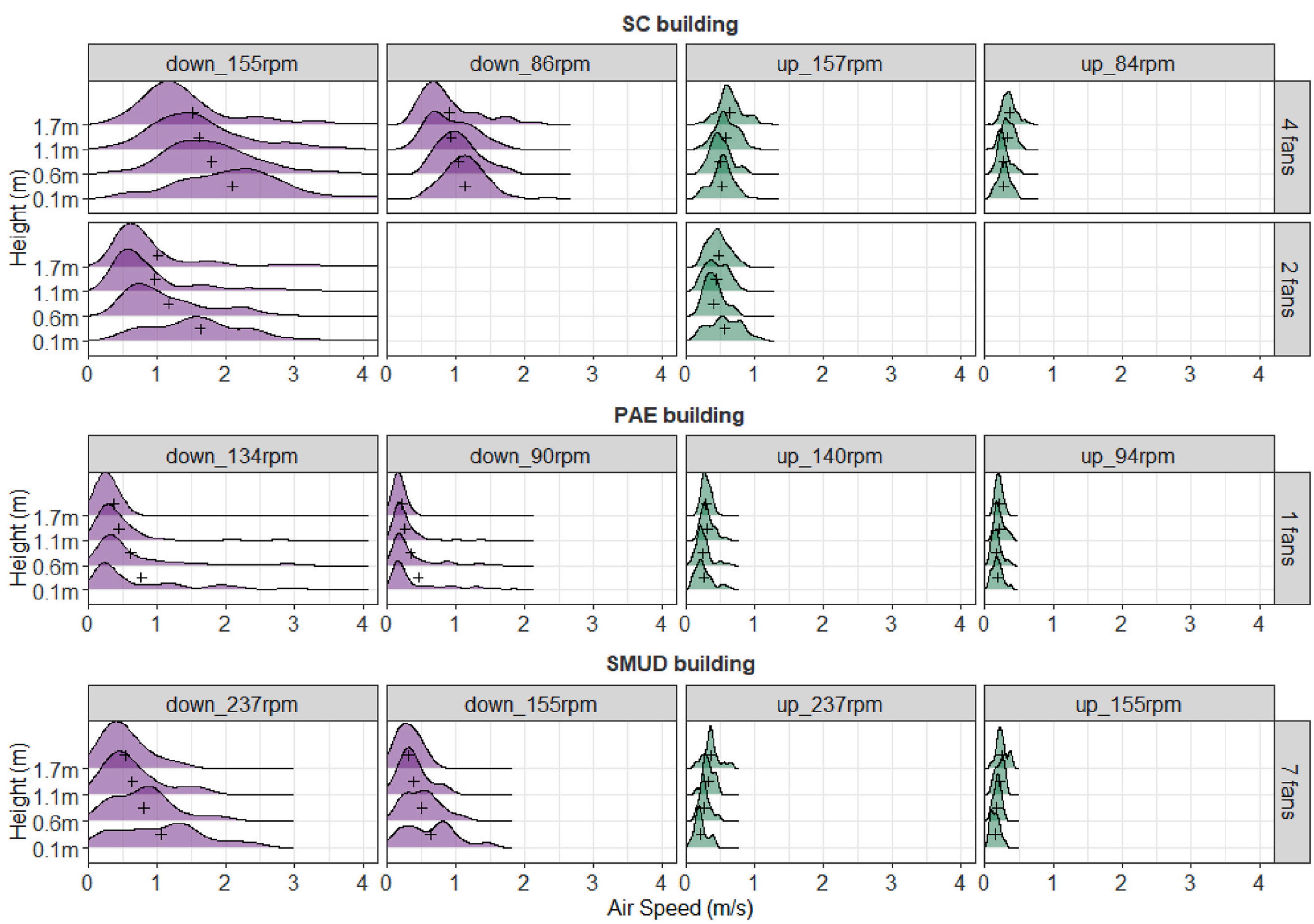


Fig. 3. Distribution of measured air speed for each test at four heights. The '+' symbol marks the mean air speed at each height across all sites. The purple and green colors represent downward and upward operating direction, respectively.

