Air movement: its role in conditioning building interiors efficiently

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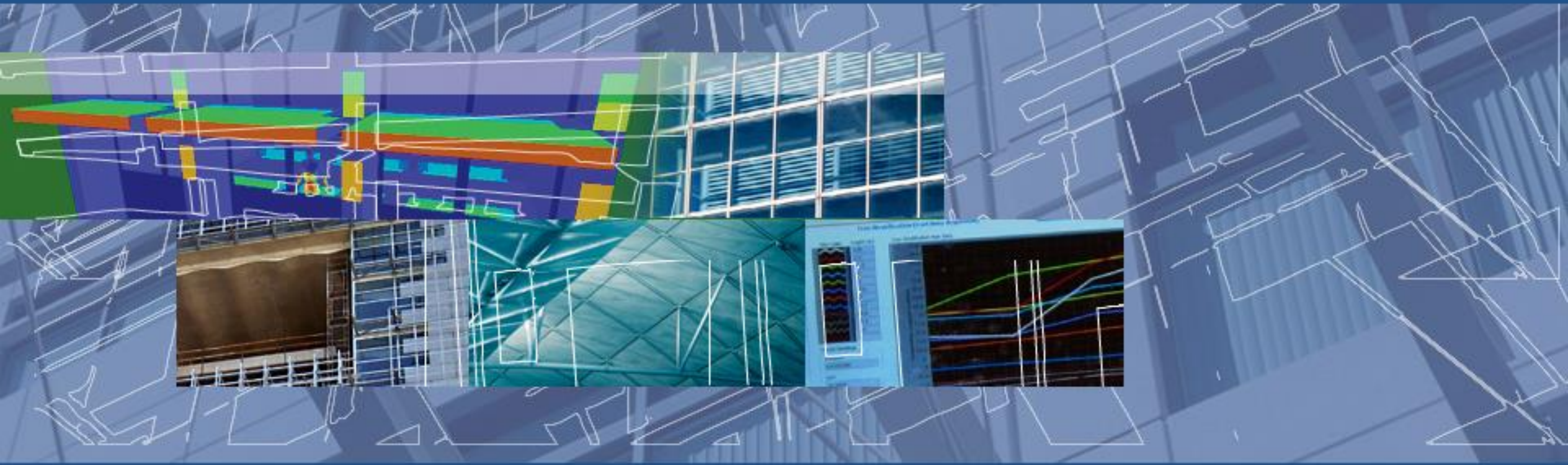
Center for the Built Environment

Funded by:

California Air Resources Board

Armstrong World Industries

CBE



MARCH 24, 2015

Presentation outline

- Building environment and human comfort
  - Cooling of the indoor environment
  - The energy problem with existing approaches
  - The comfort problem with existing approaches
- Energy-efficient cooling: the role of air movement
  - Human response
  - Practical issues of how to implement air movement indoors
- Air movement and air quality, perceived and real
- Barriers for fan adoption in practice
