Title

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Cooling energy savings and occupant feedback in a two year retrofit evaluation of 99 automated ceiling fans staged with air conditioning

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ABSTRACT

Controlled air movement is an effective strategy for maintaining occupant comfort while reducing energy consumption, since comfort at moderately warmer temperatures requires less space cooling. Modern ceiling fans provide a 2–4 °C cooling effect at power consumption comparable to LED lightbulbs (2–30 W) with gentle air speeds (0.5–1 m/s). However, very limited design guidance and performance data are available for using ceiling fans and air conditioning together, especially in commercial buildings. We present results from a 29-month field study of 99 automated ceiling fans and 12 thermostats installed in ten air-conditioned buildings in a hot/dry climate in California. Staging ceiling fans to automatically cool before, and then operate together with air conditioning enabled raising air conditioning cooling temperature setpoints in most zones, with overall positive occupant interview and survey responses. Overall measured cooling season (April– October) compressor energy savings were 36%, normalized by floor area served (41% during summer peak billing hours). Weather-normalized changes in zone energy use varied from 24% increase to 73% decrease across 13 compressors, reflecting variation in occupant schedules and other uncontrolled factors in occupied buildings. Median weather-normalized energy savings per compressor were 21%. Staging ceiling fans and air conditioning provided comfort across a wider temperature range, using less energy, than air conditioning alone.

1. Introduction

Buildings account for about 40% of US energy consumption [55] and when accounting for emissions from power generation, building energy consumption represents over one-quarter of global CO_2 emissions from fossil fuels [12]. Approximately a third to half of this energy is used to heat, cool, and ventilate buildings [56–57]. Global demand for and energy consumption from cooling is expected to grow dramatically with population growth, increased customer purchasing power, and increasing temperatures, particularly in the tropics (International Energy Agency, 2018). Accordingly, building design and operation strategies to reduce carbon emissions from cooling are a critical part of global climate mitigation and adaptation efforts [33].

One significant method for reducing cooling energy use while maintaining occupant comfort is the use of air movement, as demonstrated by decades of research [5,31]. Modern ceiling, standing, and desk fans with direct current motors can provide several degrees of cooling effect with air movement using comparable energy to an LED light bulb, using<10 W at medium speeds [13,20]. Past analysis by Arens et al. [5], as well as more recent analysis using the ASHRAE Thermal Comfort Database II [19]shows that many (40%) occupants indicate a preference for more air movement under neutral conditions, and the majority (59%) prefer more air movement when conditions are at least ‘slightly warm’ (See Supporting Information, Figure S1). Previous laboratory studies, simulation studies, and field studies have consistently demonstrated reductions in cooling energy consumption when air

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movement enables higher air conditioner cooling setpoints [7,11,22,31,46,49,51]. In addition, air movement can also improve perceived air quality [6], and reduce accumulated exhaled CO_2 levels at the breathing zone [39].

In some applications and climate zones, air movement with fans (potentially combined with natural ventilation) can provide all required comfort cooling. To meet higher cooling loads, ceiling fans can be staged to automatically cool before, and then operate together with air conditioning. While the majority of US homes have at least one ceiling fan — over 80% of single family homes and over 40% of apartments [58]— previous self-reported surveys [27] and field study measurements [26]; RLW [47]found the majority of residents with both ceiling fans and air conditioning did not increase thermostat setpoints to take advantage of the cooling effect provided by the fans. Realizing the full energy savings potential of staged operation requires sequencing fans to operate first, and then continuing to operate the fans together with air conditioning to reduce the intensity and/or duration of air conditioning power consumption while maintaining comfort.

Fans are less common in US commercial buildings than residential buildings today, and are not tracked in the US Commercial Buildings Energy Consumption Survey [59]. Historically, engineering design standards prescribed low levels of indoor air movement to avoid drafts when people are cool. However, elevated air movement indoors is now permitted by standards and voluntary certification programs under neutral or warm conditions, where it can provide increased granularity of control and contribute to low-energy operation. The thermal comfort design standard from the American Society of Heating, Refrigeration, and Air-conditioning Engineers (ASHRAE) explicitly allows design with elevated air speeds in warm conditions, and higher air speeds according to the PMV + SET thermal comfort model when occupants have elevated metabolic rates or can personally control the level of air movement [8]. European standard EN 15,251 similarly allows for elevated air movement [16]. Both LEED and WELL standards also award points for personal comfort devices, which include desk fans [25,60]. A small but growing number of new and retrofit buildings are designed to operate with both ceiling fans and air conditioning, including numerous low energy and net zero energy projects (for examples see Present et al. [42].

The objective of this field study was to evaluate the retrofit impact of staging automated ceiling fans and air conditioning in operating buildings, and to better understand human and building factors that impact energy savings in practice. Our hypothesis was that air movement from ceiling fans would keep occupants comfortable at higher temperatures, so they would operate their air conditioning at higher cooling setpoints, or less frequently, over the cooling season. In this paper, we 1) Describe field study methods, ceiling fan controls, and a novel dataset from continuous measurement of air conditioning compressor power and indoor environmental conditions; 2) Report the results of data analysis examining the relationship between indoor air temperature and energy savings, as well as occupant surveys and interviews; and 3) Summarize recommendations for staging ceiling fans and air conditioning as a building design, retrofit, or control strategy. To our knowledge this paper represents the first multi-year evaluation of occupant experience and energy use with sequenced ceiling fans and air conditioning installed as a retrofit in commercial and residential buildings in the US. Numerous previous air movement studies investigated occupant comfort using air movement from personally-controlled standing fans or desk fans in an environmental chamber, as in Schiavon et al. [50] and as reviewed in Zhang et al. [68]. Previous studies have also investigated ceiling fans in laboratory conditions or during shorter interventions, such as in an environmental chamber [40,67,65], and over a six-week period in an open-plan office [31].

2. Methods

2.1. Field study timeline and sites

We conducted the field study July 2017–October 2019 at four low-income housing sites between Stockton and Fresno, California, on a total of 14 HVAC compressors including six multifamily housing units (Residential) and eight compressors serving offices, community rooms, and computer rooms (Commercial) as Table 1 summarizes. Additional information is available about the characteristics of each site in the supplementary material and also the final project report [44]). All sites were located in disadvantaged communities in California (defined as CalEnviroScreen score $\geq$ 75%) [14]. Sites were selected from a limited number of sites owned and operated by project partner organizations. Project partner organizations were required to be selected at the research proposal writing stage, when limited site information was available. Once the project was awarded, we selected specific demonstration sites based on the following criteria: no additional planned renovations during the study period, existing air conditioning controlled by thermostats, regularly-occupied spaces over 93 m^2 (1000 ft^2), and lighting systems compatible with ceiling fan installation. During site selection, information was not available to prioritize spaces with higher cooling energy consumption for retrofit given the constraints involved. Climate characteristics of the sites can be described as hot, dry summers and cool winters, and can be labeled in terms of Köppen climate zone classifications Csa (Mediterranean/hot summer) and BWk (Semi-arid steppe) (Eric [15]; California climate zone classifications 12 and 13 (California Energy [10]; and ASHRAE climate zone classification 3B (hot/dry) (Pacific Northwest National [38].

2.2. Site descriptions

2.2.1. Buildings and occupants

Site 1 was on the first floor of a five-story building (8, 300 m^2) renovated in 200 7, with no verifiable insulation. The studied zones (C1, C2) on the first floor were primarily open pl an, with a central open-plan community room, and enclosed office and storage spaces at both the perimeter and core. All sides of the first floor had exterior overhang shading. Typical occupancy in the two enclosed offices consisted of one and three individuals respectively during business hours. Occupancy in the community room varied by time of day, ranging from unoccupied to over 50 occupants during scheduled activities.

At sites 2–4, offices and community rooms were in single-story buildings with central community rooms and adjoining enclosed perimeter offices with covered patios on one side, with a $\geq$ 0.3 m shading overhang on all sides. Typical occupancy in the offices was one to two people during business hours, with multiple children and an additional adult in computer rooms during after-school programs, and more occupants during infrequent events booked in the community room during weekends or evenings.

The six multifamily residential units at site 4 were two-bedroom (one story) or three-bedroom (two story) townhouse units with two or more occupants that shared an adjacent wall with at least one other unit, and had exterior overhang shading.

For each of the six residential units, the head of household signed a consent form outlining requirements and benefits of study participation. Households received two $100 gift cards as compensation for participating in the installation and study. For the four office sites, informed consent forms were signed by representatives of the respective property managers. Office sites did not receive any financial compensation f or study participation.

Table 1
Description of retrofit sites, totaling 14 HVAC compressors across four sites.

Site	Built [y]	Construction type	Operable windows	Interior blinds	Glazing	Site type	Compressors	Zone area [m^2]	Zone type	Occupancy type	HVAC system	Compressor cooling capacity [kW]	Total # ceiling fans installed
1	1967	Concrete masonry	No	No	2-pane	Commercial	C1	560	Community room and offices	Regular	Variable refrigerant flow	42	35
							C2			Regular		42	
2	2004	Stucco, wood framing	No	Yes	2-pane		C3	136	Community	Infrequent	Condensing units and furnaces	18	10
							C4	91	Office/computer	Regular		11	3
3	2009	Stucco, wood framing	Yes	Yes	2-pane		C5	107	Office/computer	Regular		12	4
							C6	122	Community	Infrequent		18	3
4	2009	Stucco, wood framing	Yes	Yes	2-pane		C7	107	Office/computer	Regular		12	5
							C8	122	Community	Infrequent		18	3
	2009	Stucco, wood framing	Yes	Yes	2-pane	Residential	R1, R2. R3	80	1-story townhouse	Regular		5	15 (5 per home)
							R4, R5, R6	120	2-story townhouse	Regular		7	21 (7 per home)

2.2.2. HVAC systems

At Site 1, the whole building had a variable refrigerant flow (VRF) overhead air distribution system, served by six rooftop compressors conditioning refrigerant for 24 fan coil units. Two compressors served the zones monitored in this study, and were connected to nine fan coil units via a VRF manifold that allows for simultaneous heating and cooling. The study area had six programmable thermostats (model

PAR-U01MEDU-K, Mitsubishi). At sites 2, 3, and 4, community buildings had two zones with separate programmable thermostats served by two condensing air conditioning units and two fan coils. The two zones served 1) community room, kitchen, and storage spaces, and 2) offices, computer room, and entry lobby respectively. Residential units had single-zone systems served by one compressor per unit. For sites 2–4 the existing programmable thermostats prior to replacement during the retrofit were LUX model TX1500E (Site 2), SimpleComfort 3001 (Site 3), Emerson Blue (Site 4), and an unknown model at the site 4 residential units.