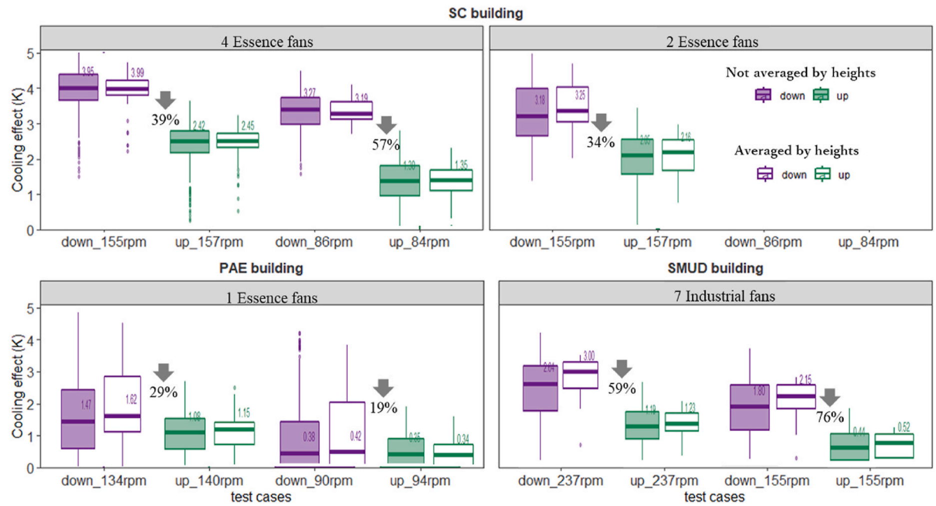


Fig. 4. Cooling effects in different test conditions and buildings. The cooling effect drop from downward to upward was calculated for the height-averaged air speed data measured at each site in each building. Each box represents one test condition.

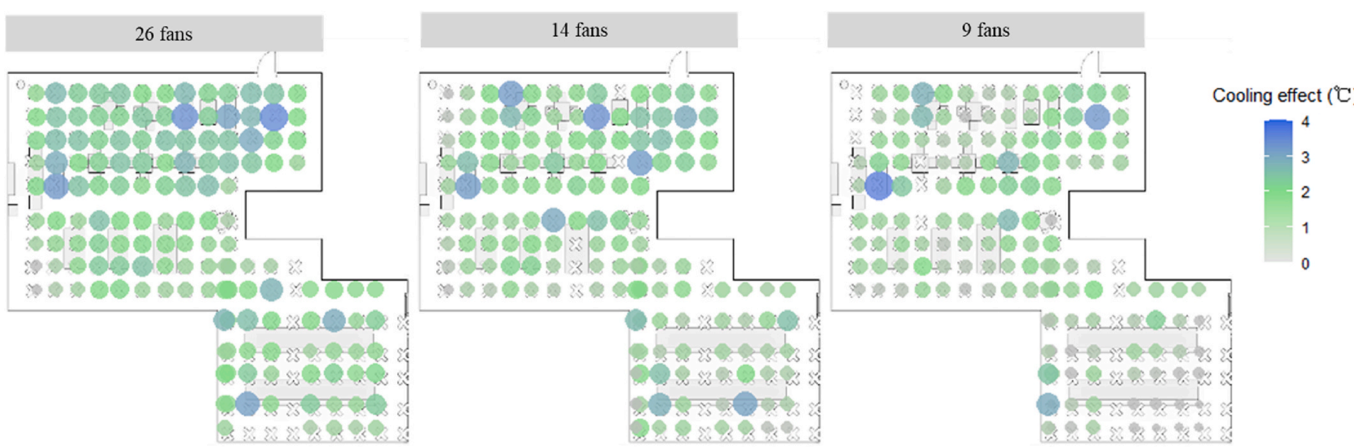


Fig. 5. Cooling effects across the room in FC building. The size of the circle represents the magnitude of the mean air speed and the color represents the magnitude of the cooling effect at each site. The background is the floorplan showing the furniture (grey squares). Appendix C contains visualization of the cooling effects in other buildings.

provided 2∼4 °C of cooling across the occupied zone when all fans were operating. The uniformity of the cooling effect depends on the number and layout of the operating fans. The strongest cooling effect was directly under operating fans and generally reduced with distance from the fan, as expected.

3.3. Air speed coverage index (ACI)

Given that air movement and cooling effects from ceiling fans are determined by multiple factors simultaneously, it would be helpful to develop some indexes that can reflect the combined effects of multiple factors.