- Future opportunities for air movement in buildings

Air movement related to thermal comfort and energy

4 environmental factors affect thermal comfort

- Air temperature
- Surrounding surface temperature
- Humidity
- Air speed

- Design has always focused on the first three (use of operative temperature and the psychrometric chart)
- Air speed has largely been seen as a problem to be avoided (draft) in conditioned spaces

ASHRAE Standard 55 comfort zones

- Winter and summer zones
- Zones satisfy 80% of people
- Require still air

- Setpoint ranges in US are narrower — winter temperatures year-round; buildings are overcooled in summer

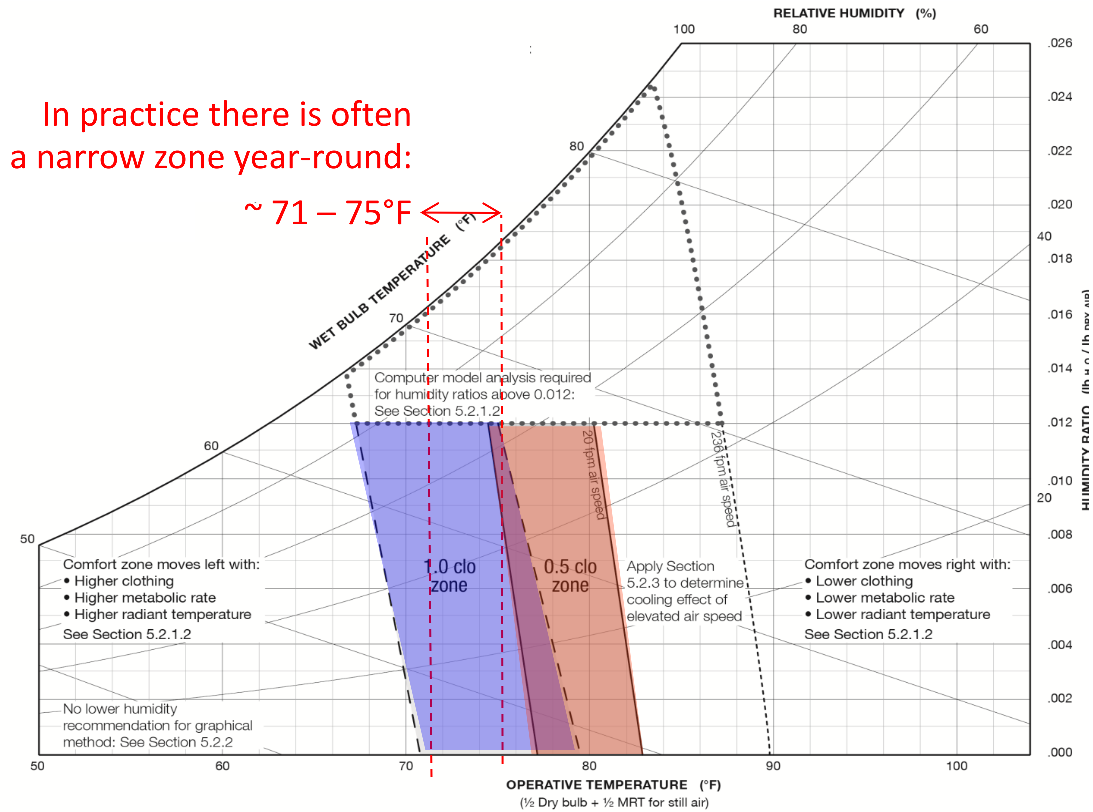
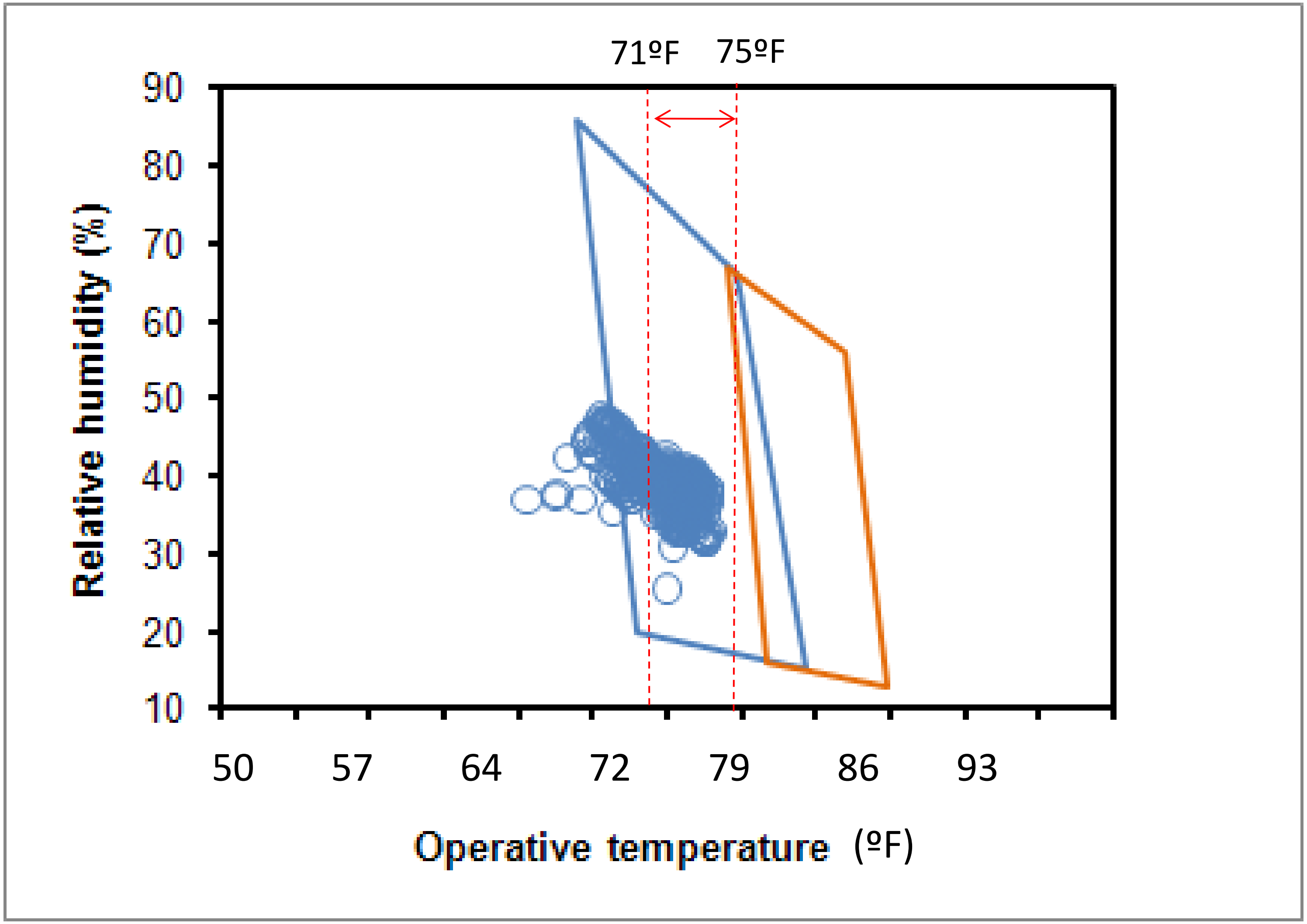
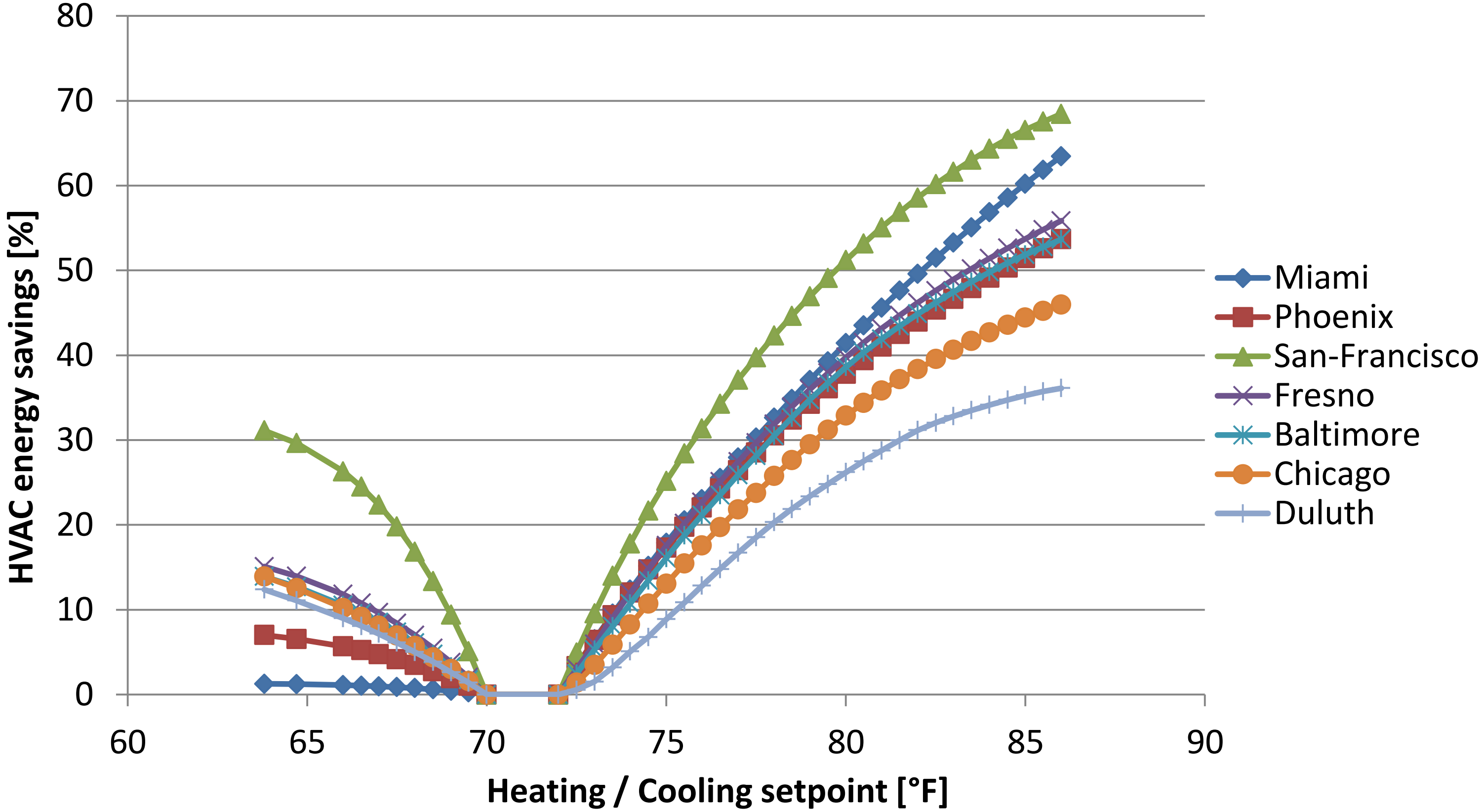