2.3. Energy-efficient ceiling fans with automatic temperature- and occupancy-based control

The automated ceiling fans installed in this study (Haiku series, Big Ass Fans) are one of multiple quiet, low-power models with four or more speeds available from commercial vendors with brushless direct current motors (Aerotron [1,13], Hunter [23]. Such fans use approximately a third or less power than older alternating current motor fan models in typical operation [52]. Rated minimum and maximum fan power consumption for fan models in this field study ranged from 2 to 20 W for the 1.32 diameter model to 4–53 W for the 2.13 m diameter model[1]. Fans installed where there were previously light fixtures also had an integrated dimmable LED light (16 W).

The installed fans operated automatically based on infrared sensors on the fan hub measuring temperature and occupancy. We configured fans to operate when spaces where occupied and had temperatures above an adjustable temperature setpoint initially set to 23.3 °C (74.0 °F), as shown in Fig. 2. Above this fan cooling setpoint, fan speed increased linearly with temperature up to an adjustable maximum automatic fan speed (level 5 of 7). Fans were also programmed to turn off after 10 min without detecting occupancy, and for all fans belonging to designated groups (e.g. all six fans assigned to the 'Activity Area' group in the community room at Site 1) to operate in unison. We additionally developed and implemented a new 'learning' feature that gradually adjusted fan cooling setpoint temperatures based on occupant adjustment, so fans would operate at higher or lower speeds (including stopping entirely) at the same temperature if occupants repeatedly adjusted them up or down respectively under similar conditions. At all times, occupants could also manually override the automatic behavior and adjust fan speed or turn the fans off by using provided handheld remotes or a free smartphone app (Haiku Home).

2.4. Baseline data collection

The field study began with one year of baseline data collection from July 2017–June 2018, as summarized in Fig. 3. Hamilton dataloggers and border routers (model H3C and HG1, Hamilton IoT) measuring temperature, relative humidity, and light [4] were installed at each site and space type. Power meters (PowerScout 3037, Dent Instruments) were installed along with current transformers (MCT- 0016–020 and MCT-0016–050, Magnelab) and sig-

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[1] The consumption of the 1.52 m diameter fan is between these two models at 2–32 W

Fig. 1. Field study sites, showing building exteriors and interiors (after ceiling fan installation).

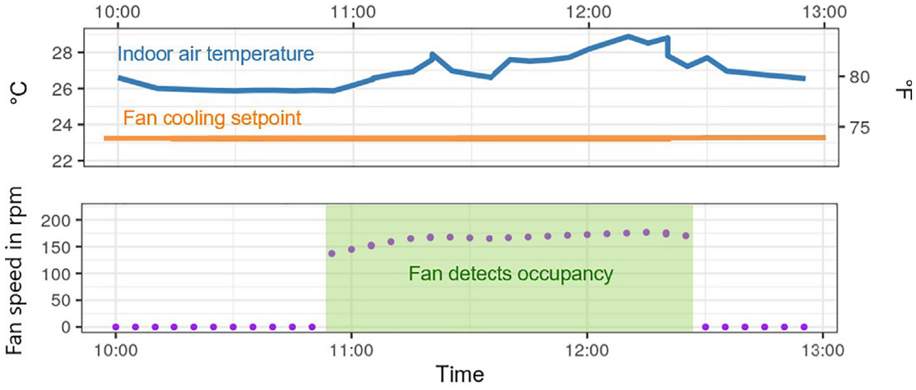

Fig. 2. Sensor data from one field study fan demonstrating temperature- and occupancy-based operation. Field study ceiling fans operated when adjusted manually by occupants, or automatically only when both detecting occu-pancy and air temperatures above the fan's cooling setpoint.

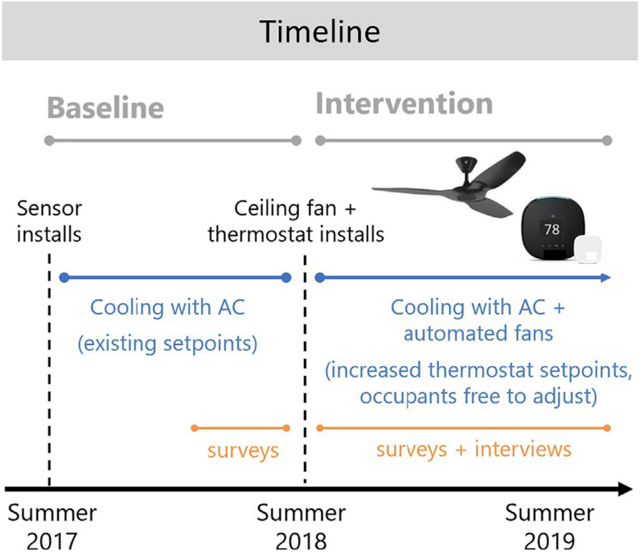

Fig. 3. Field study timeline indicating baseline (pre-retrofit) and intervention (post-retrofit) periods.

nal converters (Flexsmart TRMS, Onset) to measure current draw from compressors and fan coils (blower fans). Power meters and current transformers were connected to data loggers (Hobo U30, Onset) for data storage and wireless data transmission via a cell modem (Jetpack MiFi 7730L, Verizon) and net extender (Netgear AC1900). No changes to building operation were made or suggested by the experimenters during the baseline monitoring period.

3.4. Retrofit

During June–July 2018, 99 ceiling fans (58 × 1.32 m diameter, 37 × 1.52 m diameter, 4 × 2.13 m diameter) were installed within each of the selected HVAC zones. , Fig. 1 shows several example images of the exterior and interior of the four sites. In smaller rooms such as offices and bedrooms one to two ceiling fans were installed per room, whereas as many as twenty 1.52 m diameter fans or two 2.13 m diameter fans were installed in larger rooms. Fan layouts at each site were determined based on an average target air movement level of up to 0.76 m/s (150 feet per minute), with computational fluid dynamic modeling provided by Big Ass Fans, and subject to site-specific considerations such as light fixture, diffuser, and sprinkler ceiling placement. Since this field study aimed to evaluate as uniform levels of air movement as possible, we did not reduce the number of fans in order to minimize first cost. Floor plans of each site are in Supplemental Information S8-S13.

Automated ceiling fans were programmed as described above. At sites 2, 3, and 4, the existing programmable thermostats were replaced by programmable connected thermostats (ecobee4, ecobee). Thermostats were not replaced at Site 1 due to the vendor thermostats required for compatibility with the VRF system.

2.5.1. Thermostat settings and educational outreach

With consent of participants, office air conditioning cooling setpoints were either directly raised to 25.6 °C (78.0 °F) after fans were installed (Site 2), or initially raised to 23.3 °C (74.0 °F), and then increased weekly to 24.4 °C (76.0 °F), and then 25.6 °C (78.0 °F) over the following two weeks. At all times, occupants were free to make any desired adjustments to thermostat settings. The energy benefits of staging fan and air conditioning operation were discussed with occupants, who also received printed materials explaining fan and thermostat operation. Participants in residential units were similarly encouraged to set their thermostat cooling setpoints 25.6 °C (78.0 °F) upon fan install (on an opt-out basis), could adjust thermostats as desired, and received verbal and printed English and Spanish materials on ceiling fan and thermostat operation, including how to temporarily or permanently adjust thermostat setpoints. All educational materials are included in Supplemental Information S14-S20.

2.6. Monitoring period

Intervention period data collection continued from July 2018–October 2019. This covered two cooling seasons, which we defined as the months of April to October based on local weather data. We conducted occupant interviews at all sites, and also administered brief paper-based surveys (described in section 2.7.2 below). For the first year of data collection, the ceiling fans operated based on a new firmware version developed for this study. After the first year of data collection, each site was visited in May 2019 to update and standardize thermostat and ceiling fan settings and install a firmware update. At the end of the study period, ceiling fans and thermostats remained in operation at all sites, and all equipment to measure electricity consumption and transmit sensor data was removed.

2.7. Collected datasets

2.7.1. Indoor environmental quality, compressor power, ceiling fan, and thermostat data

At all sites throughout both the baseline and intervention periods we continuously measured HVAC system fan and compressor electrical power consumption using dedicated power meters at 5 min intervals. We also installed instruments to measure indoor temperature, humidity and light levels, typically at multiple locations within each zone, at 20 s intervals. Additionally, we downloaded data for outdoor conditions from the nearest weather stations at 1 h intervals. During the intervention period we continuously acquired data from the automated ceiling fans themselves (e.g., measured occupancy, temperature, and humidity; operating speed, cooling setpoint, and other fan settings) and the thermostats (e.g., measured temperature at the thermostat and remote sensor, occupancy; HVAC state; heating and cooling setpoints, and other thermostat settings), both at 5 min intervals. The Supplemental Information (section S5) contains more detail for each of these datasets, including the instruments used and associated accuracy.

2.7.2. Occupant surveys and interviews

Surveys were primarily administered at Site 1 due to small numbers of adult occupants in other zones. Short (<10 min) paper-based surveys were administered in the offices and community room at Site 1 before (July 2018) and after (September 2018, July 2019) ceiling fan operation. Surveys recorded occupants' self- reported demographic information and thermal comfort preferences (background survey), as well as real- time comfort perception (point-in-time survey). All participants were required to be in the space under investigation for at least 20 min before filling out the survey, and were compensated $5 per survey. Brief surveys were also collected from Site 3 office workers and residential unit owners prior to ceiling fan installation. See S19-S21 for survey questions.

Office staff were interviewed by phone between October 2018-January 2019 (three sites) and again by phone in November 2019 (four sites) in English. Residents at five out of six units were interviewed in person at their homes in May 2018 and by phone in November 2019 in Spanish or English. Interviews followed a semi-structured format, were recorded, transcribed, and translated to English where applicable, and included questions about comfort, perceptions of and experiences with the ceiling fans and thermostats, and any questions or recommendations to improve this system. Interviews were 20–30 min. Participants were compensated $50 per interview, with an additional $50 payment to residential occupants at the end of the field study. The UC Berkeley Committee for the Protection of Human Subjects (IRB-2017–12-10564) reviewed and approved the research protocol.

2.8. Analysis plan and software methods

We wrote an analysis plan for our primary hypothesis prior to data analysis, available in Supplemental Information S25. Jetstream [53,54] provided cloud compute resources. For all data analysis, we used the open source R statistical computing language (version 3.6.2) [45] with RStudio (version 1.2.5033) with tidyverse [61] software. We used additional software packages cowplot [62] and patchwork [41] for graphics, gt [24] for tables, here [35] for file p ath m anagement, s parklyr ([32] and aws.s3 [29] to acquire data, caret [28] and segmented [34] for model fitting, grateful [48] for software citation, rmarkdown [3] for interactive notebooks, and knitr [63], rticles [2], and bookdown [64] to create a journal-formatted PDF.