Raftery et al. [17] proposed several dimensionless indices to predict air speeds in the occupied zone from ceiling fans based on the different factors discussed here. The airspeed coverage index (ACI), shown in Equation (1.2), is based on fan airflow volume, fan diameter, fan density, and the floor area served by a ceiling fan. These parameters are important considerations when designing spaces that utilize ceiling fans for thermal comfort. We calculated the ACI and compared it to the observed mean air speed for all measurement cases. These is a linear correlation between the measured mean air speed and the ACI (see Fig. 7), and this linear correlation can be reflected by the logarithmic relation between the ACI and elevated air speed's cooling effect (see

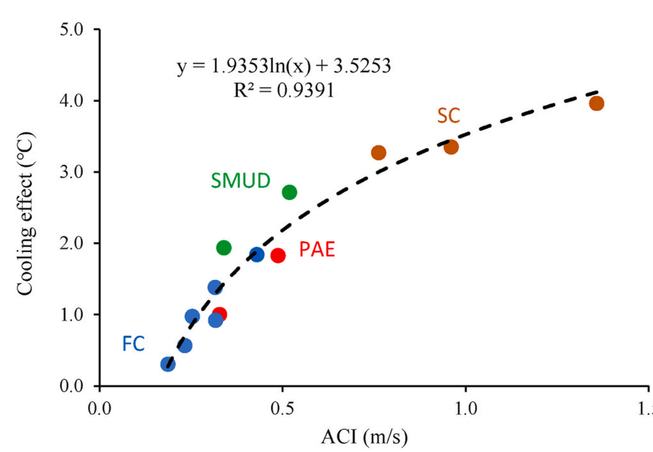


Fig. 6. Relationship between ACI and cooling effect of elevated air speeds produced by ceiling fans.

Fig. 6). This suggests that the ACI model can be used by designers to specify the ceiling fan selection and layout to best achieve the desired cooling or air speed. For example, spaces requiring higher airspeeds and

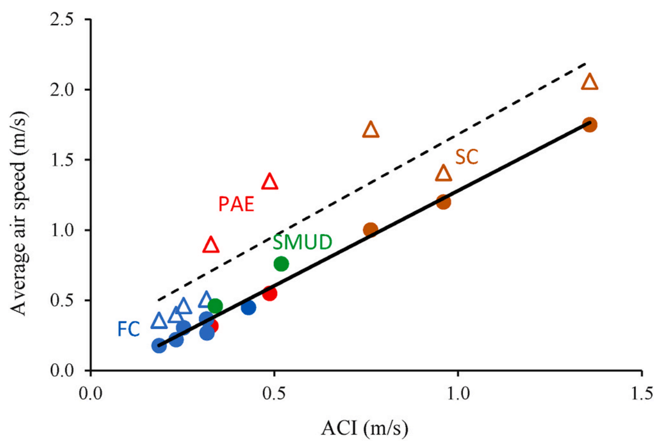


Fig. 7. Comparison of the predicted airspeeds (unfilled datapoints) and the measured airspeeds in real buildings (filled datapoints). The predicted air speeds were from the CBE fan design tool [26], assuming the tool prediction is accurate and the air movement reduction was mainly caused by furniture, and no other effects such as non-uniform room geometries and off-centered fans. Additional laboratory tests and field measurements are needed to validate and further generalize this finding.

stronger cooling effects should utilize ceiling fans with larger volumetric airflow rate, set a higher fan rotational speed, increase the fan density, or choose larger fan diameters. However, as well as the average cooling effect in the space, it is equally important to ensure that the distribution and uniformity of airspeeds within the space are appropriate for a given application [39].

