Title
Spatial Uniformity of Thermal Comfort from Ceiling Fans Blowing Upwards

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ABSTRACT

Air movement from fans is an effective way to deliver thermal comfort in warm air temperatures. We measured air speeds in a shared office at 15 sites where an occupant would typically be located. The fan speed and direction were changed to operate in either the upwards or downwards direction. Mean air speeds in the occupied zone were higher when fans were blowing downwards, but the spatial distribution across the space was less uniform. When fans are blowing upwards, thermal comfort estimates using SET indicate less risk of discomfort from high airspeed locations directly under the fans compared with the downward case. Vertical air speed gradients showed higher air speeds at head height and lower air speeds at ankle height in the upwards direction, but the opposite profile for fans blowing in the downward direction. The positive vertical gradient in the upwards direction is favorable to reduce the potential for draft at the ankles. These results suggest that despite lower air speeds, fans blowing upwards can provide more spatially uniform thermal comfort under elevated air movement, requiring less consideration of occupant and furniture placement relative to the fan.

INTRODUCTION

Ceiling fans are a common component of a thermal comfort strategy for building designs aiming for higher energy efficiency (Arens et al. 2009; He et al. 2019). This is particularly true for warmer climates, where cooling from fans can enhance occupant comfort while allowing setpoint temperatures to be widened to reduce energy expenditure (Rohles et al. 1982; Tanabe and Kimura 1989; Lipczynska et al. 2018). In cooler conditions, draft is one of the common sources of local thermal discomfort (Toftum 2004) and elevated air movement is discouraged in ASHRAE 55-2017 for buildings where indoor operative temperatures are below 23°C (73.4°F). Aside from operative temperature, the placement of ceiling fans in relation to occupants and office furniture represents a potential design challenge due to spatial inhomogeneity of the resulting air movement (Liu et al. 2018; Gao et al. 2017; Ho et al. 2009). Incorrectly positioning ceiling fans may lead to excessive air movement for occupants directly under a fan while their colleagues sitting further away experience insufficient air movement.

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There is evidence that fans blowing in the upward direction may offer a simple solution to this issue of spatial variation in air speeds from ceiling fans (Raftery et al. 2019). By reversing the rotation direction of the motor, the patterns of air movement within the space are altered in a way that can improve the uniformity of comfort conditions for occupants irrespective of furniture and layout. This can be beneficial in some applications like commercial offices

where occupants cannot freely and easily move around the space. This is considered an important step in promoting the use of ceiling fans in contemporary commercial offices. Accordingly, the aims of this paper are:

1. Measure the air speed field of fans blowing in both the upward and downward directions
2. Evaluate the uniformity of thermal comfort conditions from spatial variations in air speed within a typical office environment with ceiling fans.

Method

We conducted field measurements of air speeds from ceiling fans in a single-zoned office in Sacramento, California in May (spring) 2018. The office building, shown in Figure 1, has radiant heating and cooling delivered by thermally active building system (TABS). It is LEED Platinum certified with numerous energy efficiency strategies. Ceiling fans are distributed throughout the zone for occupant comfort and to supplement the dedicated outdoor air system (DOAS) with overhead air distribution for ventilation. The space is a mix of cubicle-style workspaces, and print and archival areas. A floorplan of the office space is shown in Figure 5.

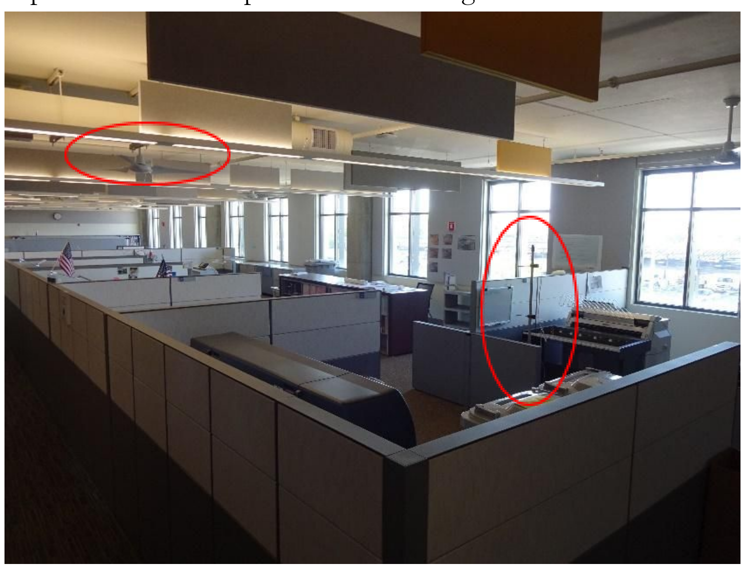

Figure 1 Photo of the field site where measurements were performed. Red circles highlight the anemometer stand used to measure air speed at four heights, and one of the seven ceiling fans.