2.9. Weather normalization

Outdoor temperatures during the intervention period were warmer than during the baseline period. We normalized savings data using both breakpoint regression and random forest model methods. We fit individual models for each compressor during the baseline period, then used them to predict power consumption during the intervention period. As presented in Results Section 3.5.2, we report weather-normalized energy savings as the difference between the predicted and observed intervention period power consumption, and report overall weather-normalized savings as the average of savings estimated from each model.

The breakpoint (or 'piecewise linear') regression model used outdoor air temperature to fit a linear model for power consumption above a specific temperature ('breakpoint'); linear models and breakpoints were computed using the segmented package, constrained to have only one breakpoint, optimized from an initial suggested value of 20 °C, and zero gradient prior. Means from 40 iterations of model fitting with different random seeds were averaged since breakpoint estimation proved sensitive to initial random seed.

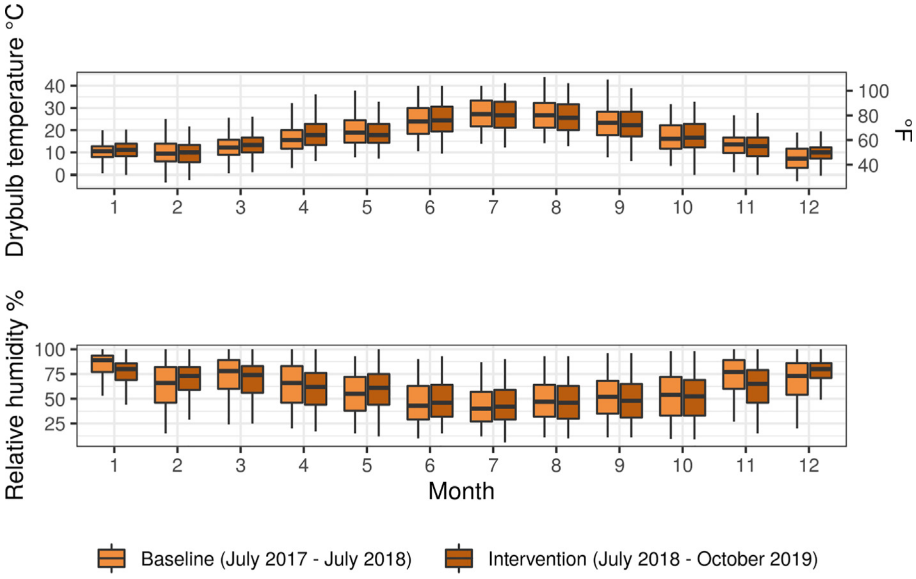

Fig. 4. Average outdoor air temperature and relative humidity across all three locations during field study period.

Table 2
Summary of outdoor weather conditions by site and field study period.

	Mean hourly air temperature (°C)			Mean hourly relative humidity (%)		
	Baseline	Intervention	Δ	Baseline	Intervention	Δ
Site 1	21.3	23.9	2.6	52.6	44	−8.6
Site 2	21.8	22	0.2	50	52.3	2.3
Site 3 and 4	22.4	22.7	0.2	51.8	50	−1.7

For the random forest model, five features (hourly outdoor air temperature, day of week, hour of day, daily mean hourly temperature, daily maximum hourly temperature) were used to predict hourly power consumption on 80% of the baseline period data (training subset), and then tested against the remaining 20% of the baseline period data (test subset). The rf implementation in caret package was used to perform computations, with 10-fold cross validation repeated thrice, and the default number of trees (500).

3. Results

3.1. Outdoor weather conditions

Fig. 4 summarizes the outdoor air temperature and humidity for the entire field study period. Measured temperatures and humidities were representative of this region's climate. During the cooling season (April–October), mean daily high temperatures ranged from 13.3 to 43.9 °C (56–111 °F). Cooling season mean hourly outdoor temperatures at all three locations were higher during the intervention period than the baseline period, with a mean increase of 0.8 °C (1.4 °F). During the intervention period, mean hourly relative humidity and absolute humidity decreased slightly at Sites 1, 3, and 4 compared to the baseline period, but increased at Site 2, as shown in Table 2 below.

3.2. Equipment usage

3.2.1. Compressors

We monitored a total of 14 HVAC compressors across 10 buildings for the duration of the field study[2]. A hardware issue prevented successful data collection in one residential unit (Zone R 3). All 13 compressors with data available operated during both the intervention and baseline periods. At Site 1, the two compressors did not operate from August 2018 – June 2019 due to a mechanical system fault; these hours are excluded from our analysis unless specified otherwise. During the baseline period, total compressor usage per zone varied almost 40-fold from only 3% of monitored hours (in infrequently occupied zone C8) to 88% (in C1, a large, regularly occupied zone without temperature setbacks). During the intervention period, zone C8 continued to have the least air conditioning runtime at only 1% of monitored hours, and C1 continued to operate most frequently at 69% of monitored hours, as shown in Fig. 5. Overall, median compressor runtime decreased from 36% of monitored hours during baseline period to 28% during the intervention period.

Real-time occupancy data was not measured during the baseline period; typical occupancy schedules were compiled based on site hours and occupant interviews. To reflect known variation in occupancy pat- terns (based on site schedules and occupant interviews), zones were classified as 1) Commercial – regularly occupied (e.g., offices with employees and regular working hours), 2) Commercial – infrequently and irregularly occupied (e.g., a common room only used for occasional reservations by residents), or 3) Residential.

3.2.2. Ceiling fans

Ceiling fans began operating between July 6–20, 2018 (varied by site) during the intervention period. Across all sites, the ceiling fans operated frequently, typically at low speeds, and used an average of 8.1 W of power per fan when operating, as shown in Fig. 6.

In commercial spaces across all temperatures, the automated ceiling fans operated the majority of occupied hours (81%), ranging from a minimum of 29% to a maximum of 96% of occupied hours

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[2] The six individual residential units were multifamily units in three buildings

Table 3
Indoor environmental conditions, hourly means from all sensors per zone.

	Indoor environmental conditions per zone					
	Hourly means, during April - October cooling period					
	Air temperature (°C)			Relative humidity (%)		
	Baseline	Intervention	Δ T	Baseline	Intervention	Δ RH
Commercial - regular occupancy						
C1+C2	21.2	25.9	4.6	50	56	6
C4	24.7	26.9	2.1	42	44	2
C7	23.7	24.8	1	45	47	3
Commercial - irregular occupancy						
C3	26	25.3	-0.7	39	47	8
C6	24.3	25.9	1.6	47	54	7
C8	23.4	24.4	1	47	53	7
Residential						
R1	24.1	25.9	1.8	47	51	5
R2	23.9	24.8	0.8	55	66	10
R3	23.7	24.9	1.2	55	65	10
R4	24.9	26.6	1.6	53	58	5
R5	25.2	25.9	0.7	49	57	8
R6	23.3	23.6	0.3	47	52	5

Data for C5 baseline period indoor temperature not available

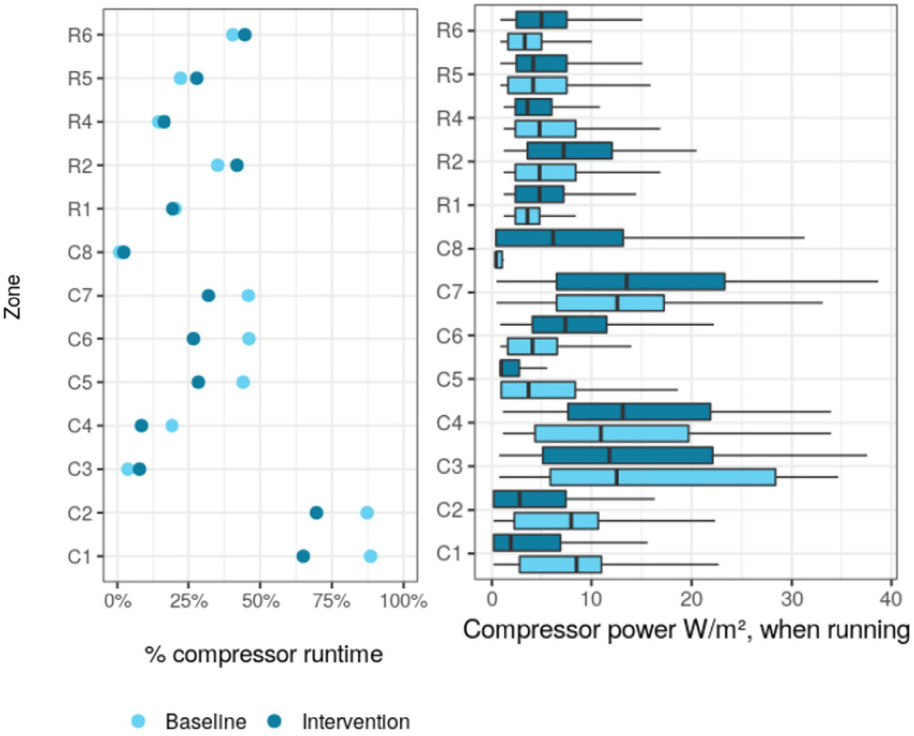

Fig. 5. Operation of all 13 compressors during April-October cooling seasons between July 2017 and October 2019. Left plot shows compressor runtime as percent of observations, right plot shows hourly compressor power consumption when running. All values are from measured data, not normalized for weather or changes in occupancy.

for fans in different locations. Variation in runtimes likely comes from variation in indoor temperatures (occupants are less likely to desire air movement at cooler temperatures) and variation in occupant preferences. In residential spaces across all temperatures, the fans operated about half (45%) of occupied hours, ranging from a minimum of 2% to a maximum of 83% of occupied hours for fans in different locations, with similar variation likely from indoor air temperatures, occupancy frequency, and occupant preferences.

Mean hourly speeds during operation for fans in commercial spaces and residential spaces were 56% and 42% of the maximum fan speed respectively. Mean hourly fan power consumption during operation for fans in commercial spaces and residential spaces were 9.0 W and 5.1 W respectively, less than one-third of maximum fan power. While occupants were free to adjust fan speeds across their entire range, about one-third of fans (30 devices) never operated above 80% of their maximum speed.

In residential spaces, the frequency of fan usage in different rooms varied more between households than between room types, demonstrating the significance of individual differences. On average, fans in residential living rooms and bedrooms operated for the greatest fraction of occupied hours (49% and 47% respectively), but this varied from 10% to 74% of occupied hours across households.