3.4. *Effects of furniture and room configurations*

Considering the difference between laboratory measurement and the constraints and scenarios encountered in real buildings, the furniture and room configuration are two important aspects that should not be ignored when designing and operating ceiling fans. To fill this gap, we wanted to understand how furniture layout and room configurations affect air movement in real buildings. To do this, we compared our field measurements with predictions from the simple linear models in the CBE fan tool [26] that were developed from laboratory tests in simplified settings. Fig. 6 shows an overestimation of air speeds by the model. The lower measured air speeds are likely due to furniture and room configurations (e.g. non-square floor plans, off-centered fans, or multiple fans) that do not match the simplified lab conditions used for model development (e.g. fan centered in a square room, without furniture or other obstructions in the airflow path). Table 4 extends this analysis by considering the different furniture densities (the ratio of area occupied by furniture and the total floor area) of the four buildings. Although the sample size is small, there appears to be a negative linear relationship between furniture density and air speed in the occupied zone. For lightly furnished spaces (e.g. FC building) the air speed reduction is less than 0.2 m/s. But for densely furnished spaces like the seminar room in SC building and office room in PAE building, the air speed reduction

Table 4
The relationship between furniture area percentage and the air speed difference.

	Percentage of furniture area in plan view	Difference between the predicted airspeeds and the measured airspeeds (m/s)
PAE building	31.5%	0.67
SC building	24%	0.41
FC building	12.5%	0.18

increased up to 0.4–0.7 m/s. This suggests that furniture in real buildings lowers the air movement in occupied zone by impeding the path of air movement[2].

In addition to a reduction in average air speed across the space, furniture also affects the vertical profile of air speeds. There were several measurement sites in the FC building where the distance between fans were the same, but some were without furniture and some had a table about 0.2 *m* away (see the note in Fig. 8). Fig. 8 compares the average air speed of those sites with and without the table at four heights. Air speed measurements show that the table blocked downward-moving air from the ceiling fan. At heights above the table, the sites with furniture ware approximately 0.05–0.1 m/s faster than the site without furniture. However, there was a decrease at the ankle height (0.1 *m*) from 0.89 m/s to 0.65 m/s (27%) when furniture was present.

3.5. *Maximizing the percentage of desired air speed ranges*

In real buildings, it is not always true that the higher air speed the better. To this end, it is necessary to investigate the capability of the ceiling fans to provide desired air speed range.

Fig. 9 shows the air speed contours across the floorplate for the tests in FC building. We classified air speed distributions into low (<0.3 m/s; <1.4 °C cooling effect), medium (0.3–1.2 m/s; 1.4–3.4 °C cooling effect), and high (>1.2 m/s; >3.4 °C cooling effect.) ranges to help summarize the results. These ranges were used to calculate the area and volume percentages of air speeds which are shown inset. Turning on all 26 ceiling fans at higher rotational speed (level 4, 95 rpm) did not cause excessive (‘high’) air speeds. Most of the floor area (88%) and space volume (73%) in the activity space (second row in Fig. 9) are within the medium range of air speeds. It is slightly lower for the dining space, where 77% for the floor area and 61% for the space volume (fourth row in Fig. 9) are medium range air speeds. Among the reasons, one is the increased furniture density in the dining space. Reducing the number of operating fans significantly increased the percentage of low range air speeds for both the activity and dining spaces.

To maximizing the percentage of desired air speed, one can refer to the relationship between the mean air speed and the ACI shown in Fig. 7.

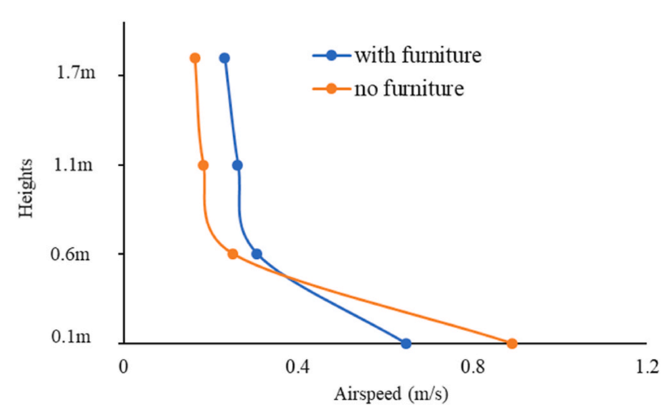


Fig. 8. Vertical air speed distribution comparison before and after removing the furniture. The air speeds with furniture are from sites 9–6 and 10–6 in activity area in FC building with one third of fans operating at 95 rpm. The air speed with no furniture are from sites 37–0 and 45–0 in the two fans interaction test of case 1. Sites 9–6 and 37–0, 10–6 and 45–0 are identical, respectively.