Figure 5.2.1.1 (IP) Acceptable range of operative temperature and humidity for spaces that meet the criteria specified in Section 5.2.1.1.
1.1 met, 0.5 & 1.0 clo

Actual temperatures lower than setpoints (BASE data: 95 office buildings, 1994 – 1998)

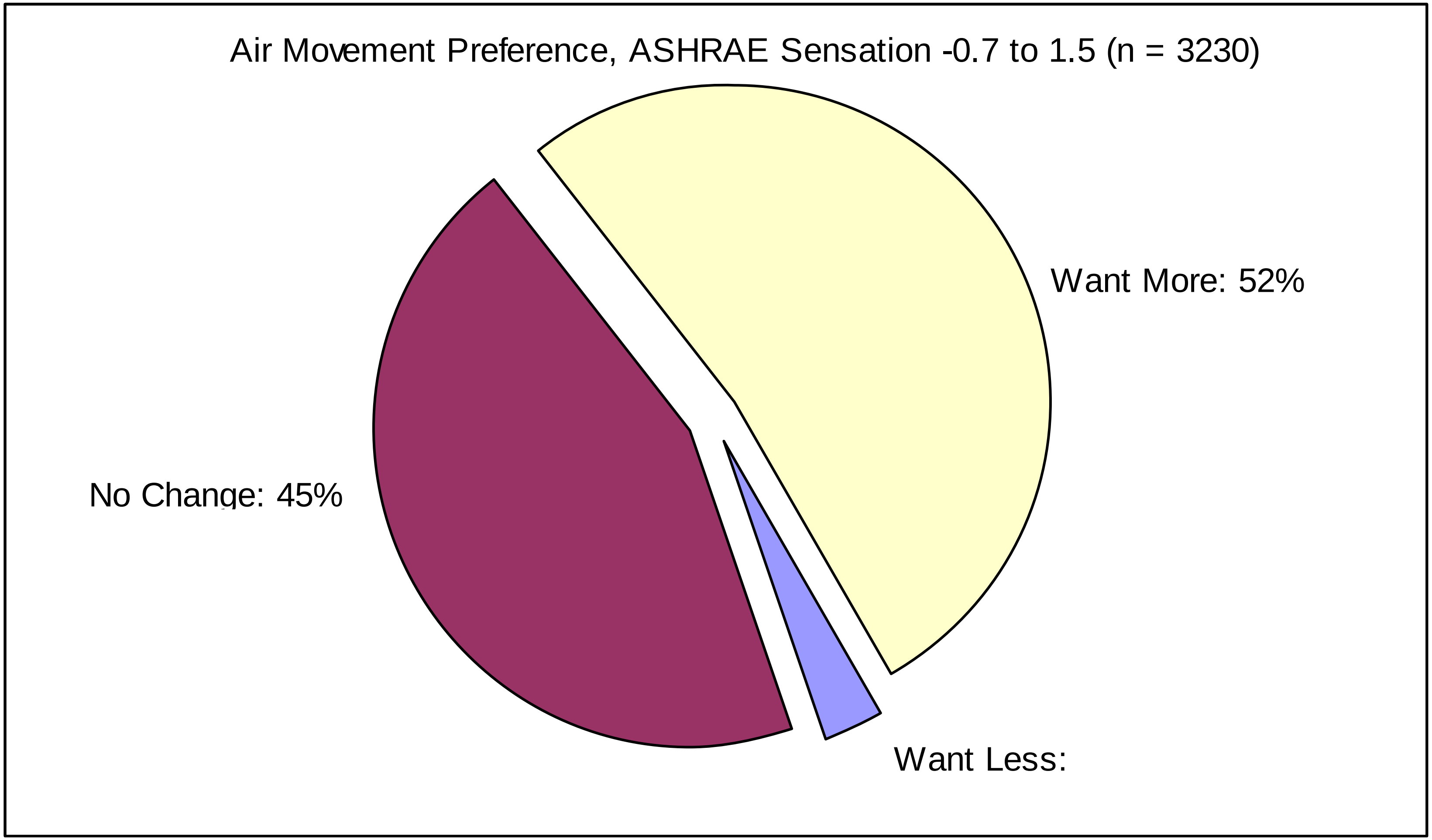


The cost of maintaining range of indoor conditions



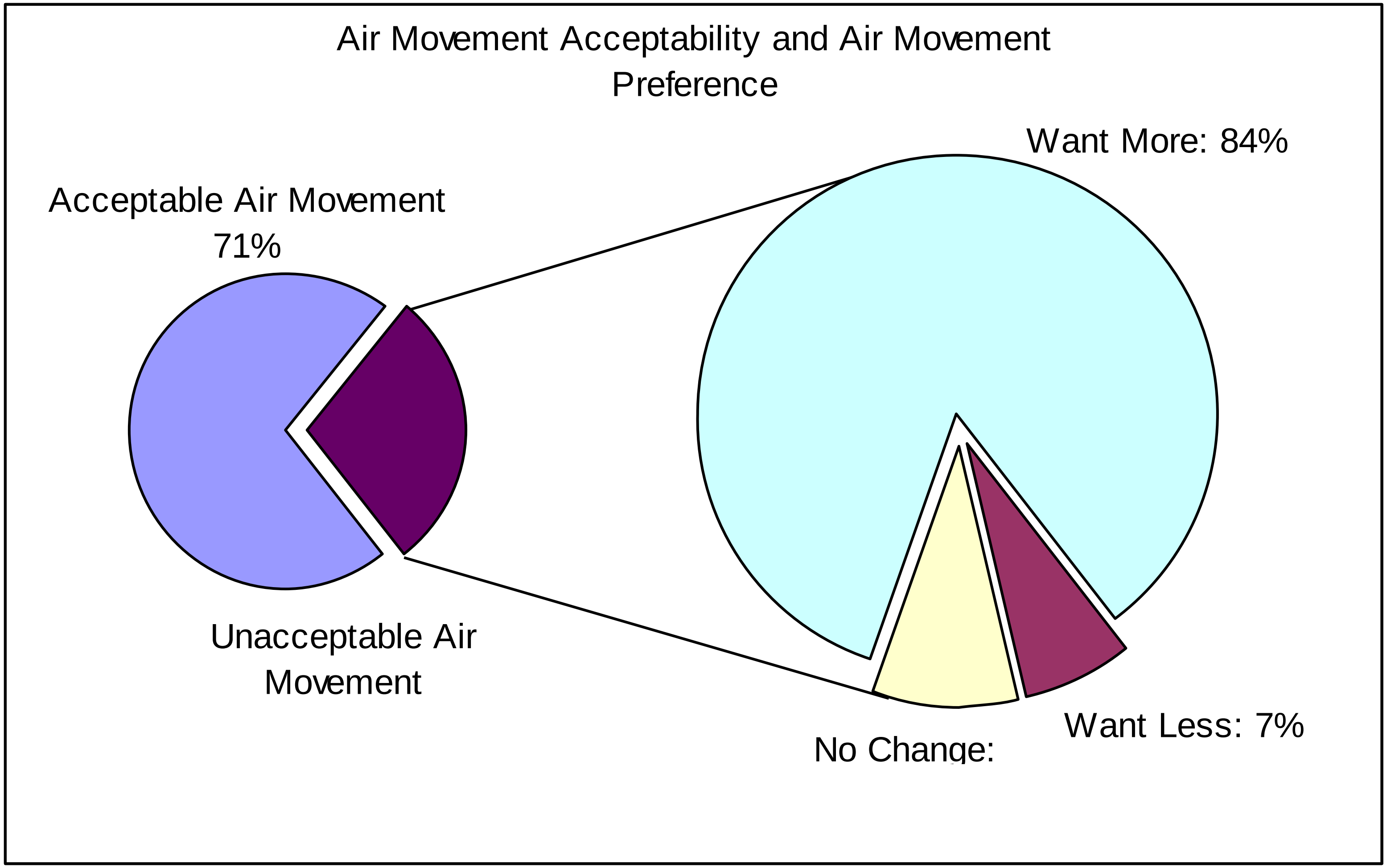
Hoyt, T., E. Arens, and H. Zhang. 2014. Extending air temperature setpoints: Simulated energy savings and design considerations for new and retrofit buildings. *Building and Environment*. doi: 10.1016/j.buildenv.2014.09.010
https://escholarship.org/uc/item/13s1q2xc

Air movement: building occupants often want more



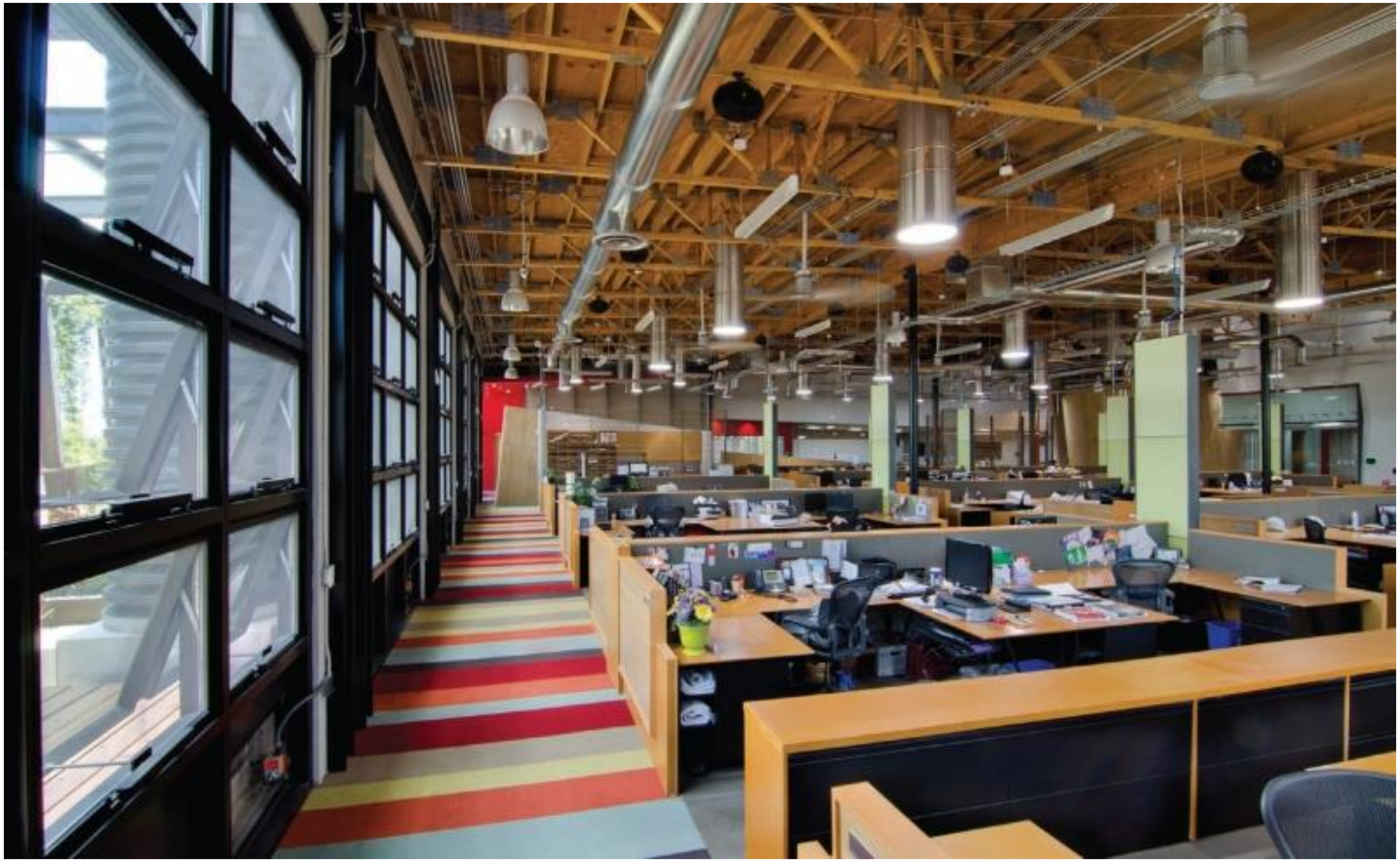
Zhang, H., E. Arens, S. Abbaszadeh, C. Huizenga, G. Brager, G. Paliaga, and L. Zagreus, 2007. Air movement preferences observed in office buildings. *International Journal of Biometeorology,* 51, 349–360