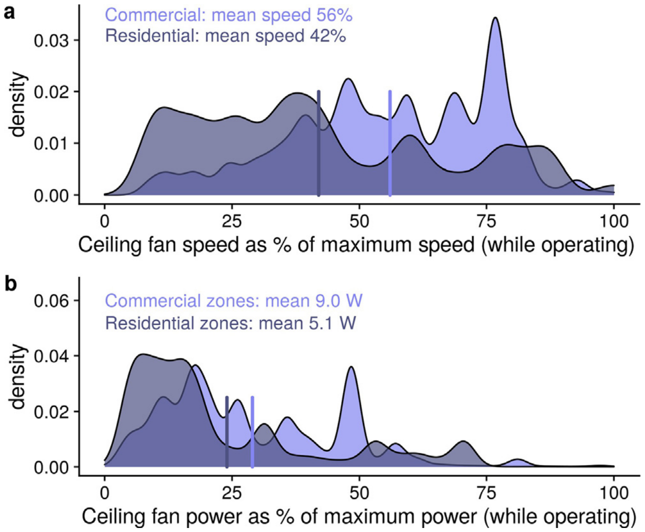

Fig. 6. Distribution of ceiling fan a) speed and b) power consumption while operating for all 99 fans (63 commercial and 36 residential). Solid lines on x-axis indicate mean values. Overall mean fan speed is 50 percent of maximum. Overall mean fan power is 8.1 W. Fan speed is measured in revolutions per minute (rpm). Maximum fan speeds are 200 rpm for 1.32 and 1.52 m diameter fans and 137 rpm for 2.13 m diameter fans. Maximum fan power is 20 W, 32 W, and 54 W for 1.32, 1.52, and 2.13 m diameter fans respectively. Measured data for July 2018 - Oct 2019, filtered for cooling season (April - Oct).

Over the course of the field study, 4 of the installed 99 ceiling fans appeared to encounter hardware or software issues though continued to operate. Two fans' temperature sensors consistently reported 0 °C while indoors but appeared to continue to operate normally, and for a short period two infrequently-used fans produced audible scraping noises when rotating, which resolved without intervention.

3.3. Indoor temperature

Consistent with observed increases in thermostat setpoints and higher outdoor temperatures during the intervention period, mean measured indoor air temperatures were higher in the intervention period compared to the baseline period, increasing by an average of 1.9 °C (3.4 °F) across all sites and all hours, as shown in Fig. 7 and summarized in Table 3 Mean differences in indoor temperature for each mechanical zone are shown in Table 4 below. Assuming 'still air' conditions during the Baseline period (air speeds < 0.05 m/s (10 rpm)), and air speeds up to 0.5 m/s (100 fpm) in the intervention period, the respective comfort temperature ranges estimated from ASHRAE Standard 55 with typical office conditions[3] are 22.2 °C (72 °F) - 25.6 °C (78 °F) and 22.2 °C (72 °F) - 28.3 °C (83 °F). Across all hours from all sites (including unoccupied hours), 32% were below and 22% were above the 'still air' comfort range during the Baseline period. The exceedance percentage reduced to 9% of hours below and 7% above the 'up to 0.5 m/s' estimated comfort range in the Intervention period with ceiling fans, and increased air conditioner cooling setpoints and thermostat deadbands in most zones.

3.4. Indoor humidity

Across all sites, mean measured indoor hourly relative humidity (RH) was higher in the intervention period compared to the baseline period, increasing by an average of 6 percentage points (2.6 g/m3 absolute humidity). Mean hourly humidity per zone ranged from 39 to 50 % RH (commercial zones) and 47 – 55 % RH (residential zones) in the baseline period to 44 – 56 % RH (commercial zones) and 51–66 % RH (residential zones) in the intervention period, which is within recommendations in ASHRAE Standard 62.1 for indoor air quality in commercial buildings for controlling relative humidity $\leq$ 65%. Measured relative humidity at all zones increased by more than sensor measurement precision (±2%) by

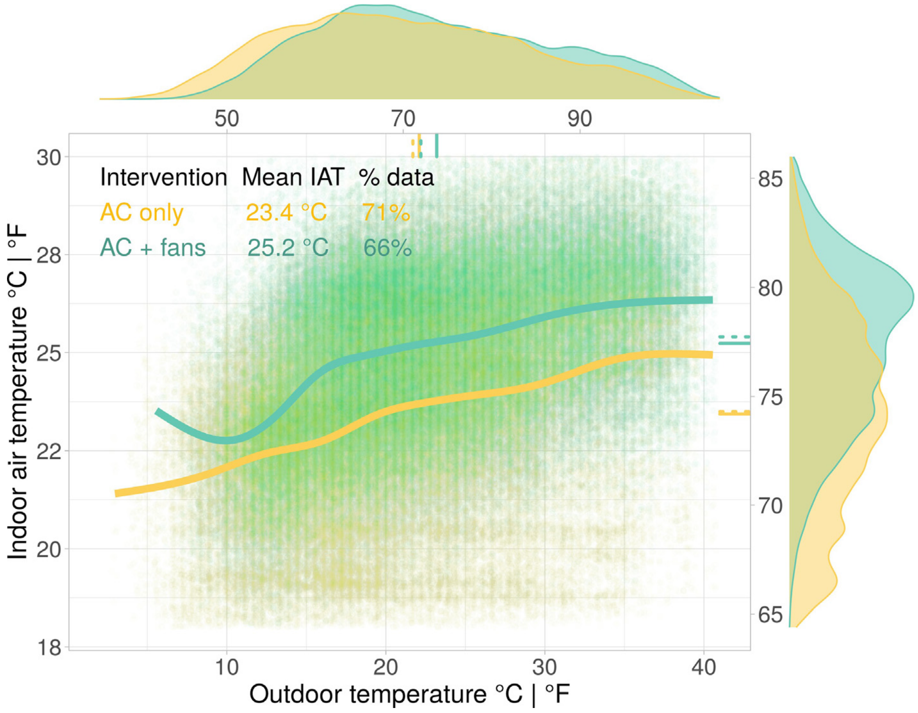

Fig. 7. Mean hourly indoor air temperatures, as measured by 32 sensors across 12 HVAC zones. Dashed lines on x and y axes represent medians, solid lines represent means. Total data collection from July 18, 2017 to October 31, 2019.

Table 4
Summary of measured and weather-normalized energy savings and estimated cost savings for all zones.

Measured compressor energy use and weather-normalized energy savings per zone

	Zone area [m²]	Measured compressor power Cooling season (April - Oct)		Measured compressor energy savings			Weather normalized energy savings	Mean zone temperature Cooling season (April - Oct)			Weather-normalized cost savings @ $0.19/kWh
		Baseline [W/m²]	Intervention [W/m²]	Whole year	Cooling season (April - Oct)	Peak cooling (June-Sept)	Cooling season (April - Oct)	Baseline [°C]	Intervention [°C]	Δ	Cooling season (April - Oct)
Commercial - regular occupancy											
C1	564	6.8	2.4	57%	65%	72%	70%	21.2	25.9	4.6	$3,100
C2	564	6.4	2.8	47%	56%	66%	62%	21.2	25.9	4.6	$2,600
C4	91	2.5	1.1	43%	54%	61%	57%	24.7	26.9	2.1	$130
C5	107	2.7	0.8	61%	69%	74%	67%	NA	NA	NA	$190
C7	107	5.9	4.7	7%	21%	15%	0%	23.7	24.8	1.0	$1
Commercial - irregular occupancy											
C3	136	0.7	1.1	−95%	−54%	−39%	−13%	26.0	25.3	−0.7	−$18
C6	122	2.4	2.2	−5%	8%	2%	9%	24.3	25.9	1.6	$26
C8	122	0.2	0.1	66%	71%	62%	73%	23.4	24.4	1.0	$23
Residential											
R1	83	0.9	1	−38%	−12%	8%	21%	24.1	25.9	1.8	$23
R2	83	2.2	3.4	−176%	−51%	−5%	0%	23.9	24.8	0.8	$6
R3	119	NA	NA	NA	NA	NA	NA	23.7	24.9	1.2	NA
R4	83	0.8	0.7	−10%	19%	55%	45%	24.9	26.6	1.6	$49
R5	119	1.2	1.5	−78%	−31%	20%	7%	25.2	25.9	0.7	$18
R6	119	1.5	2.5	−219%	−65%	−4%	−24%	23.3	23.6	0.3	−$52

the end of the intervention period, both in zones where indoor temperatures did not increase (C3), and in zones at sites where outdoor relative and absolute humidity decreased in the intervention period (Sites 1, 3, 4). Looking specifically at humidity changes within the first month of ceiling fan operation, six zones had RH increases comparable to their overall intervention period increase, suggesting that this reflects a change in building operation (all six zones also had increased indoor air temperatures), and not sensor drift. While sensor drift cannot be discounted given lack of calibration of humidity and temperature sensors, the observed increase in indoor humidity is also consistent with building materials gradually releasing moisture as expected at higher temperatures over weeks to months.

3.5. Cooling energy use

3.5.1. Measured compressor energy savings

Overall, the field demonstration resulted in 36% measured compressor energy savings during the April– October cooling season compared to baseline conditions, normalized for floor area, despite the warmer outdoor temperatures during the intervention period, as shown in Fig. 8. Since two of the 12 compressors served a variable refrigerant flow system providing both heating and cooling, it is expected to see some hours of runtime at lower temperatures. The size and energy consumption of a compressor correlates with floor area, and zone floor areas ranged from 83 to 564 m^2. As specified in the analysis plan, we present results normalized by floor area to prevent the larger sites having more of an impact on the percentage savings estimate. The percentage reduction in average power during the cooling season without normalizing by floor area was 62%. This value is higher than the value normalized by floor area since the majority of the savings come from the largest zones. At Site 1 (compressors C1 and C2), savings estimates are comparable using data from either before or after the HVAC equipment was repaired, so the HVAC failure was not a driver of the large energy savings. In addition, during the warmest months of June–September, overall measured savings normalized for floor area were slightly higher — 41% — during the hours (4 – 9pm) corresponding to recent peak Time-Of-Use electricity rates from regional utility Pacific Gas and Electric [36–37].

3.5.2. Weather-normalized energy savings

When weather-normalized due to warmer outdoor conditions during the intervention period, changes in cooling energy consumption per zone varied from a 24% increase to 73% savings, as shown in Fig. 9. Median savings per zone was 21%. This variability reflects diversity in buildings construction, mechanical systems, and prior operation settings for each zone as well as occupants' schedules and preferences.

All commercial spaces with regular occupancy schedules (as well as two irregularly-occupied commercial spaces, and one home) had measured energy savings on an absolute basis before normalizing for warmer intervention temperatures, and 9 of 13 compressorsshowed energy savings on a weather-normalized basis. Zones where occupants did not raise air conditioning setpoints (indoor air temperatures did not increase) did not realize energy savings. The zones with the largest increase in air conditioning temperature setpoints and largest increase in indoor air temperatures realized the largest energy savings. Four zones did not realize energy savings on a weather-normalized basis. Two were residences where occupants opted to operate at cooling setpoint temperatures typically below 24 °C (~75 °F), one was an infrequently-occupied commercial space with sporadic air conditioning usage, and one was a regularly-occupied office space that had savings on a measured basis, and with one of two weather normalization methods.