[2] Because the CBE ceiling fan design tool [26] cannot fully reproduce all the real measured conditions (due to a lack of rated fan airflows for fans operating in the upwards direction), the number of unfilled points is less than the filled points.

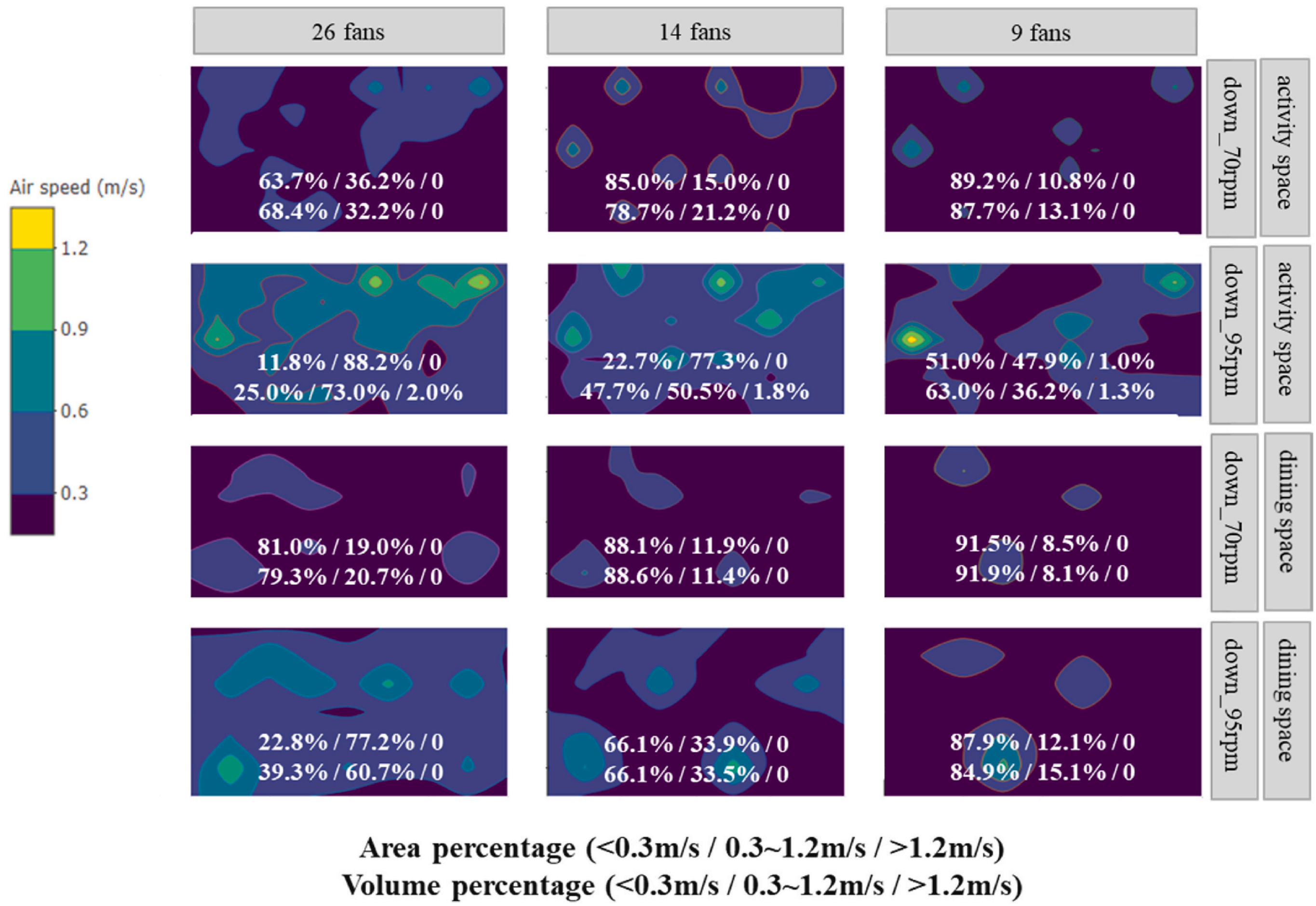


Fig. 9. The area and volume percentages of three air speed ranges in FC building for the activity and dining spaces separately. Each background graph represents the floor plan air speed contour for a test condition. The area percentage was calculated as the percent of sites with air speeds fall in a specific range. The volume percentage considered the four heights at each site.