Air movement acceptability, and preferences



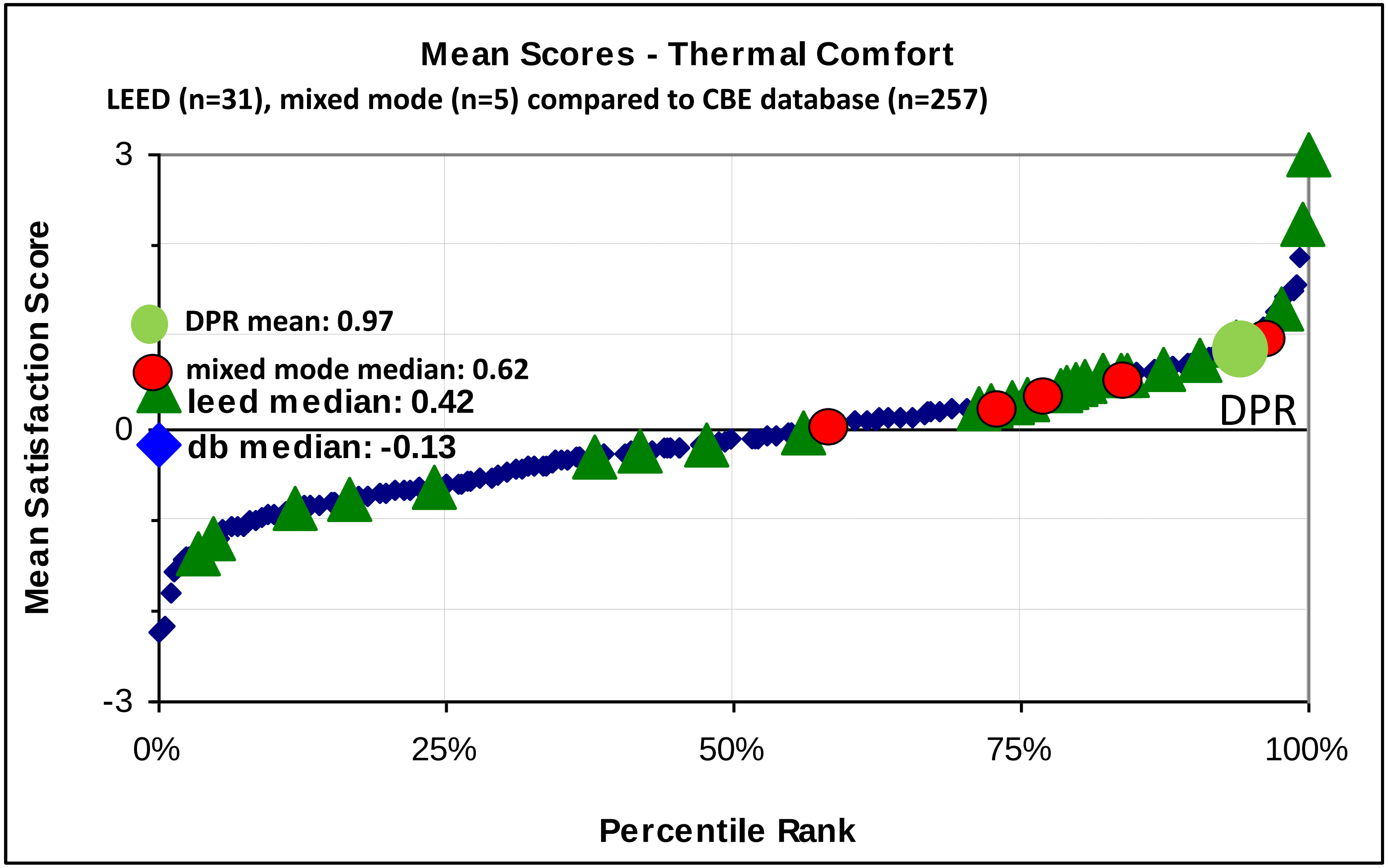
ibid

Example of what is possible: a zero net energy building in Phoenix Arizona, 82ºF (28ºC)



But is it OK for its white-collar occupants?

Thermal satisfaction ranking 91% in the CBE database



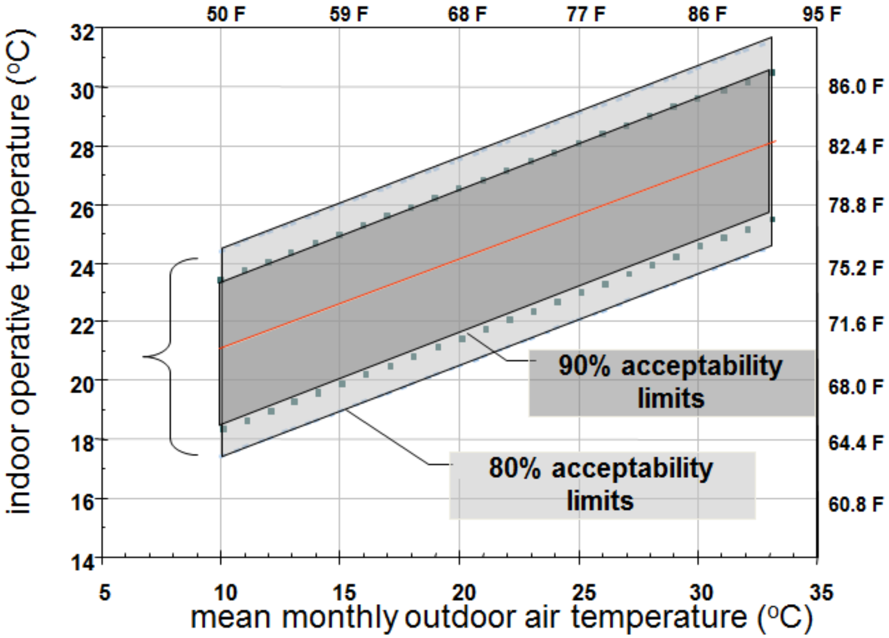
Windows (aka 'natural ventilation') and fans

Operable windows

Operable windows and fans

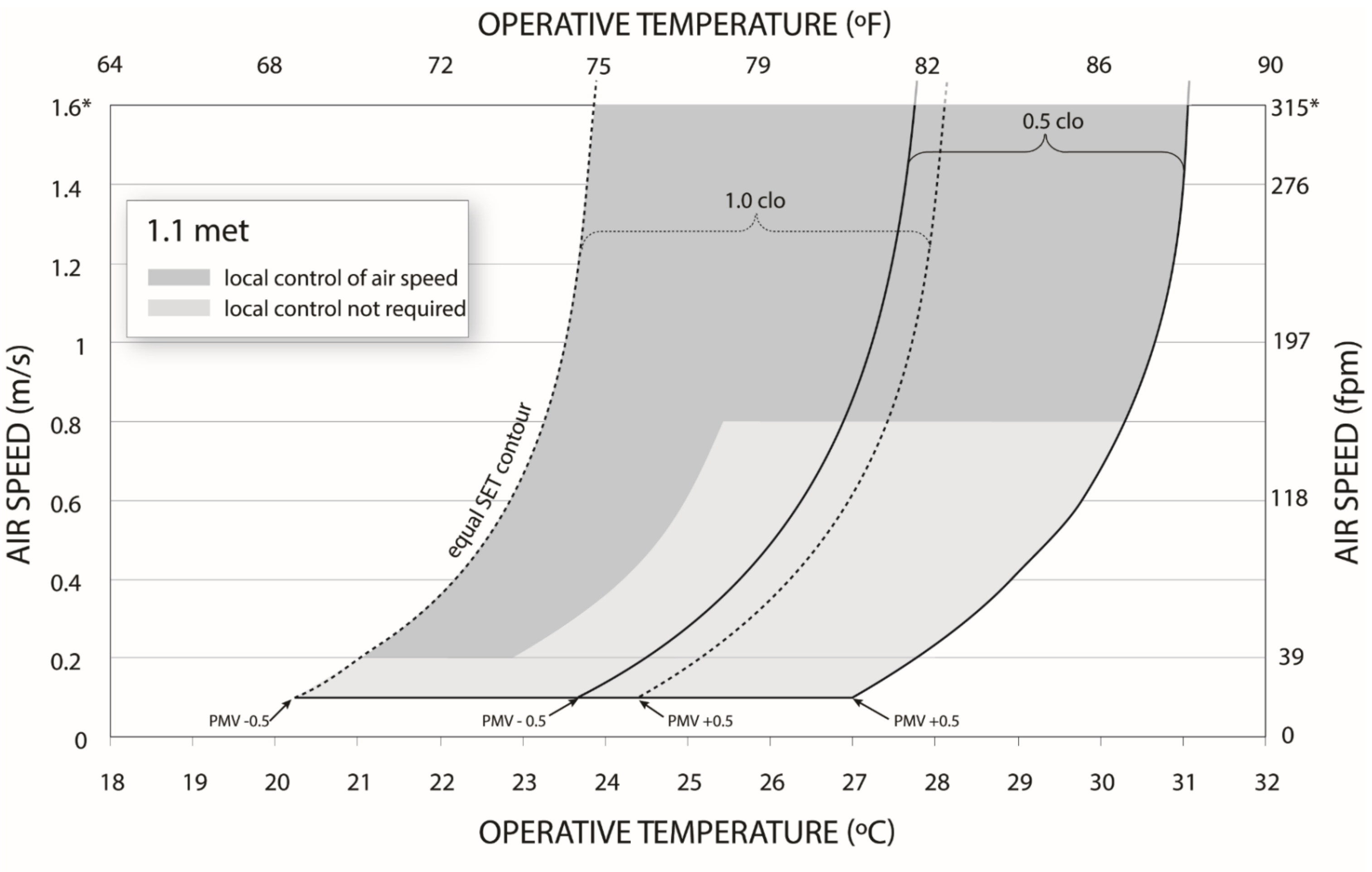
Standard 55 comfort zone for naturally ventilated buildings