Ceiling fans installed in the space have three blades with a 60" diameter, an airflow rating of 9,602 cfm, and a maximum motor speed of 247 RPM. Fan speeds are set using a rotary dial on a controller located in a locked utility space. As required for all ceiling fans sold in the USA, the fans can be switched to operate in reverse direction. The field study involved in situ spot measurements of air speeds at multiple sites within the occupied zoned with the fans at two different speeds – nominally "medium" (~155 RPM) and "high" (~237 RPM) – blowing in both the upward and downward direction. The location of the measurement sites were at least 6" away from any furniture, and are shown along with a floorplan in Figure 5. Air speeds were also measured when the ceiling fans were off to establish baseline conditions. All fans in the zone had approximately the same settings during the tests, resulting in five different test conditions (off, up medium, up maximum, down medium, down maximum).

Measurements

Air speed measurements were taken at 15 sites within the space that were considered representative of typically occupied areas. A stand with omni-directional anemometers (5100SF, Sensor Electronic, Poland) mounted at four different heights (0.1 m, 0.6 m, 1.1 m, 1.7 m; 0.33 ft, 1.97 ft, 3.61 ft, 5.58 ft) measured both air speed (±0.02 m/s ±1.5%; ±3.94 fpm ±1.5%) and air temperature (±0.2°C; ±0.36°F) in accordance with ASHRAE 55-2017. For the calculation of thermal comfort indices, operative temperature was assumed to be equal to air temperature, relative humidity was assumed to be 50%, and the personal factors were set for an office worker in summer (1.1 met, 0.5 clo).

Analysis

We used the open source R statistical computing language (R Core Team 2018) with tidyverse (Wickham 2017) for all analysis, and additional software packages comf (Schweiker et al. 2019) for thermal comfort calculations, imager (Barthelme 2019) for some graphics, and here (Müller 2017) for file path management.

RESULTS AND DISCUSSION

Summary statistics of the measured air speeds and air temperatures for each test condition are shown in Table 1. Air speeds were highest when the fans were blowing in the downward direction. The mean air temperature was stable and identical across all tests, but the resulting predicted mean vote (PMV) and standard effective temperature (SET) are markedly different between test cases. A PMV of -0.6 in the initial case with fans off suggests the space is slightly cool, likely due to the assumed value of clothing and metabolic rate. Both PMV and SET decrease as the mean air speed increases. This shows the significance of the cooling effect of elevated air movement on the predicted thermal comfort of occupants.

Table 1. Summary Statistics Across all Measurements Sites (Mean and Standard Deviation)

	Physical Measurements		Thermal Comfort Indices	
Test	**Air Temperature °C (°F)**	**Air Speed m/s (fpm)**	**SET °C (°F)**	**PMV**
Off (off)	23.6 ± 0.0 (74.5 ± 0.0)	0.09 ± 0.04 (17.72 ± 7.87)	22.8 ± 0.1 (73.0 ± 0.2)	-0.6 ± 0.1
Up Medium (upmed)	23.6 ± 0.0 (74.5 ± 0.0)	0.20 ± 0.07 (39.37 ± 13.78)	22.3 ± 0.5 (72.1 ± 0.9)	-0.9 ± 0.2
Up Maximum	23.6 ± 0.0 (74.5 ± 0.0)	0.30 ± 011	21.7 ± 0.7	-1.1 ± 0.2

(upmax)		(59.06 ± 21.65)	(71.1 ± 1.3)	
Down Medium (downmed)	23.6 ± 0.0 (74.5 ± 0.0)	0.46 ± 0.28 (90.56 ± 55.12)	21.1 ± 1.1 (70.0 ± 2.0)	-1.3 ± 0.4
Down Maximum (downmax)	23.6 ± 0.0 (74.5 ± 0.0)	0.76 ± 0.50 (149.61 ± 98.43)	20.3 ± 1.3 (68.5 ± 2.3)	-1.6 ± 0.4