By choosing or adjusting ACI values, one can get favorable air speed range in the space.

3.6. Multiple fan interactions

When operating multiple ceiling fans simultaneously, the airflow field from each fan may interact with each other. These interactions may affect the room air speed magnitude and its distribution, but are largely

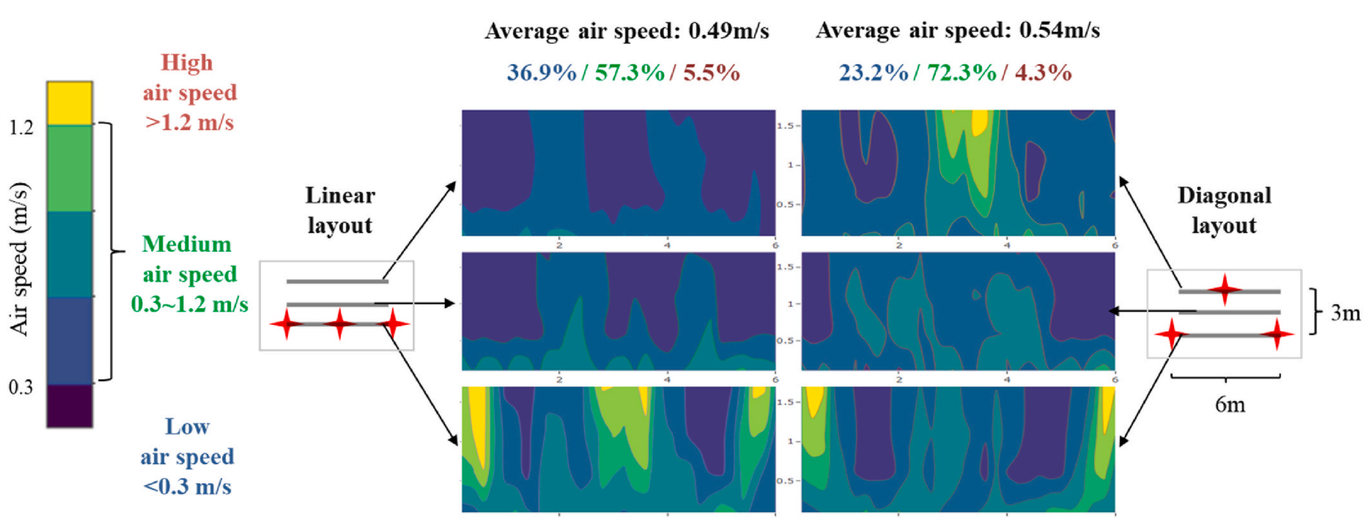


Fig. 10. Three 1.5 *m* diameter fan interactions. The three grey lines represent the three measurement sections where the air speeds were measured horizontally every 0.2 *m* distance and vertically at 0.1, 0.6, 1.1, and 1.7 *m*. The average air speed values are the average of the three sections. The percentage of the air speed ranges were the area percentage over the three sections.

determined by the layout of ceiling fans. There is a large distance between the walls and ceiling fans in the center of the room in the FC building. This generous floor area means that walls do not impinge upon air flow profiles of the ceiling fans. We could therefore explore 2-fan and 3-fan interactions independent of wall boundary effects. Here we report only the 3-fan interactions; details on the 2-fan interactions can be found in the Supplementary Materials file. Fig. 10 shows three vertical sections of air speed contours when the three fans were arranged linearly (left figure) or diagonally (right figure) over the same floor area. A diagonal layout had a larger share of air speeds within the medium range (72% compared to 57%, see the values on top of the figure) and more uniform air speed distribution than the linear layout.

3.7. Interior surface convection effects

Along with providing cooling for occupants, increasing air speeds within a space will also increase the convective heat transfer from interior surfaces. Fig. 11 shows a side-by-side comparison of surface temperatures when the HVAC was operating in cooling mode to maintain an ambient temperature of 22 °C. Thirty minutes after switching on the ceiling fan, the average surface temperature of the wall in the image decreased 0.8 °C compared to the surface temperatures when the ceiling fan was off. This is due to the increased convective heat transfer from elevated air movement bringing the surface temperature and the air temperature closer. This at least temporarily increases the cooling load on the HVAC equipment, and also further cools the occupants than is apparent from a comparison of air temperatures and air speeds alone For an all-air system in cooling mode, the mean radiant temperature (MRT) is usually higher than air temperature because surfaces absorb and store radiative heat and then emit it into the indoor air volume. Ceiling fans decreases MRT but increases the cooling load of HVAC systems due to the increased convective heat transfer from walls. This same effect is can be advantageous for radiant cooling systems, where MRT is usually near or slightly below the air temperature. Using ceiling fans in a space conditioned by radiant systems increases the heat transfer between the radiant surface and the occupied space, thereby increasing the thermal efficacy and capacity of the radiant system.