- Empirical adaptive comfort model (adopted 2004)
- Limited to buildings with operable windows
- Local conditioning of environment– air movement cooling
- 13 degree F range!
- Causes not fully known; occupants' personal control of air movement seems to be a major factor



de Dear, Richard; & Brager, G. S.(1998). Developing an adaptive model of thermal comfort and preference. ASHRAE Transaction, 104

Elevated air movement ASHRAE standard (2013,4)

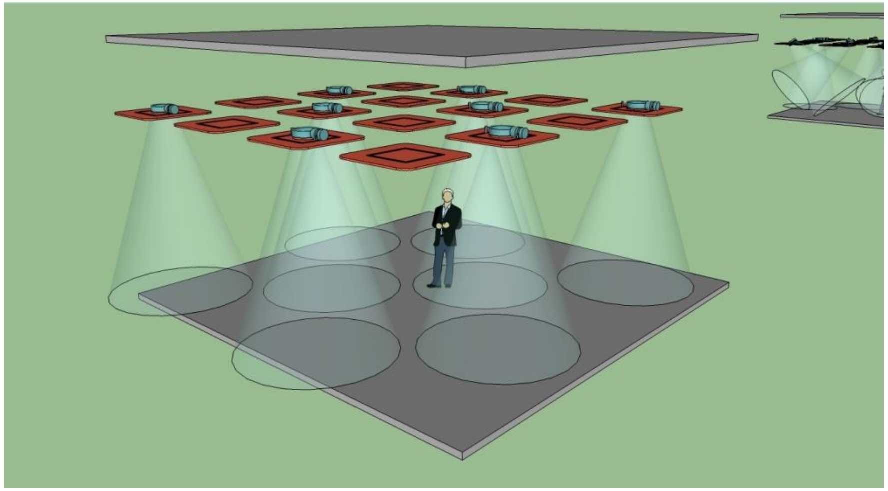


* There is no upper limit to air speed when occupants have local control.

Arens E., S. Turner, H. Zhang, G. Paliaga, 2009, "A Standard for Elevated Air Speed in Neutral and Warm Environments," *ASHRAE Journal*, May 51 (25), 8 – 18

Implementing air movement within a space

- Overhead fans are most general source
- Design guidance lacking
- Objective of CARB study: determine cooling effectiveness under several conditions at 82.5°F
  - With and without desks
  - Fan fixed and oscillating
  - Low and medium fan speed levels
  - Varying distance from the fan
- Added tests to cover hotter and more humid environmental conditions



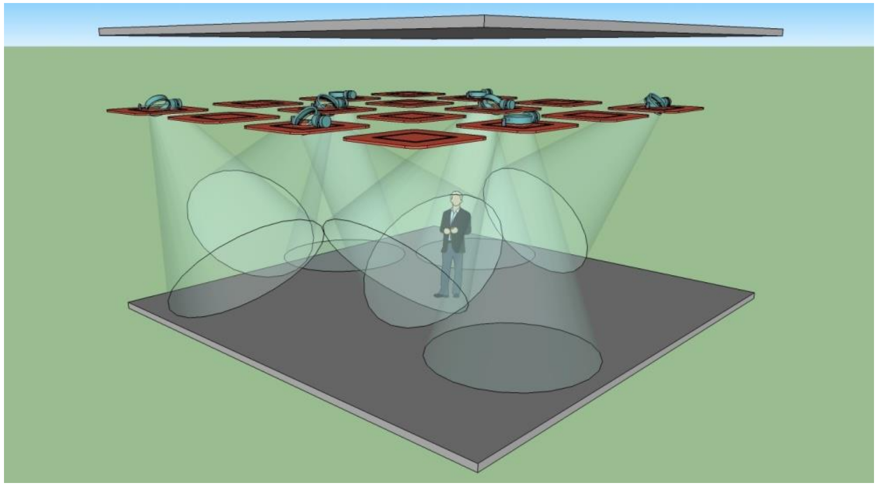
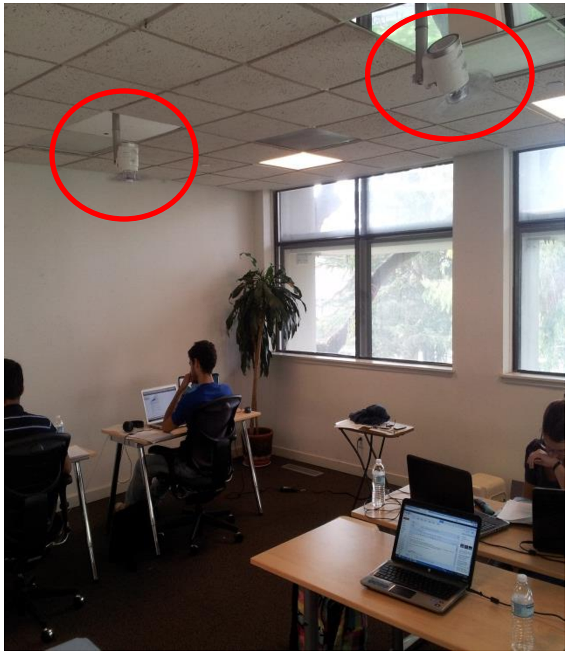
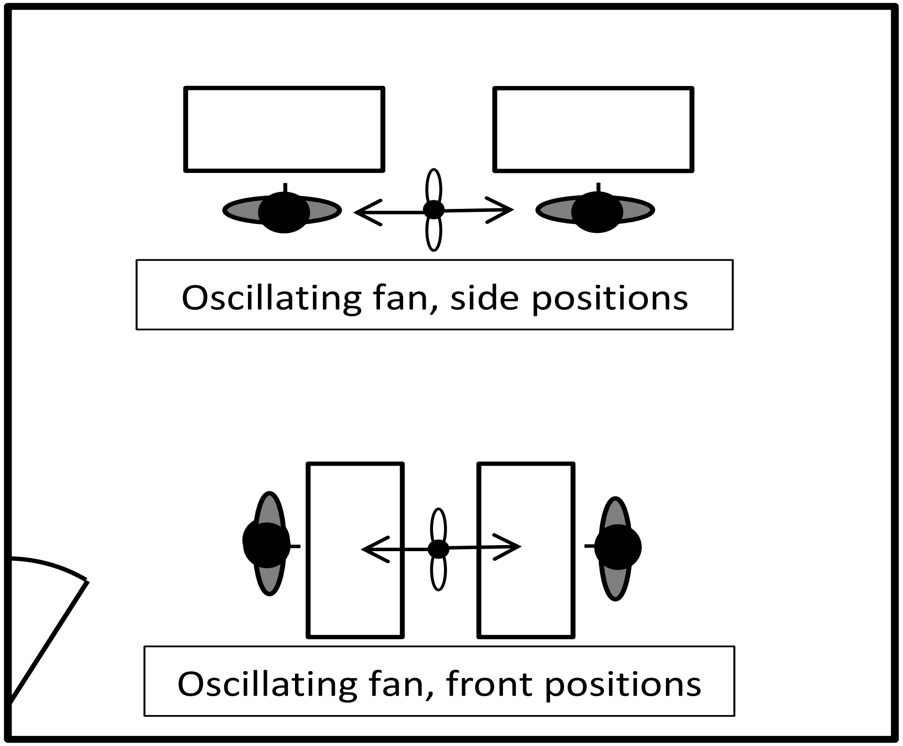


Image from Armstrong World Industries

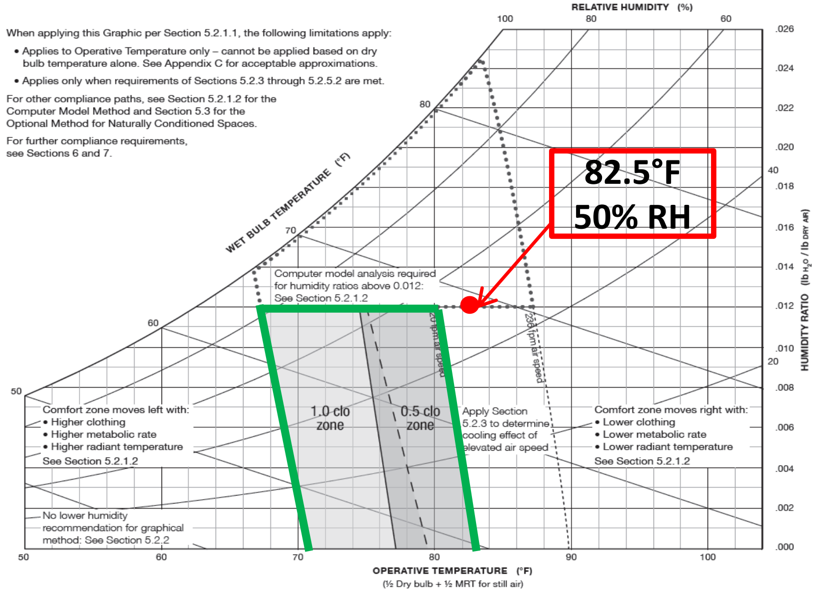
Study 1: test of fixed and oscillating fan 82.5°F