The mean air speed was different between tests, with large spatial variation between measurement sites across the zone. Mean air speeds across the four heights for different measurement sites ranged from 0.21 m/s (41.34 fpm) to 1.20 m/s (236.22 fpm) in the downmax test, and 0.17 m/s (33.46 fpm) to 0.43 m/s (84.65 fpm) in the upmax test. This is mostly due to the smaller mean air speeds measured in the upwards blowing tests. However, we observed generally more uniform spatial distribution when the fans were blowing upwards. Figure 2 shows the mean air speed for each test by measurement site under sitting (excluding 1.7 m measurements) and standing (excluding 0.6 m measurements) configurations. There is much larger difference in air speeds experienced by a seated occupant compared to standing. The trends in air speed between sites was different in the downwards and upwards tests - in other words, the locations of the highest and lowest airspeeds vary depending on the direction the fan is blowing.

Measured air speeds were much lower when fans were blowing upwards compared to downwards. It was recently shown by Raftery et al. (2019) that the various parameters governing air movement in the occupied zone from ceiling fans can be used to predict the resulting air speeds. We performed a simplified version of that approach in Figure 3 that shows an approximately linear relationship between fan speed setting and mean air speeds for both the upwards and downwards blowing directions. This suggests that the modelling approach used by Raftery et al. (2019) may also apply in the case of upward blowing fans if a rated airflow was available for the upwards direction, as is currently required for all ceiling fans sold in the USA for the downwards direction.

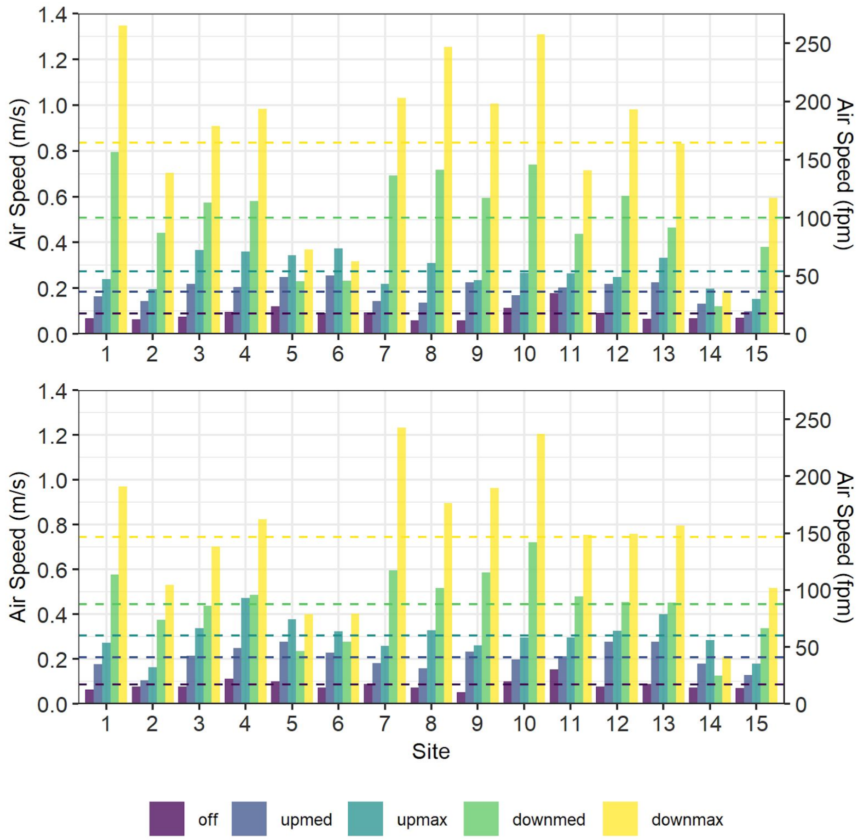

Figure 2 Mean air speeds of measurement sites for each fan test for sitting (top) and standing (bottom) measurements. Dashed lines represent the group mean.