We specified two weather normalization methods in our analysis plan prior to analyzing the data, and report the analysis as planned (with mean values from the two normalization methods). While all normalization methods are imperfect estimates, one of

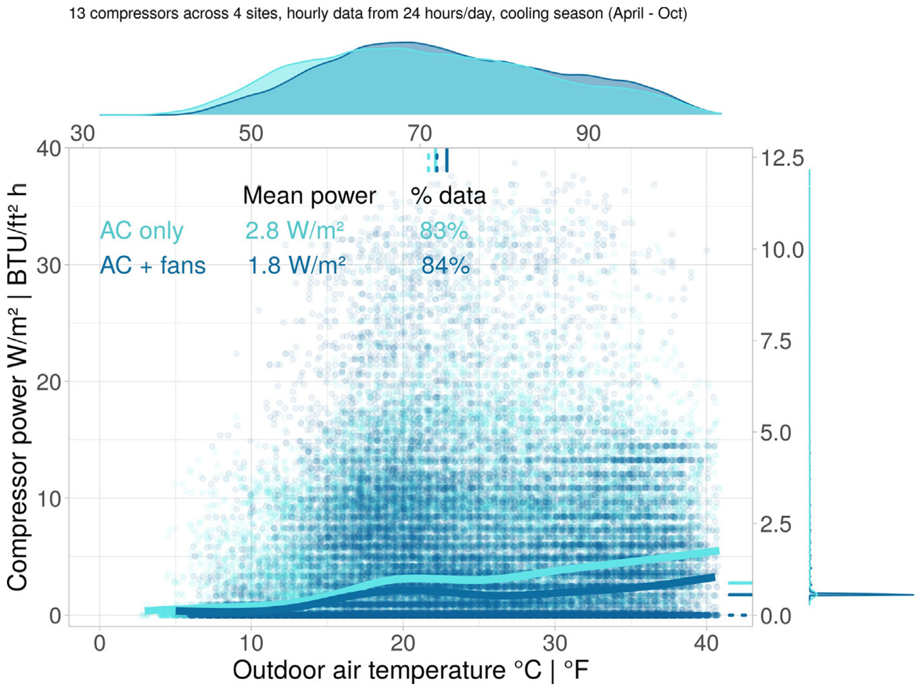

Fig. 8. Mean hourly power consumption for each of 13 separate compressors. Dashed lines on x and y axes represent medians, solid line represent means. Total data collection from July 18, 2017 to October 31, 2019.

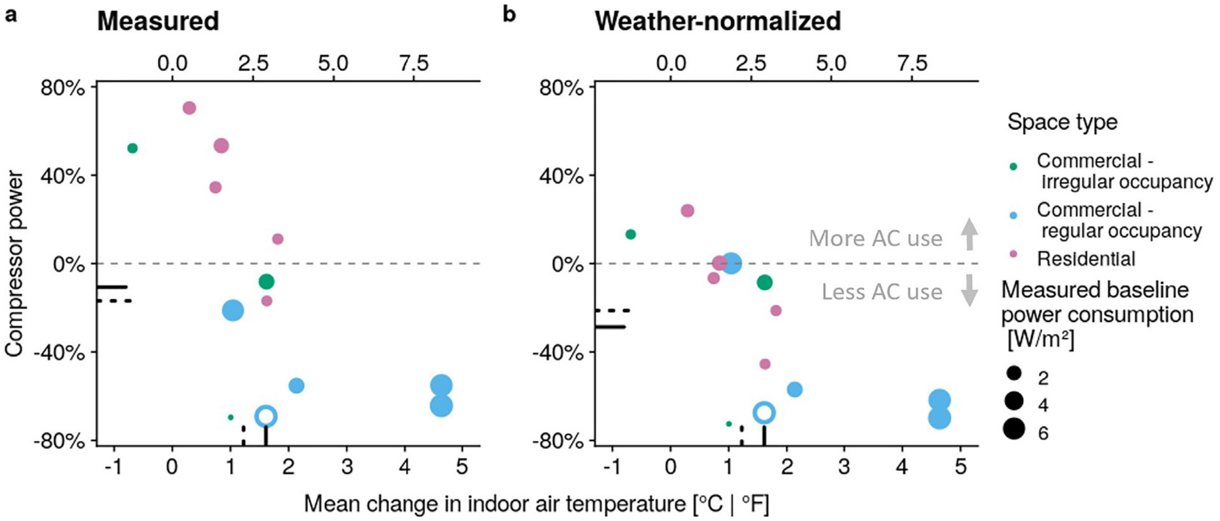

Fig. 9. Comparison of measured and weather-normalized compressor energy usage during April-October cooling seasons with the mean hourly increase in indoor temperatures in each HVAC zone after ceiling fans began to operate and occupants were encouraged to increase air conditioner setpoints. Means shown as solid lines, medians as dashed lines. Hollow point indicates zone C5, where indoor air temperature measurements were not available, plotted here with the mean change in zone temperature. Median savings per compressor, normalized for weather and floor area, are 21 percent, and ranged from an increase of 24 percent (in an infrequently used space), to savings of 73 percent (in a large zone with low initial air conditioning setpoints). Differences in indoor air temperatures are not normalized for weather, and are expected to be warmer in part because of warmer outdoor temps in intervention period, and correlation between indoor and outdoor temperatures. Data from July 2018 - Oct 2019, from 13 compressors and 32 temperature sensors.

the two methods used, segmented regression, had poor model fit on baseline testing data, particularly for sites with infrequent occupancy or daily schedules w here energy consumption is not simply linearly correlated with outdoor air temperature, leading to one site with measured energy savings estimating a weather-normalized savings of 0% despite warmer outdoor temperatures. More sophisticated models that reflect both outdoor air temperature and estimated occupancy (e.g., linear piecewise Time of Week and Temperature) would likely better reflect occupancy and also yield higher savings estimates than reported here.

3.5.3. Measured ceiling fan power consumption

Ceiling fan energy consumption summed for all fans in each HVAC zone is shown in Fig. 10, across the same range of outdoor air temperatures plotted for compressor power in Fig. 8 above. Averaging across all zones and all hours, mean ceiling fan power

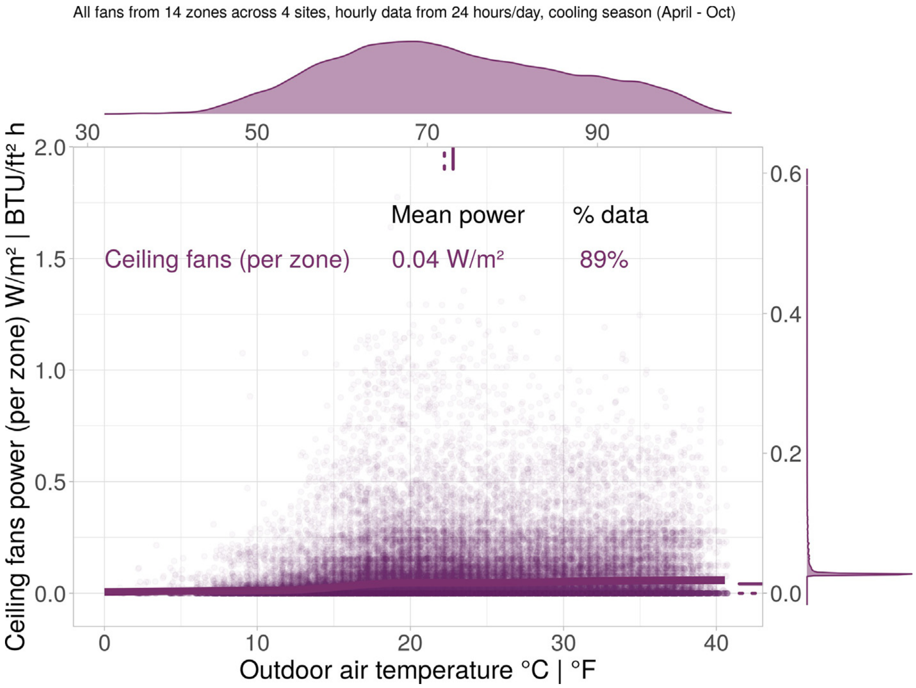

Fig. 10. Mean hourly ceiling fan power consumption (per zone), across all hours (comparable to period of compressor power graph), during intervention period. Dashed lines on x-axes indicates median, solid line indicates mean. Total data collection from July 6, 2018, to October 31 2019.

consumption was 2% of compressor power consumption during the same period. Across different zones, ceiling fan power consumption ranged from 0% to 18% of compressor power.

3.6. Electricity cost savings

Estimated electricity cost savings for all zones are summarized in Table 4. Electrical bills and rate schedules were only available for one site (Site 1), so cost savings are estimated for compressor energy consumption only, and do not include other potential savings from demand charges.

3.7. Occupant interviews and surveys

3.7.1. Office worker and resident interviews

We conducted interviews with one office worker from each of the four field sites, and one adult household member from five of the s ix residential units.

In terms of overall experience, all nine interviewees reported the fans provided adequate cooling and improved their overall indoor environmental quality. One resident reported the use of an additional portable fan during the cooling season in a space (bathroom) that did not have ceiling fans, and one office worker also used a small desktop fan. In general, occupants reported positive feedback about fans regarding automatic operation, ease of adjustment with the remote control, provision of rapid cooling, and that fans in large spaces were synchronized to operate as a group rather than requiring individual adjustment. Shared areas of negative feedback from both residents and office workers included that, in some cases, the fans cooled too much or provided more air movement than they desired. Two residential occupants reported having had issues with Wi-Fi internet after fan installation (due to the maximum number of devices supported per router). Respondents did not report concerns with noise levels, ceiling clearance, or safety during operation. One respondent reported the new fan-integrated light was less bright than their previous fluorescent ceiling fixture and was provided a standing lamp, others did not report concerns with light levels. At sites that did not realize energy savings, occupants still used the fans and reported being satisfied with them.

To interact with the ceiling fans, all respondents used the fan remote. No residents regularly used the fan mobile phone app. Numerous interviewees reported that they found the ecobee thermostat challenging to operate and understand (in part due to lack of Spanish-language interface). At the end of the study, occupants at all sites with the exception of one resident opted to keep the temperature-based automatic fan operation settings. The remaining resident preferred to operate the fans manually only.