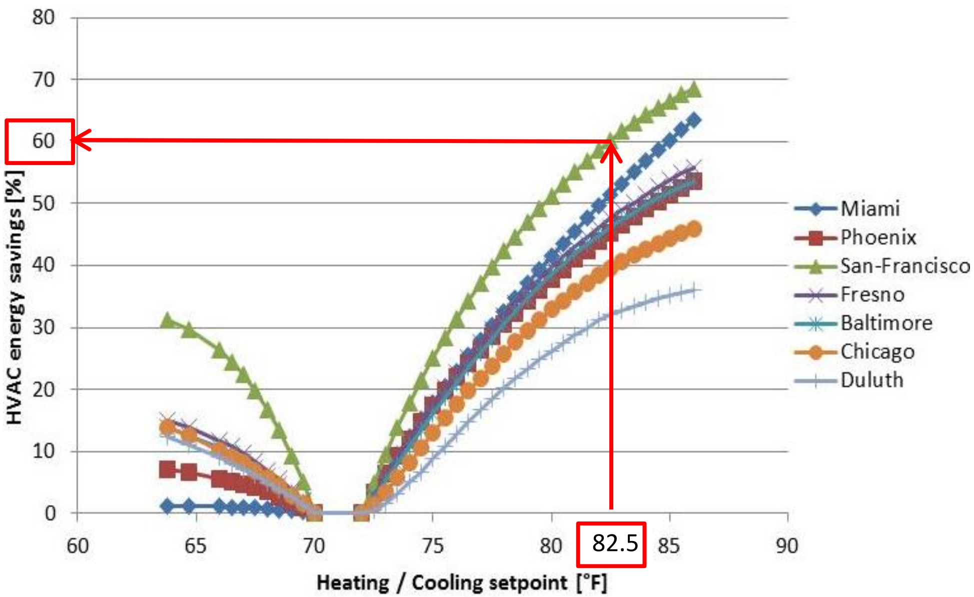


Summer clothing with short-sleeve shirts; 0.5clo
Office tasks

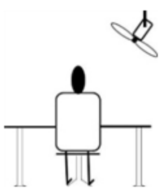
Test condition—comfort and energy



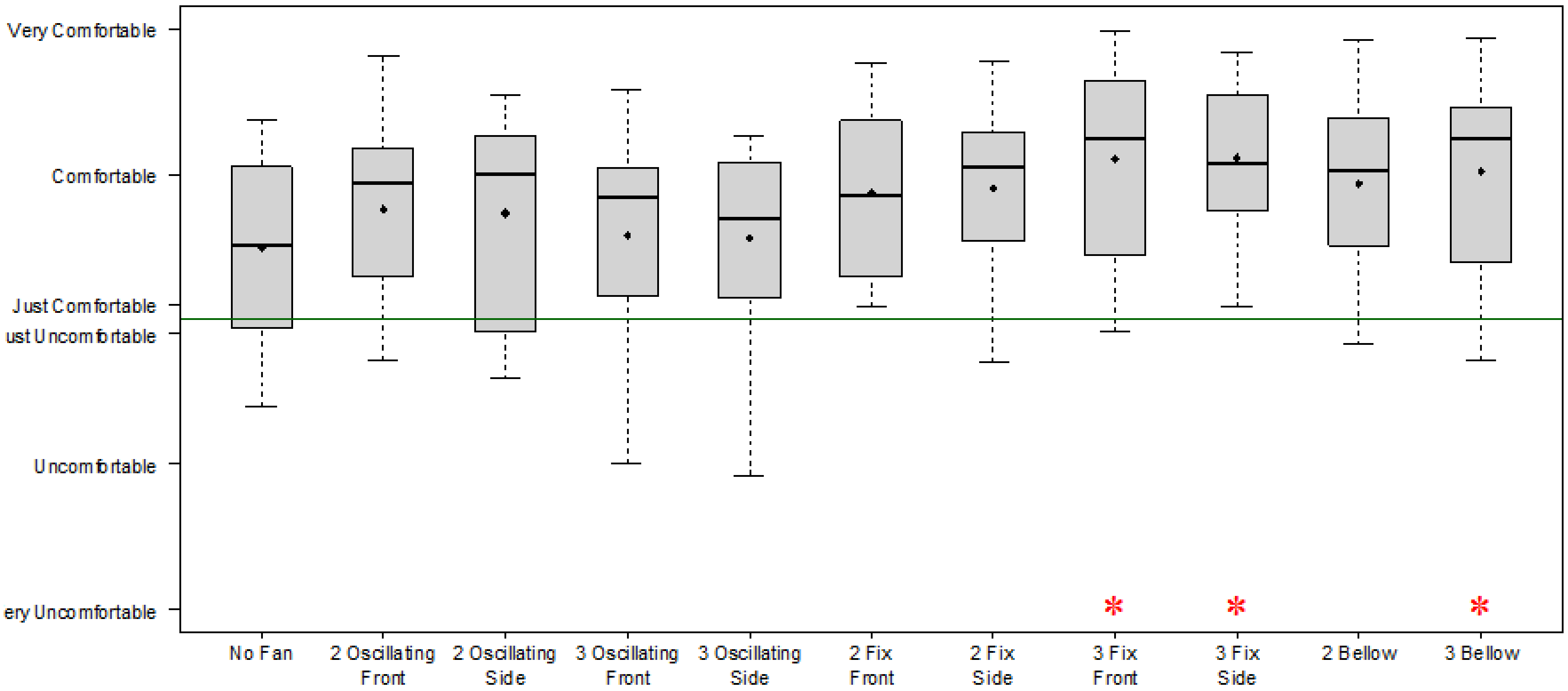
ASHRAE Standard 55



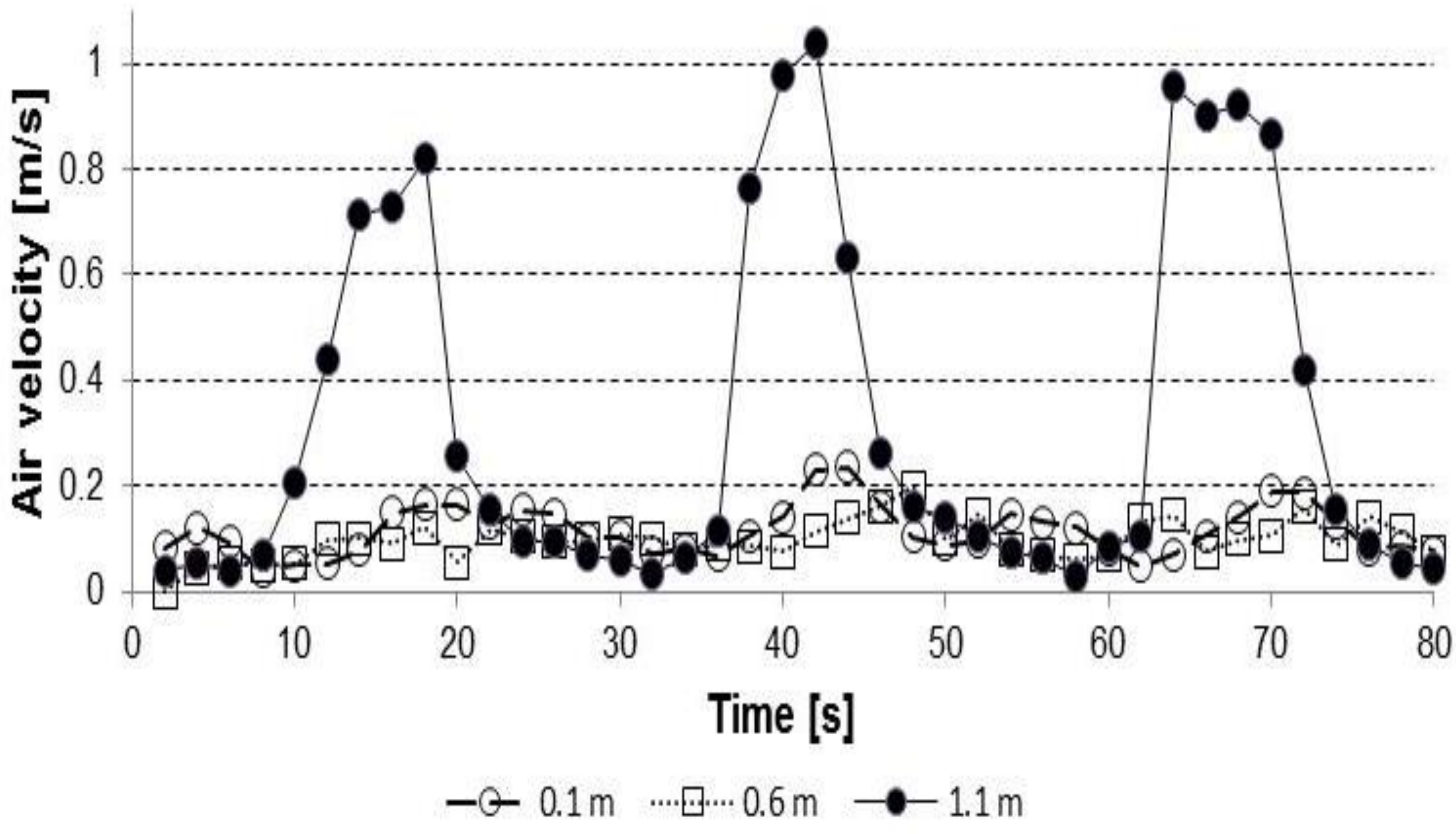
Air flow configurations

Subject position	Fan mode	Power level	Configuration code
 Front	Fix	2	2 Fix Front
		3	3 Fix Front
	Oscillating	2	2 Oscillating Front
		3	3 Oscillating Front
 Side	Fix	2	2 Fix Side
		3	3 Fix Side
	Oscillating	2	2 Oscillating Side
		3	3 Oscillating Side
 Below	Fix	2	2 Fix Below
		3	3 Fix Below