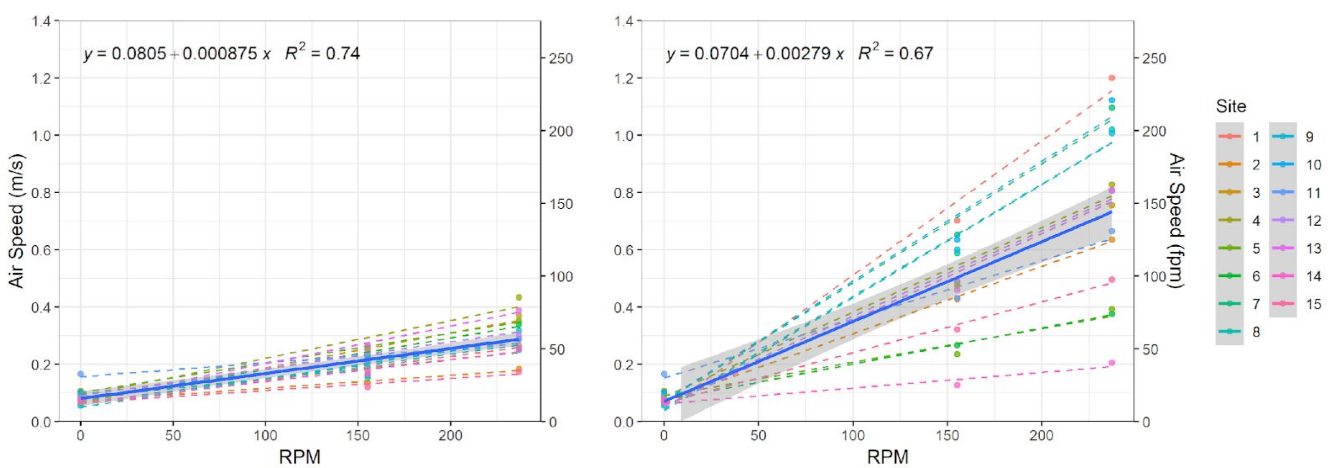

Figure 3 Mean air speeds by site for the off (0 RPM), medium (~155 RPM), and maximum (~237 RPM) speed settings in the upwards (left) and downwards (right) direction. The solid blue line is the mean for all sites and shading shows the confidence interval of the linear regression.

Vertical Air Speed Gradient

Mean air speed is an important parameter for determining occupant thermal comfort when using popular models like PMV and SET. However, the magnitude of local air movement at different body sites has been shown to exert a large influence on overall comfort due to draft sensation. ASHRAE 55-2017 generally estimates that 10% of all thermal dissatisfaction arises from some kind of local discomfort. It is for this reason that vertical air speed gradients are an important consideration for thermal comfort under elevated air movement. Figure 4 shows the distribution of all air speed measurements (0.5 Hz) from each test at the four heights. There is much larger variance in air speeds in the downward blowing direction, similar to what was observed when summarizing the data by site in Figure 2. There is an approximately normal distribution of air speeds in the upwards blowing tests, with the downwards blowing direction exhibiting a bimodal or multimodal distribution that suggests more inhomogeneity across measurement sites.

The key finding in Figure 4 is that the vertical air speed gradient is flipped when the fans are blowing in the downwards and upwards directions. Under normal operation, fans blowing downwards will create a negative vertical gradient where air speeds are fastest at the ankle height of occupants, and slowest at head height. In contrast, air speeds from upwards blowing fans are highest at the head and lowest at the ankle. This has very important consequences for overall comfort due to the sensitivity of the ankles to draft (Schiavon et al. 2016). In fact, 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 neutral vertical temperature gradient ("ideal piste") by Wyon et al. (1989) and consistent 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 (2015).