3.7.2. Surveys at community events

Prior to ceiling fan operation at Site 1, 26 respondents (11 female, 10 male, 5 no response) completed our surveys during a July 2018 community event. Mean age for these occupants was 66 years ± 13. After ceiling fans were operating (July 2019), 30 respondents completed surveys (15 female, 12 male, 3 no response); mean participant age was 65 years ± 15.

While a range in perceived thermal comfort is expected in any group survey, the percentage of occupants comfortable at higher cooling setpoints when ceiling fans were operating was comparable to the percentage comfortable when only air conditioning was operating at pre-retrofit cooling setpoints (see Fig. 11)

4. Discussion

4.1. Energy savings and sources of variation

Total energy consumption across all sites (normalized for floor area) decreased on both an absolute measured and weather-normalized basis after ceiling fan installation. At the individual zone level, results varied from substantial energy savings to increases in cooling use. Based on our observations, factors contributing to difference outcomes across zones included occupancy schedules, occupant preferences, initial HVAC setpoints, HVAC system type, and building typology.

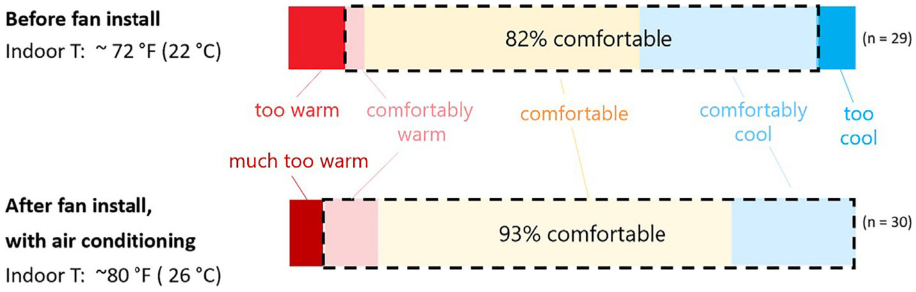

Fig. 11. Responses from point-in-time thermal comfort surveys administered during group events at Site 1 community room before and after retrofit.

Given that measured occupancy information was not available for the baseline period, estimated savings, particularly for the five residential units and three infrequently-occupied commercial spaces ('community rooms'), could be affected by changes in occupancy frequency and duration. In particular, compressors in zones C3 and C8 ran for only 4% and 3% of monitored hours in the baseline period respectively, and 8% and 1% of monitored hours in the intervention period. As such, estimated savings or increased compressor cooling usage at each site reflects a percentage change in a small value. While air conditioning compressor runtime can be a proxy for occupancy (all other things being equal), air conditioning did not actually run during many occupied hours in residences, and runtimes were expected to be lower in the intervention period after thermostat setpoint adjustment. To our knowledge, the regularly-occupied commercial spaces that maintained comparable staffing and working hours were less affected by this source of variation, though at least two sites had employee turnover during the study period.

Differences in occupant preference were another observed source of variation. Known variation in personal thermal comfort preferences can be as much as 2–3 °C (3.6–5.4 °F) between people at the same temperature [30]. Two zones where occupants opted not to increase thermostat cooling setpoints and used more cooling energy during the intervention period also reported additional motivations. Unlike other residents, occupants in zone R6 did not pay their own utility bill, and occupants in zone R2 preferred less air movement around their newborn infant.

Residential sites that did realize savings saw relatively small savings in both absolute and financial terms, likely in part due to being well insulated, relatively new construction (built in 2009), relatively small (80–120 m2) units that share adjacent walls with other units. All of these substantially decrease cooling energy consumption compared to larger, older, less-insulated, free-standing California homes. In addition, residents in this affordable housing development may have been more sensitive to electricity costs. Prior to the study, at least one household was using a standing fan for cooling, and another anecdotally already maintained higher cooling setpoints during some periods at home.

The two compressors with the largest measured energy savings (C1, C2) served a large (560 m2) primarily open-plan space with relatively low baseline mean hourly air temperatures of 21.2 °C (70.2 °F) and observed thermostat setpoints (in "cooling" or "drying" mode) of 19.4–22.8 °C (67–73 °F) during baseline period site visits. The HVAC system also appeared to be operating with minimal, if any, temperature setbacks during unoccupied hours[4], and served a VRF system supplying nine fan coils which sometimes appeared to produce simultaneous heating and cooling in adjacent zones, though this was relatively rare. We expected standardizing thermostat modes and gradually increasing thermostat setpoints to 74 °F, then 76 °F, 78 °F and in some cases 80 °F would reduce compressor runtime hours and compressor power when operating as well as reducing cycling between heating and cooling. The site's practice was that only the facility manager could adjust thermostats in common areas, which ensured setpoint adjustments persisted, while office setpoints could be individually adjusted. While substantial, these energy savings opportunities are comparable to the range of estimated savings available through controls improvements in inefficiently operated commercial buildings [17].

4.2. Ceiling fan operation

The fans in this field study offered a greater number of speed options (seven levels) than the three speed levels available from the majority of ceiling fans in the California Energy Commission's Modernized Appliance Efficiency Database System of fans on the market in the state (California Energy [9]. The fans in this field study also offered turndown ratios (ratio of minimum speed divided by maximum speed) of 0.1–0.2 for the 1.32 and 1.52 m diameter fans[5], allowing lower speeds than the average turndown ratio of ~ 0.4 for ceiling fans in the database [43]. More granular speed control and options for low speed operation are notable since in practice between automatic operation and occupant adjustment the fans operated at an average of 53 % of maximum speed. Occupants tending to select lower speeds in residential units and higher speeds in commercial spaces may be partially explained by the difference in ceiling heights, since fans in residences were closer to occupants (at the minimum clearance of 2.13 m (7 ft) from floor), compared to fan heights of up to 2.96 m (9.7 ft) in commercial spaces. As noted above, fans operated in all zones, including spaces that did not increase temperature setpoints, and in rooms where ceiling fans are less commonly installed (kitchens). Additional work is underway on the frequency and nature of occupant fan and thermostat interactions, and measuring air speeds at occupant height during fan operation at Site 1.

4.3. Indoor temperature and humidity measurements

Previous lab study findings in controlled environments have suggested temperatures above 26.7 °C (80 °F) are feasible and comfortable in the presence of air movement [66,70,69]. However, in this field study, 92% and 77% of all hours (including unoccupied hours) in the baseline and intervention periods respectively were below 27 °C (80.6 °F), suggesting that occupants did not prefer to experience temperatures above this for long periods of time, as also observed in a previous field study of ceiling fans in a hot climate [31].

As noted above, measured hourly indoor relative humidity in all zones increased slightly in the intervention period compared to the baseline period. Comparing the month immediately after the fan

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[4] Baseline period mean hourly temperatures between 8 am – 5 pm: 22.1 +- 1.9 °C, and 5 pm – 8am: 22.3 +- 1.8 °C

[5] Airflow turndown ratios: 52″ Haiku: 0.22, 60″ Haiku: 0.13, 84″ Haiku: 0.31

intervention (August 2018) to the month immediately prior (June 2018), average hourly relative humidity increases of 2% or more were observed in 6 of 12 zones. Buildings (especially wood frame structures) absorb and release moisture on timescales of months, so the difference in indoor humidity is likely due to a combination of increased outdoor absolute and relative humidity at one site (Site 2), in addition to increases in indoor temperature, decreases in compressor use, and potentially also from sensor drift and increased evaporation of moisture from surfaces with higher air velocities. A limitation of this study is that it was not possible to calibrate all of the Hamilton temperature sensors before or after their deployment for two years at field sites. While the sensors were observed to have high correlation prior to deployment, it is possible some sensor drift occurred.

4.4. Recommendations for application

Based on our experience in this study and parallel work developing a ceiling fan design guide [43], we recommend that the design strategy of staging air movement and air conditioning prioritize targeting zones with high cooling energy consumption in order to maximize savings and cost- effectiveness. We were not able to do so in this study, as sites were already constrained at the proposal stage, and participating buildings were selected without access to occupancy or energy consumption data. Costs are also expected to be lower for integrating ceiling fans in new construction as opposed to retrofit due to integration with other required electrical and installation work.

In commercial buildings, when technically feasible, it can be beneficial to interlock cooling setpoints for automated ceiling fans and zone air conditioning to ensure staged operation where air conditioning cooling setpoints remain above fan cooling setpoints. In residential buildings, installing automated fans in bedrooms also requires special attention to controls. Occupants sleeping under blankets may have a lower metabolic rate and accordingly desire a higher fan setpoint, and may not be detected by motion- or infrared-based occupancy sensors. In addition, blinking indicator lights can be disruptive at night, and occupants may prefer they are disabled (as experienced in this field study). In this field study, we disabled occupancy sensing for fans installed in bedrooms.

5. Limitations

While this work included more automated fans and buildings, and a longer monitoring period, than other air movement retrofit studies we are aware of to date, the study also had several limitations. 1) As discussed in 2.1, sites were selected without detailed information about energy use or occupancy patterns per zone. 2) Only one site (Site 1, zones C1 and C2) tested the addition of automated ceiling fans only. All other zones at Sites 2–4 also installed new programmable internet-connected thermostats. Based on our interviews, some users found the new thermostats challenging to understand. 3) Devices in some zones, especially R1, had periods of missing data due to network connectivity issues. 4) The automatic fan control software generally operated as expected in summer 2019, but was still undergoing troubleshooting in summer 2018 and did not necessarily automate fans as intended. 5) As discussed in 3.5.2, weather normalization methods were specified prior to analysis and more sophisticated models that reflect both outdoor air temperature and estimated occupancy (e.g. Time of Week and Temperature) would likely better reflect site operation and also yield higher savings estimates. 6) Due to limited occupancy and occupant schedules, it was only possible to conduct thermal comfort surveys with small numbers of occupants at one site. Occupants were not able to complete online surveys for reasons including physical ability, limited access to computers or smartphones, and work responsibilities. This also inhibited our ability to deploy an adequate number of surveys over the duration of the field study to gain enough statistical power to assess the perceptions and behaviors of the occupants accurately. 7) At most homes and offices, it was only possible to conduct an interview with one person, which doesn't necessarily reflect the experiences of other occupants. It is also possible that respondents felt pressure to respond favorably about technology the project team installed, despite multiple measures to reassure respondents otherwise.