Whole-body thermal comfort



Velocity profiles for "oscillating" configuration



Results of the first study

- Both the fixed and oscillating fans provided comfort at the test condition
- However the oscillating mode was not statistically different from the base case without a fan
- The chosen oscillation frequency was too low, causing discomfort in the ~15 second period that air movement was absent. The recurrence interval should be shortened.

Study 2 and 3: Ceiling and floor fan comfort studies in warm and humid environments

Study 2:
Vertical airflow

Ceiling fan

No control

Six environmental conditions

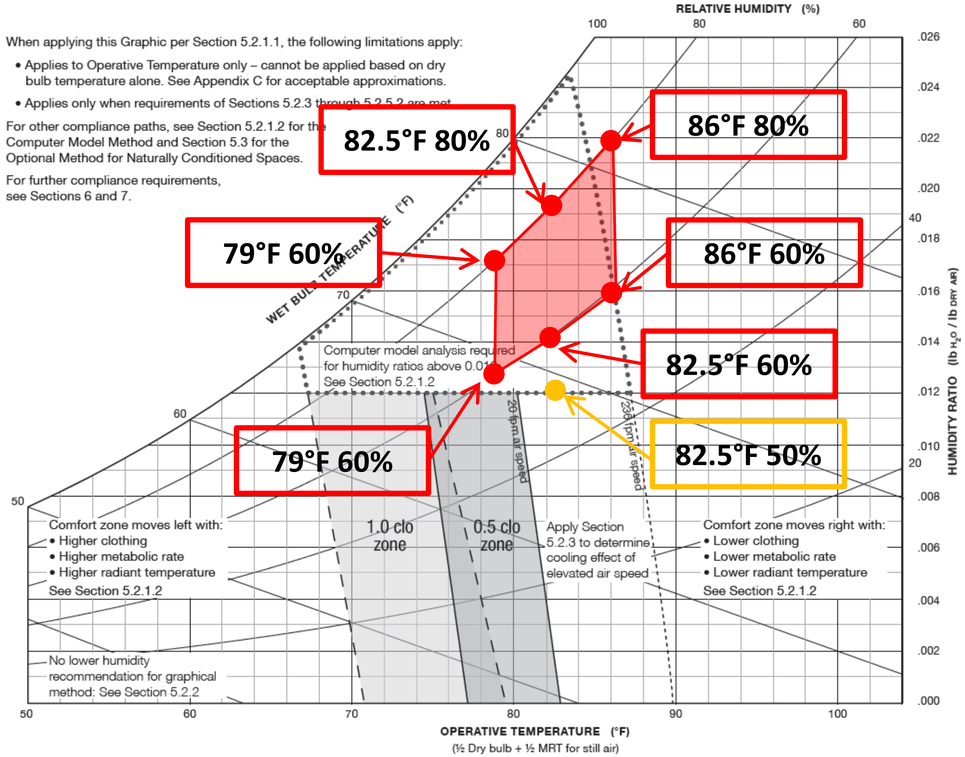
Study 3:
Horizontal airflow

Floor fan

Control

Six environmental conditions

Test conditions

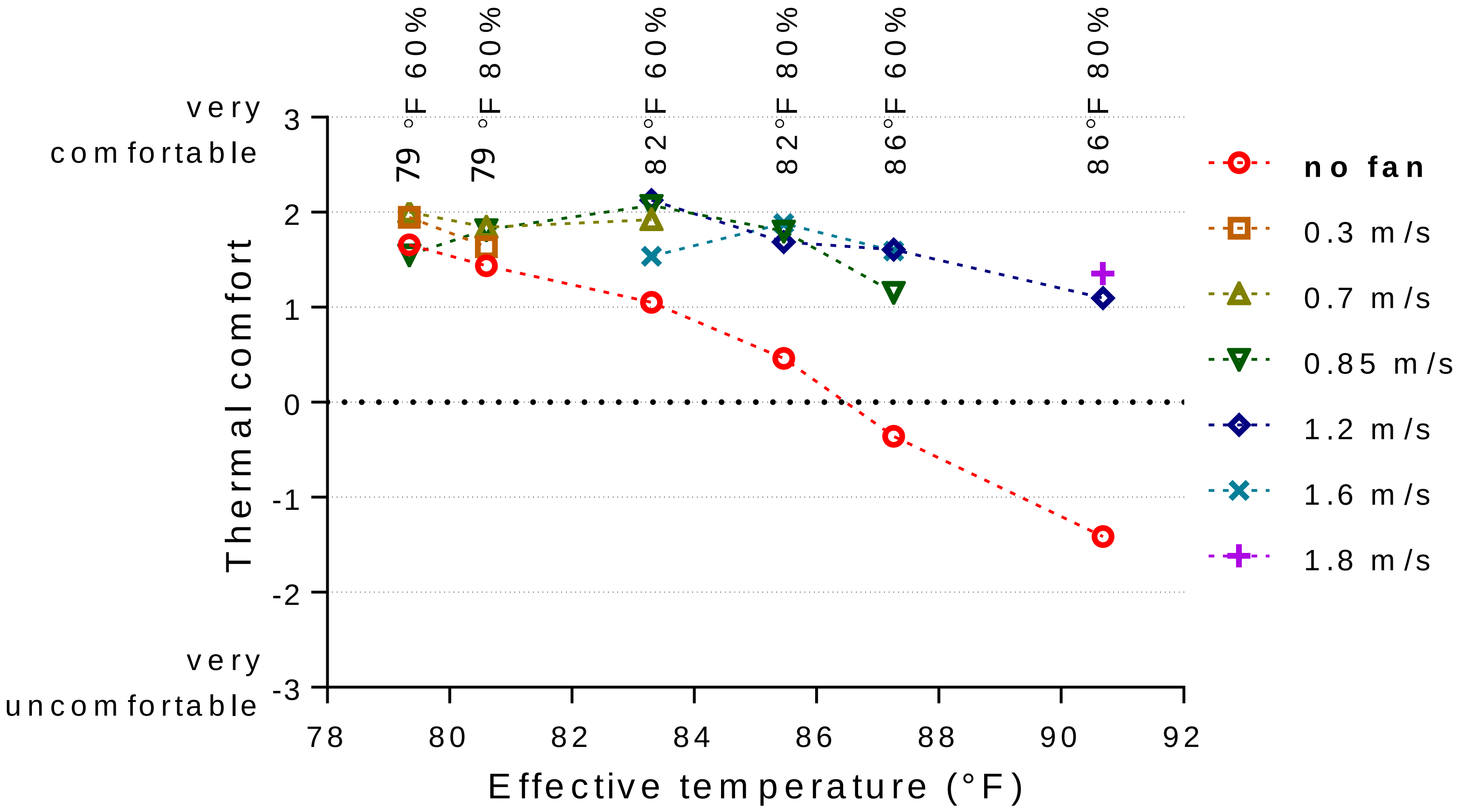


ASHRAE Standard 55

- Studies 2,3