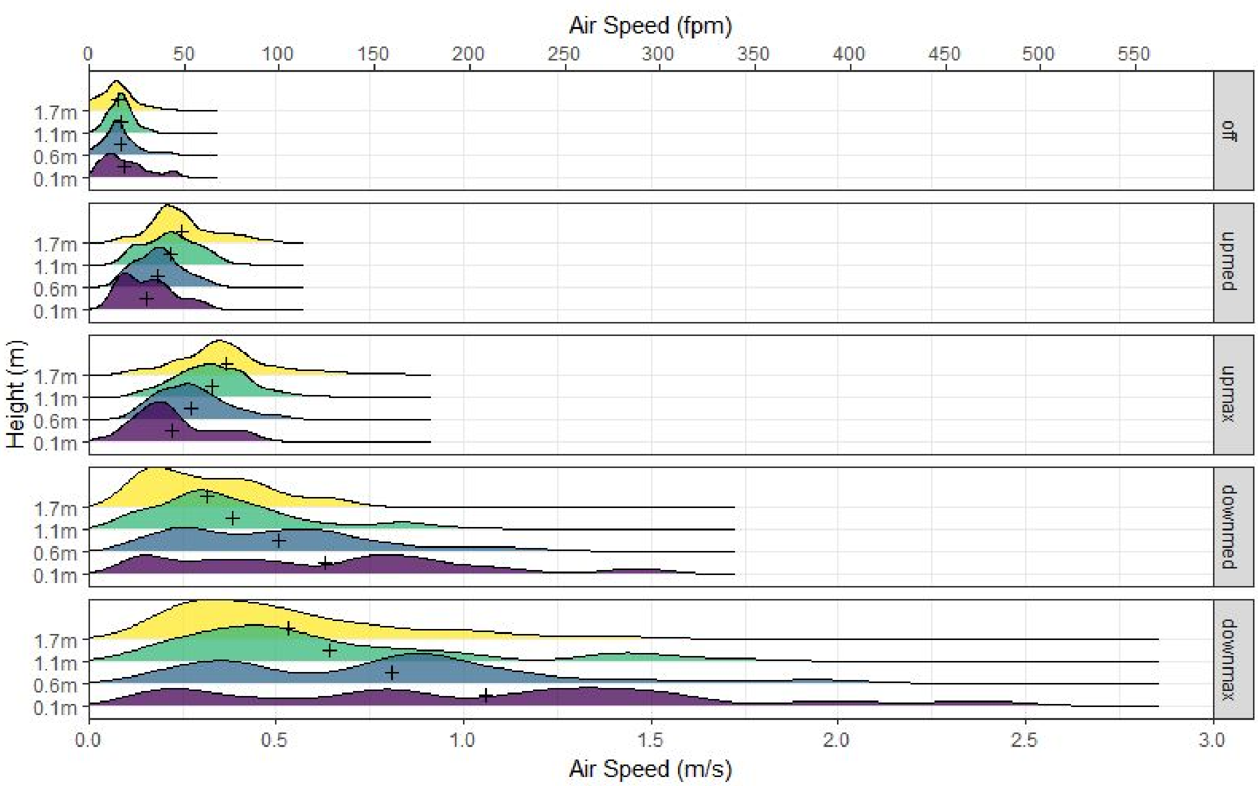

Figure 4 Distribution of measured air speeds for each test at the four measurement heights using the raw data (0.5 Hz). The '+' symbol marks the mean air speed at each height across all measurement sites.

Spatial Uniformity of Thermal Comfort

The vertical air speed gradient from upward blowing fans is likely to have positive benefits for occupant thermal comfort. Another key advantage of upward blowing fans is a more spatially uniform distribution of air speeds across the floorplate, as shown earlier in this section. To visualize the implications of this uniformity of air speed on thermal comfort, the mean air speed across the four heights was used to determine the neutral operative temperature for the space in the upmax and downmax tests – 27.0°C (80.6°F) and 28.6°C (83.5°F) respectively – where SET was 25°C (77°F) and PMV was 0 for a standard office worker in summer (50% relative humidity, 1.1 met, 0.5 clo). Thus, these fans allow for neutral comfort conditions at an operative temperature that is 2°C and 3.6°C higher than the still air case respectively for the upwards and downwards direction tests. This has significant energy savings potential reducing HVAC energy consumption by approximately 30% and 40% respectively for upwards and downwards respectively in this climate zone using the simulation data from Hoyt et al. (2014). The results are shown in Figure 5 along with a floorplan of the office space showing the placement of ceiling fans and office furniture in relation to the measurement sites.