It is worth noting that the increased convection from ceiling fans also increases the heat transfer through the building envelope. This is less relevant for buildings using modern construction techniques as the interior convection heat transfer coefficient is a very small fraction of the overall thermal resistance, but it may significantly increase heat transfer in older buildings with poorly insulated envelopes, particularly single-pane windows. For example, the increased convective heat transfer coefficient caused by a fan on the inside surface of a single-pane window could cause a substantial increase in total heat transfer coefficient between the room and the outdoors. Similarly, ceiling fans can substantially increase infiltration between a space and the outdoors, especially if there are open exterior windows or doors.

3.8. Acoustics

Changes to the mode or the number of operating fans will affect the acoustics of a space. This may be an important consideration when using ceiling fans in the design of an office space. We used a SoundTrack LxT sound level meter (class 1) to measure A-weighted sound pressure level (Leq in dB(A)) across the floorplate of the SC and FC buildings under different ceiling fan operating conditions. The measurement procedure followed the 'Basic' level of acoustic measurements outlined in Performance Measurement Protocols for Commercial Buildings (PMP) guidelines [40].

Summaries of sound pressure level in Table 5 shows that the seminar

Table 5
Measured ceiling fan noise in SC and FC buildings.

SC building (seminar room)		FC building (community center)	
Fan condition	Noise level (dB(A))	Fan condition	Noise level (dB(A))
All fan off (background)	28	All fan off (background)	43
4 Essence fans, downward, ~155 rpm	60	26 Haiku fans, downward, ~95 rpm	49
4 Essence fans, downward, ~87 rpm	42	26 Haiku fans, downward, ~70 rpm	45
2 Essence fans, downward, ~155 rpm	55	26 Haiku fans, downward, ~45 rpm	44
2 Essence fans, downward, ~84 rpm	38		
4 Essence fans, upward, ~156 rpm	60		
4 Essence fans, upward, ~84 rpm	51		
2 Essence fans, upward, ~156 rpm	54		