6. Conclusion

The purpose of this paper is to report findings from a July 2017-October 2019 field study from of auto- mated ceiling fans staged with air conditioning. We conducted the field study in 14 zones in ten buildings across four sites in central California, installed 99 ceiling fans automated to operate prior to and then together with air conditioning, and concurrently encouraged occupants to raise air conditioning cooling setpoints. Dur- ing the study period, we collected continuous measurements of compressor and ceiling fan usage, in addition to environmental conditions, and a smaller number of brief thermal comfort surveys (~65 respondents) and in-depth occupant interviews (9 respondents). Key findings of our evaluation include:

- Overall, the field demonstration resulted in 36% measured compressor energy savings during the April– October cooling season compared to baseline conditions, aggregated across all sites and normalized for floor area served. After weather normalization, energy use per zone ranged from a 24% increase in compressor energy use to savings of 73% across 13 compressors, with median savings of 21%.
- All commercial spaces with regular occupancy schedules showed energy savings on an absolute basis before normalizing for warmer intervention temperatures, and 9 of 13 compressorsshowed energy savings on a weather-normalized basis. Zones that did not realize weather-normalized energy savings were two zones that did not increase thermostat setpoints, one zone with infrequent and irregular occupancy, and one zone with measured energy savings prior to weather normalization.
- Ceiling fans frequently operated during occupancy in most zones, operating for an average of 81% and 45% of occupied hours in commercial and residential zones respectively. Mean ceiling fan power during operation was 8.1 W per fan, and mean ceiling fan power consumption per compressor zone (0.04 W/m2) was 2% of compressor energy (mean 1.75 W/m^2) during the cooling season.
- Across all zones, average indoor air temperatures increased an average of 1.9 °C (3.4 °F) after the installation of automated fans and raising of air conditioner cooling setpoints, ranging from an increase of 0.3 to 4.6 °C in zones with increased air temperatures.
- All interviewees reported the fans provided adequate cooling and improved indoor environmental quality. The majority of participants preferred the convenience of the temperature- and occupancy-based fan automation to manual-only control. The overall percentage of hours with temperatures exceeding and below the comfort range estimated by ASHRAE Standard 55 decreased after fan installation and raising thermostat cooling setpoints (from 54% to 16%). In addition, based on thermal comfort surveys at one site (n = 30), fans provided comparable thermal comfort at 26.7 °C (80 °F) with air movement and air conditioning than 22.2 °C (72 °F) with air conditioning only.

- Estimated weather-normalized cost savings for cooling energy using existing rates ranged from tens of dollars per summer in small, well-insulated residential zones with low air conditioning consumption to thousands of dollars per zone for a large VRF system with low initial cooling setpoints. Overall measured energy savings were higher – 41% - during June - September 4–9 pm, corresponding to summer peak hours under new, higher, regional Time-Of-Use electricity rates. Reducing power consumption at these times during the cooling season has more benefit in terms of both grid stability and carbon emission reduction than energy efficiency measures which do not correlate as closely with peak demand events. Similarly, though we did not demonstrate this in the study, we note that the wider range of indoor temperatures made comfortable by the ceiling fans should facilitate pre-cooling strategies (i.e. load-shifting) more effectively than in spaces without ceiling fans. Spaces could be pre-cooled to temperatures typical of still air conditions in advance of a peak grid event, and then coast through that event with minimal compressor use relying on the ceiling fans to provide comfort as temperatures rise in the space.

Our findings demonstrate that sequencing air movement and air conditioning can provide substantial energy savings as a retrofit intervention while maintaining comparable occupant comfort. This design strategy could be encouraged in both new and retrofit construction through credits in energy code or building rating programs (which as of this writing exist for residential ceiling fans in Florida and Hawai'i (Florida Building [18,21], as well as improved interface options and consumer education around both ceiling fans and thermostats. While ceiling fans from decades ago used markedly more energy and are sometimes perceived as an inferior substitute for air conditioning, modern ceiling fans are stylish, quiet, low energy, precisely controllable, and can play an important role on their own or sequenced with air conditioning in low energy and low carbon comfort cooling systems.

CRediT authorship contribution statement

Dana Miller: Data curation, Formal analysis, Methodology, Investigation, Project administration, Software, Visualization, Writing - original draft, Writing - review & editing. **Paul Raftery:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Investigation, Project administration, Software, Supervision, Writing - original draft, Writing - review & editing. **Mia Nakajima:** Data curation, Formal analysis, Investigation, Software, Visualization, Writing - review & editing. **Sonja Salo:** Data curation, Formal analysis, Investigation, Software, Visualization, Writing - original draft, Writing - review & editing. **Lindsay T. Graham:** Data curation, Formal analysis, Methodology, Investigation, Writing - original draft, Writing - review & editing. **Therese Peffer:** Conceptualization, Funding acquisition, Methodology, Investigation, Project administration. **Marta Delgado:** Investigation, Writing - review & editing. **Hui Zhang:** Conceptualization, Funding acquisition, Methodology, Investigation, Supervision, Writing - review & editing. **Gail Brager:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing - review & editing. **David Douglass-Jaimes:** Investigation, Project administration, Writing - original draft, Writing - review & editing. **Gwelen Paliaga:** Conceptualization, Funding acquisition, Investigation, Writing - review & editing. **Sebastian Cohn:** Data curation, Methodology, Investigation, Writing - review & editing. **Mitch Greene:** Data curation, Methodology, Investigation, Writing - review & editing. **Andy Brooks:** Supervision, Writing - review & editing.

Declaration of Competing Interest

Fan hardware was contributed by one ceiling fan manufacturer (prior to start of the project), who also provided computational fluid dynamics simulations to inform fan placement, and installed fan hardware. The manufacturer had no role in data collection other than providing access to raw ceiling fan sensor data. They had no role in the analysis, decision to publish, preparation, or submission of this manuscript. All authors declare no interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2021.111319.

References

[1] Aerotron Fans. (2019). Aerotron Fans - AE3+ Series. In Aeratron. https://aeratron.com/products/ae3- series.

[2] J. Allaire, R Foundation, Wickham, H., Journal of Statistical Software, Xie, Y., Vaidyanathan, R., Association for Computing Machinery, Boettiger, C., Elsevier, Broman, K., Mueller, K., Quast, B., Pruim, R., Marwick, B., Wickham, C., Keyes, O., & Yu, M. (2017). Rticles: Article Formats for R Markdown.

[3] Allaire, J., Xie, Y., McPherson, J., Luraschi, J., Ushey, K., Atkins, A., Wickham, H., Cheng, J., & Chang, W. (2018). Rmarkdown: Dynamic Documents for R.

[4] M.P. Andersen, H.-S. Kim, D.E. Culler, Hamilton: A Cost-effective, Low Power Networked Sensor for Indoor Environment Monitoring, in: Proceedings of the 4th ACM International Conference on Systems for Energy-Efficient Built Environments, 2017, https://doi.org/10.1145/3137133.3141453, 1–36:2.

[5] E. Arens, S. Turner, H. Zhang, G. Paliaga. Moving air for comfort. ASHRAE Journal, May 2009, 18–28.

[6] E. Arens, H. Zhang, D. Kim, E. Buchberger, F. Bauman, H. Higuchi, Impact of a task- ambient ventilation system on perceived air quality, Indoor Air 9 (2008).

[7] E. Arens, H. Zhang, W. Pasut, Y. Zhai, T. Hoyt, L. Huang, Air Movement as an Energy Efficient Means Toward Occupant Comfort, Center for the Built Environment, UC Berkeley, 2013.

[8] ASHRAE. (2017). ANSI/ASHRAE Standard 55 for Human Occupancy.

[9] California Energy Commission. (2020). Modernized Appliance Efficiency Database System. In Appliance Regulations Certification Assistance. https://www.energy.ca.gov/rules-and-regulations/appliance-efficiency- regulations-title-20/appliance-regulations-certification#webdocs.

[10] California Energy Commission. (2017). California Building Climate Zone Areas - Climate Zones by ZIPcode list. https://www.energy.ca.gov/maps/renewable/BuildingClimateZonesByZIPCode.pdf.

[11] C. Duarte, P. Raftery, S. Schiavon. SinBerBEST Technology Energy Assessment Report, 2016 https://escholarship.org/uc/item/7k1796zv.

[12] J. Dulac, T. Abergel, C. Delmastro, Tracking Buildings International Energy Administration. 2019 https://www.iea.org/reports/tracking-buildings.

[13] EnergyStar. (2019). ENERGY STAR Most Efficient 2019. https://www.energystar.gov/most-efficient/me- certified-ceiling-fans.

[14] Environmental Hazard Health Assessment, C. O. of. (2016). CalEnviroScreen 3.0 [Text]. https://oehha. ca.gov/calenviroscreen/report/calenviroscreen-30.

[15] Eric Kauffman. (2003). Climate and Topography. In Atlas of the Biodiversity of California (p. 15). California Department of Fish and Game.

[16] European Commitee for Standardization. European standard en 15251 indoor environmental input parameters for design andassessment of energy performance of buildings addressingindoor air quality, thermal environment, lighting and acoustics (2007).

[17] N.E. Fernandez, S. Katipamula, W. Wang, Y. Xie, M. Zhao, C.D. Corbin. Impacts of Commercial Building Controls on Energy Savings and Peak Load Reduction (Nos PNNL–25985 1400347 2017 pp. PNNL–25985, 1400347) doi:10.2172/1400347.

[18] Florida Building Code. (2017). Chapter 4 Residential Energy Efficiency. In 2017 Florida Building Code - Energy Conservation, Sixth Edition. International Code Council. https://codes.iccsafe.org/content/ FEC2017/chapter-4-re-residential-energy-efficiency.

[19] V. Földváry Ličina, T. Cheung, H. Zhang, R. de Dear, T. Parkinson, E. Arens, C. Chun, S. Schiavon, M. Luo, G. Brager, P. Li, S. Kaam, M.A. Adebamowo, M.M. Andamon, F. Babich, C. Bouden, H. Bukovianska, C. Candido, B. Cao, X. Zhou, Development of the ASHRAE Global Thermal Comfort Database II, Build. Environ. 142 (2018) 502–512, https://doi.org/10.1016/j.buildenv.2018.06. 022.

[20] Y. Gao, H. Zhang, E. Arens, E. Present, B. Ning, Y. Zhai, J. Pantelic, M. Luo, L. Zhao, P. Raftery, S. Liu, Ceiling fan air speeds around desks and office partitions, Build. Environ. 124 (2017) 412–440, https://doi.org/10.1016/j.buildenv.2017.08.029.

[21] Hawai'i Energy. (2017). IECC 2015 - Understanding Hawai'i's Residential Tropical Energy Code Option. Hawai'i Energy. https://hawaiienergy.com/files/resources/codes/ResidentialTropicalKeyChanges.pdf.

[22] T. Hoyt, E. Arens, H. Zhang (2014). Extending air temperature setpoints: Simulated energy savings and design considerations for new and retrofit buildings. doi:10.1016/j.buildenv.2014.09.010.

[23] Hunter Fan. (2018). Hunter Fan - Bureau with LED Light 60 inch Ceiling Fan. https://www.hunterfan.com/ceiling- fans/bureau-with-led-light-60-inch-fam789.