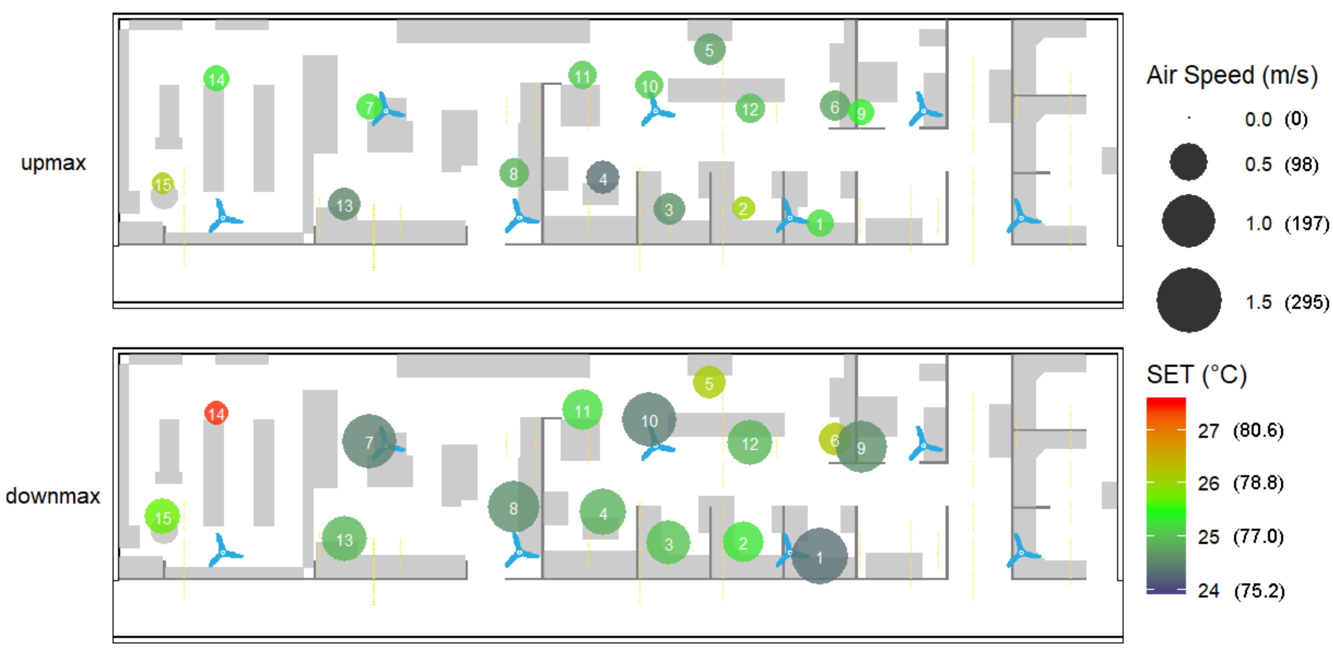

Figure 5 Mean SET and air speeds at each measurement site for the upmax (top) and downmax (bottom) test conditions. The SET calculation used an operative temperature corresponding to thermal neutrality based on the mean air speed of each test as a way to normalize the cooling effects of elevated air movement across the upwards and downwards blowing tests. The background is the floorplan showing the location of fans (blue symbols), office furniture (grey squares) and partitions (solid grey lines). Note the fan in the lower right was not able to be reversed

and was off for all tests.

Figure 5 shows the variability in air speed in the tests when the fans are blowing downwards, and the implications of that variability on thermal comfort conditions across the zone. Even after being corrected for mean air speed, the SET under the downward blowing fans varies across the different sites. In some cases (e.g. site 14 and 6) there is significant likelihood of warm discomfort, while occupants of other sites located under the ceiling fans (e.g. site 1 and 10) could be experiencing cool discomfort. When the fans are blowing upwards there is a smaller difference in SET across the zone, with the greatest cooling effect at sites positioned near the convergence zone of two fans (e.g. site 4 and 13). The greater uniformity of air speeds when fans are blowing upwards would make it easier for a designer to ensure thermal comfort for all occupants of the space without having to know the position of the fans and the occupants, or the furniture layout which is likely to change more often than the position of ceiling fans. Even if the upwards case was designed with faster fans such that the average air speed matched the downwards case, the resulting air speed distribution would still be more uniform.

CONCLUSION

We measured air speeds at multiple spots across a single zone within an office building while ceiling fans were operating in an upwards or downwards direction at different speeds. The purpose was to determine the spatial uniformity of air speeds from ceiling fans and assess the impact on thermal comfort at different positions within the occupied zone. Mean air speeds were lower when fans were set to blow in the upwards direction. We found less spatial uniformity in mean air speed measurements (averaged over 3 or 4 heights) across the zone when fans were blowing downwards, with the highest air speeds observed directly below the fans. In contrast, the highest air speeds when blowing upwards were spots positioned in the convergence zone between two fans. The vertical air speed gradient reversed when the direction of the fans was switched, with the positive gradient when blowing upwards less likely to result in local thermal discomfort from draft. These results show that fans blowing upwards can provide more spatially uniform thermal comfort under elevated air movement. Although this is a small-scale study, we believe this is an important finding as it suggests that designers can more reliably predict thermal comfort when ceiling fans are operating in the upward direction regardless of occupants' location in the zone, the position of the fans, or the placement of furniture.

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