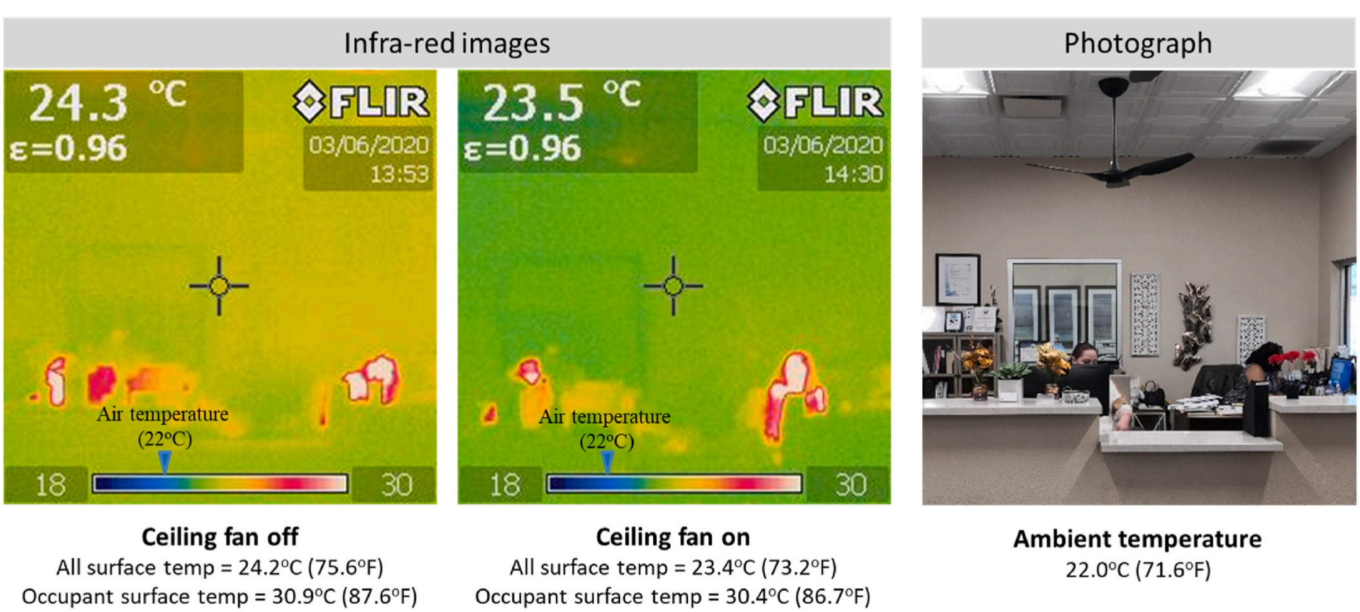


Fig. 11. Side by side IR images of surface temperature comparison in ~30 min in an office room, Franco Community Center, Stockton, CA.

room in SC building has background sound level of 28 dB(A) while that of the community center of FC building is 43 dB(A). Noise levels caused by ceiling fans depend on fan type and fan rotational speed. The larger Essence fan, has a higher airflow and maximum fan air speed) than the Haiku fan under the tested conditions, and measured noise levels were correspondingly higher in these spaces. Increasing the fan rotational speeds and the number of operating fans also leads to higher noise levels but changing the fan operating direction doesn't notably change the noise level, which can be seen from the downward/upward fan conditions in SC building. In FC, operating 26 Haiku fans at 45, 70, and 95 rpm only added 1, 2, and 6 dB(A) to the background noise level. With measured sound levels ranged from 44–49 dB(A), they are within the PMP recommended range (35–45 dB(A) for open offices without sound masking, 40–50 dB(A) for corridors and lobbies) [34].

4. Conclusions

This study investigates how ceiling fans work in four real buildings with different space types, ceiling fan types, numbers of operating fans, direction of operation, room geometry (size, shape and location of the fans), and furniture density. They are some of the many factors influencing the air speeds yielded by ceiling fans in real buildings. Downward operating ceiling fans have higher air speeds and stronger cooling effects; upward operating fans have better uniformity of air speed distribution, horizontally and vertically, but with significantly lower air speeds, and fans will consume more power to generate a comparable air speed.

The results show that the airspeed coverage index (ACI), which considers multiple influencing factors simultaneously, can be applied to predict the average air speed and cooling effects very well (with regression confidence higher than 0.95) for the studied test conditions in these four buildings. The ACI allows designers to decide fan operating speed, density, or diameters based on the target cooling temperature. In combination with other existing tools, this information can be used by designers to improve a priori estimated airspeeds in a space. To maximizing the percentage of desired air speed, one can refer to the relationship between the mean air speed and the ACI. By choosing or adjusting ACI values, one can get a favorable air speed range in the space.

Previous laboratory studies have reported the linear relationship between ceiling fan rotational speed and the air speed across the measured sites. This study validated this in real spaces over a wide range of operating conditions. The comparison between measured air speeds in real spaces to values output from the simplified models underlying the CBE Fan tool demonstrates that furniture, and other characteristics of real buildings (e.g. non-square rooms, off-center fans, other obstructions to airflow, etc.) tend to lower the average air speed in space. The higher percentage of furniture area, the stronger this effect appears to be. The CBE Fan tool will be updated to allow users to approximately account for this effect.

The layout of ceiling fans can influence the magnitude and uniformity of air speeds in a space. Evenly placing fans over a given area will produce higher average airspeeds and more uniform distribution, as will larger diameter fans, or more fans serving the same area.

Author contribution clarification

Raftery, Zhang, and Luo conceived the study; Luo, Lin, Zhang, He, and Elaina conducted the field measurements; Luo did the data analysis; Zhang, Raftery, Parkinson, and Arens guided and interpreted the analysis; Luo drafted the manuscript; Raftery, Zhang, and Parkinson revised the manuscript; Raftery, Zhang, and Parkinson finalized the reviewing and approved the final manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2021.107979.

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