[24] R. Iannone, J. Cheng, B. Schloerke (2019). Gt: Easily Create Presentation-Ready Display Tables. International Energy Agency. (2018). Future of cooling. International Energy Agency.

[25] International WELL Building Institute. (2018). WELL V2.2 Feature T04 - Individual Thermal Control. https://v2.wellcertified.com/v2.2/en/thermal%20comfort/feature/4.

[26] P.W. James. Are Energy Savings Due to Ceiling Fans Just Hot Air? ACEEE Summer Study on Energy Efficiency in Buildings (1996).

[27] C. Kantner, S. Young, S. Donovan, K. Garbesi. Ceiling Fan and Ceiling Fan Light Kit use in the U.S. Results of a Survey on Amazon Mechanical Turk (Nos. LBNL-6332E, 1165855; pp. LBNL–6332E, 1165855) (2013). doi:10.2172/1165855.

[28] Kuhn, M. (2020). Caret: Classification and regression training. https://CRAN.R-project.org/package=caret.

[29] T.J. Leeper, (2018). Aws.s3: AWS s3 client package.

[30] P. Li, T. Parkinson, G. Brager, S. Schiavon, T.C. Cheung, T. Froese, A data-driven approach to defining acceptable temperature ranges in buildings, Build. Environ. 153 (2019) 302–312, https://doi.org/10.1016/j.buildenv.2019.02.020.

[31] A. Lipczynska, S. Schiavon, L.T. Graham. Thermal comfort and self-reported productivity in an office with ceiling fans in the tropics. Building and Environment (2018), 135, 202–212. doi:10. 1016/j.buildenv.2018.03.013.

[32] J. Luraschi, K. Kuo, K. Ushey, J. Allaire. The Apache Software Foundation. (2018). Sparklyr: R interface to apache spark. https://CRAN.R-project.org/package=sparklyr.

[33] V. Masson-Delmotte, P. Zhai, H.O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, Y. Chen, S. Connors, M. Gomis, E. Lonnoy, J.B.R. Matthews, W. Moufouma-Okia, C. Péan, R. Pidcock, N. Reay, M. Tignor, T. Waterfield, X. Zhou, X. (Eds.). (2018). Global warming of 1.5C. An IPCC Special Report on the impacts of global warming of 1.5C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.

[34] V.M. Muggeo. Segmented: An r package to fit regression models with broken-line relationships (2008) R News, 8 (1), 20–25. https://cran.r-project.org/doc/Rnews/ .

[35] K. Müller. (2017). Here: A Simpler Way to Find Your Files.

[36] Pacific Gas and Electric. (2021a). Commercial Time-of-Use rate plans. https://www.pge.com/en_US/ small-medium-business/your-account/rates-and-rate-options/time-of-use-rates.page.

[37] Pacific Gas and Electric. (2021b). Residential Time-of-Use rate plans. https://www.pge.com/en_US/ residential/rate-plans/rate-plan-options/time-of-use-base-plan/time-of-use-plan/time-of-use-transition.page?.

[38] Pacific Northwest National Lab. (2015). Guide to Determining Climate Regions by County. Volume 7.3.

[39] Pantelic, J., Liu, S., Pistore, L., Licina, D., Vannucci, M., Sadrizadeh, S., Ghahramani, A., Gilligan, B., Sternberg, E., Kampschroer, K., & Schiavon, S. (2020). Personal CO 2 cloud: Laboratory measurements of metabolic CO 2 inhalation zone concentration and dispersion in a typical office desk setting. Journal of Exposure Science & Environmental Epidemiology, 30 (2), 328–337. https://doi.org/10.1038/s41370-019-0179-5

[40] Wilmer Pasut, Edward Arens, Hui Zhang, Yongchao Zhai, Enabling energy-efficient approaches to thermal comfort using room air motion, Build. Environ. 79 (2014) 13–19.

[41] T.L. Pedersen. (2020). Patchwork: The composer of plots. https://CRAN.R-project.org/package= patchwork.

[42] E. Present, P. Raftery, G. Brager, L.T. Graham, Ceiling fans in commercial buildings: In situ airspeeds & practitioner experience, Build. Environ. 147 (2019) 241–257, https://doi.org/10.1016/j.buildenv.2018.10.012.

[43] P. Raftery, D. Douglass-Jaimes, (2020). Ceiling Fan Design Guide. Center for the Built Environment, UC Berkeley. https://escholarship.org/uc/item/6s44510d.

[44] P. Raftery, D. Miller, H. Zhang, T. Peffer, G. Brager, L.T. Graham, E. Present, E. Arens, D. Douglas- Jaimes, G. Paliaga, A. Brooks, S. Cohn, M. Greene, Integrating Smart Ceiling Fans and Communicating Thermostats to Provide Energy-Efficient Comfort Final project Report, California Energy Commission, 2020. https://escholarship.org/uc/item/91z0m3xw.

[45] R Core Team. (2018). R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing.

[46] D. Rim, S. Schiavon, W.W. Nazaroff, Energy and Cost Associated with Ventilating Of- fice Buildings in a Tropical Climate, PLOS One 10 (3) (2015), https://doi.org/10.1371/journal.pone. 0122310 e0122310.

[47] RLW Analytics. (2002). Statewide Investor Owned Utility Ceiling Fan Study - Final Report. Prepared for: San Diego Gas and Electric.

[48] F. Rodriguez-Sanchez. Grateful: Facilitate Citation of R Packages (2018).

[49] S. Schiavon, A.K. Melikov. Energy saving and improved comfort by increased air movement Energy and Buildings (2008), 40 (10), 1954–1960. doi:10.1016/j.enbuild.2008.05.001.

[50] S. Schiavon, B. Yang, Y. Donner, V.W.-C. Chang, W.W. Nazaroff, Thermal comfort, perceived air quality, and cognitive performance when personally controlled air movement is used by tropically acclimatized persons, Indoor Air 27 (3) (2017) 690–702, https://doi.org/10.1111/ina.12352.

[51] S. Sekhar, Higher space temperatures and better thermal comfort — a tropical analysis, Energy Build. 23 (1) (1995) 63–70, https://doi.org/10.1016/0378-7788(95)00932-N.

[52] J.K. Sonne, D.S. Parker (1998). Measured Ceiling Fan Performance and Usage Patterns: Implications for Efficiency and Comfort Improvement. 1, 335–341. http://www.fsec.ucf.edu/en/publications/pdf/FSEC- CR-1770-98.pdf.

[53] C.A. Stewart, T.M. Cockerill, I. Foster, D. Hancock, N. Merchant, E. Skidmore, D. Stanzione, J. Taylor, S. Tuecke, G. Turner, M. Vaughn, N.I. Gaffney, Jetstream: A Self-provisioned, Scalable Science and Engineering Cloud Environment, in: Proceedings of the 2015 XSEDE Conference: Scientific Ad- vancements Enabled by Enhanced Cyberinfrastructure, 2015, https://doi.org/10.1145/2792745.2792774, 1–29:8.

[54] Towns, J., Cockerill, T., Dahan, M., Foster, I., Gaither, K., Grimshaw, A., Hazlewood, V., Lathrop, S., Lifka, D., Peterson, G. D., Roskies, R., Scott, J. R., & Wilkins-Diehr, N. (2014). XSEDE: Accelerating Scientific Discovery. Computing in Science Engineering, 16 (5), 62–74. https://doi.org/10.1109/MCSE.2014. 80

[55] United States Energy Information Administration. (2018). How much energy is consumed in U.S. Resi- dential and commercial buildings? - FAQ. https://www.eia.gov/tools/faqs/faq.php?id=86&t=1.

[56] U.S. Energy Information Administration. (2016). 2012 Commercial Buildings Energy Consumption Sur- vey: Energy Usage Summar. https://www.eia.gov/consumption/commercial/reports/2012/energyusage/.

[57] U.S. Energy Information Administration. (2018). EIA's residential energy survey now includes estimates for more than 20 new end uses. In Today in Energy. https://www.eia.gov/todayinenergy/detail.php?id= 36412&src=%E2%80%B9%20Consumption%20%20%20%20%20Residential%20Energy%20Consumption% 20Survey%20(RECS)-b2.

[58] US Energy Information Administration Air conditioning and other appliances increase residential electricity use in the summer - Today in Energy, 2017 https://www.eia.gov/todayinenergy/detail.php?id=31312.

[59] U.S. Energy Information Administration. (2015). Form eia-871A of the 2012 commercial buildings energy consumption survey. https://www.eia.gov/consumption/commercial/data/2012/bc/cfm/b41.php.

[60] U.S. Green Building Council. (2014). LEED BD+C: New Constructionv - LEED v4 - Thermal Comfort. https://www.usgbc.org/credits/new-construction/v4-draft/eqc5.

[61] H. Wickham. (2017). Tidyverse: Easily Install and Load the 'Tidyverse'.

[62] C.O. Wilke, (2019). Cowplot: Streamlined plot theme and plot annotations for 'ggplot2'. https://CRAN. R-project.org/package=cowplot.

[63] Y. Xie, Dynamic Documents with R and knitr, 2nd ed., Chapman and Hall/CRC, 2015.

[64] Y. Xie, Bookdown: Authoring Books and Technical Documents with R Markdown, Chapman and Hall/CRC, 2016.

[65] Y. Zhai, E. Arens, K. Elsworth, H. Zhang, Selecting air speeds for cooling at sedentary and non-sedentary office activity levels, Build. Environ. 122 (2017) 247–257, https://doi.org/10.1016/j.buildenv.2017.06.027.

[66] Y. Zhai, H. Zhang, Y. Zhang, W. Pasut, E. Arens, Q. Meng, Comfort under personally controlled air movement in warm and humid environments Building and Environment 65 2013 109 117 https://escholarship.org/uc/item/9s12q89q.

[67] Y. Zhai, Y. Zhang, H. Zhang, W. Pasut, E. Arens, Q. Meng, Human comfort and perceived air quality in warm and humid environments with ceiling fans, Build. Environ. 90 (2015) 178–185, https://doi.org/10.1016/j.buildenv.2015.04.003.

[68] Zhang, H., Arens, E., & Zhai, Y. (2015a). A review of the corrective power of personal comfort systems in non-neutral ambient environments. 91, 15–41. doi:10.1016/j.buildenv.2015.03.013.

[69] H. Zhang, E. Arens, Y. Zhai, A review of the corrective power of personal comfort systems in non-neutral ambient environments, Build. Environ. 91 (2015) 15–41, https://doi.org/10.1016/j. buildenv.2015.03.013.

[70] H. Zhang, Y. Zhang, W. Pasut, E. Arens, Q. Meng, Comfort under personally controlled air movement in warm and humid environments, Build. Environ. 65 (2013), https://doi.org/10.1016/j. buildenv.2013.03.022.