- Study 1

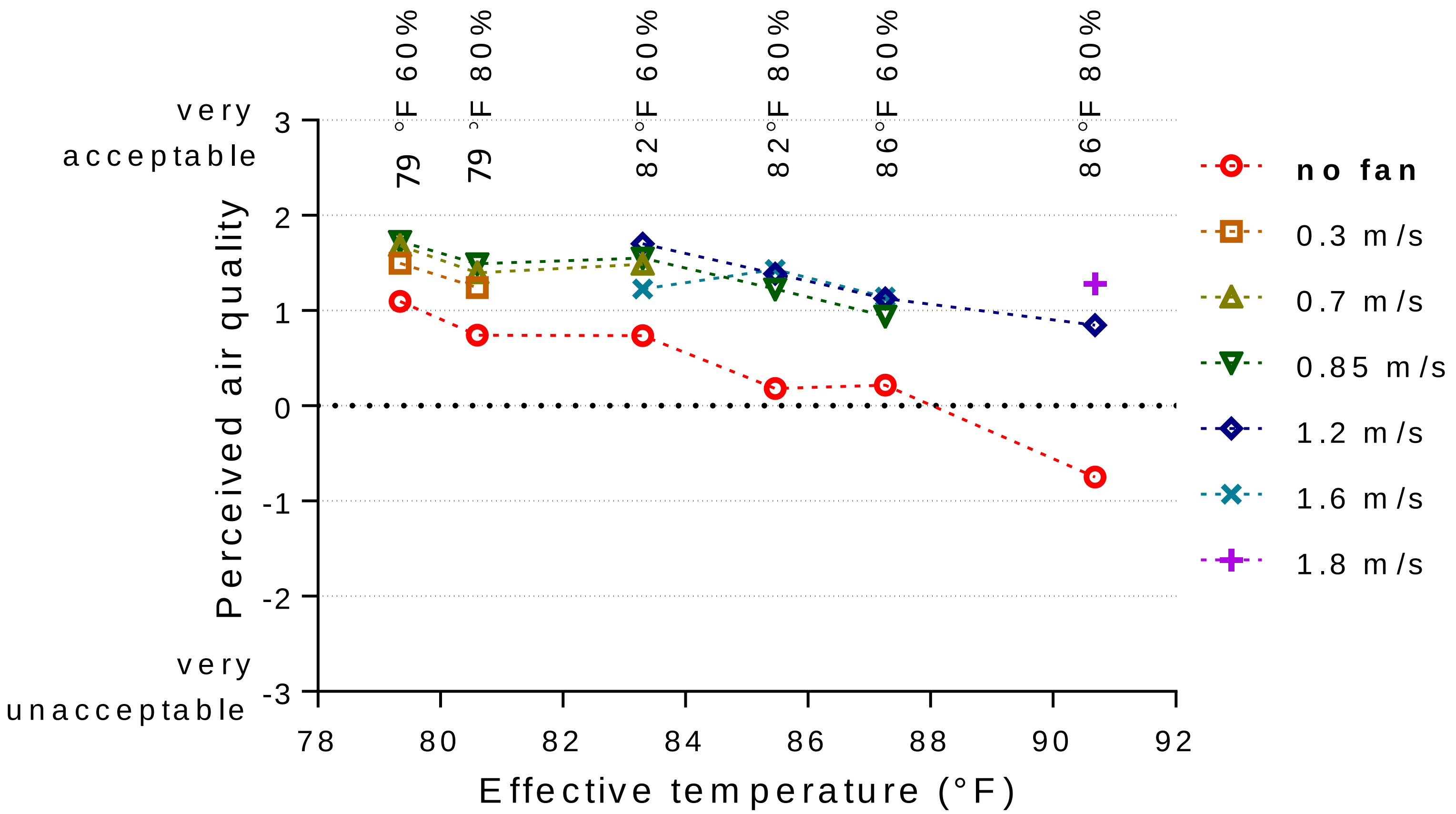
Thermal comfort with ceiling fan

Vertical air movement maintains thermal comfort



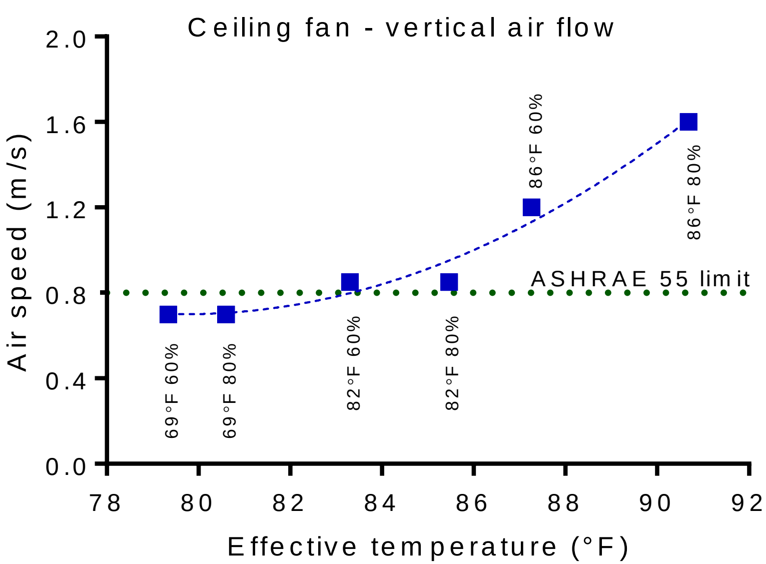
Perceived air quality with ceiling fan

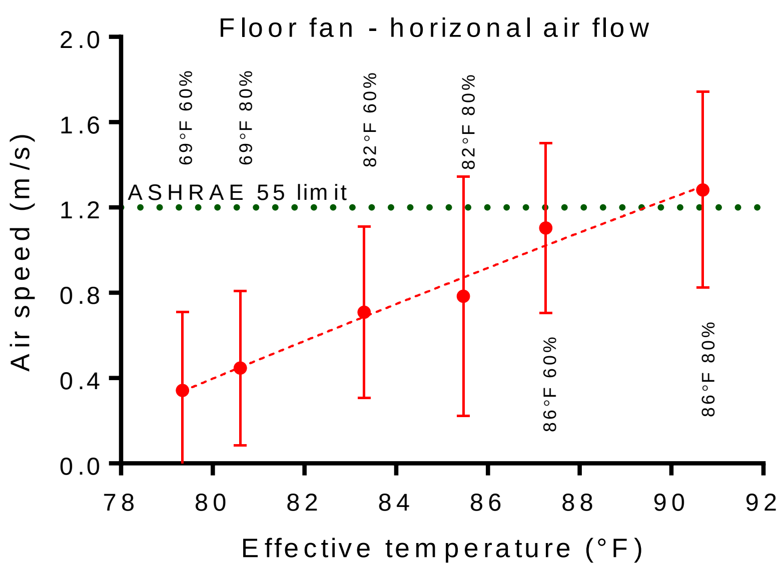
Air movement maintains perceived air quality



Preferred air speed for comfort

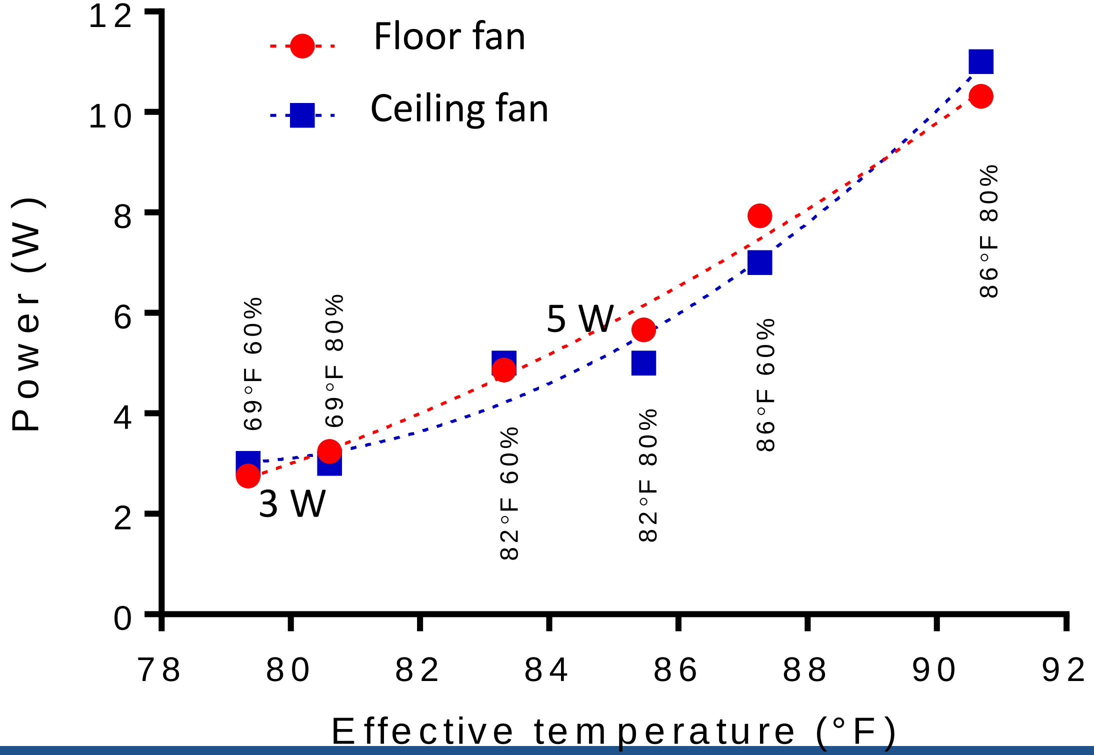
- With vertical air flow, subjects' preferred air speed can exceed ASHRAE 55 limit (existing no-control limit is 0.8 m/s)
- Air speed chosen by subjects with horizontal air flow vary but can also exceed the ASHRAE 55 with-control limit of 1.2 m/s)





Measured power consumption of fans

Power consumption of both ceiling and floor fans is very low. Fan power per occupant was around 3W at 79º F, 5W at 82.4º F, and around 10W at 86º F.



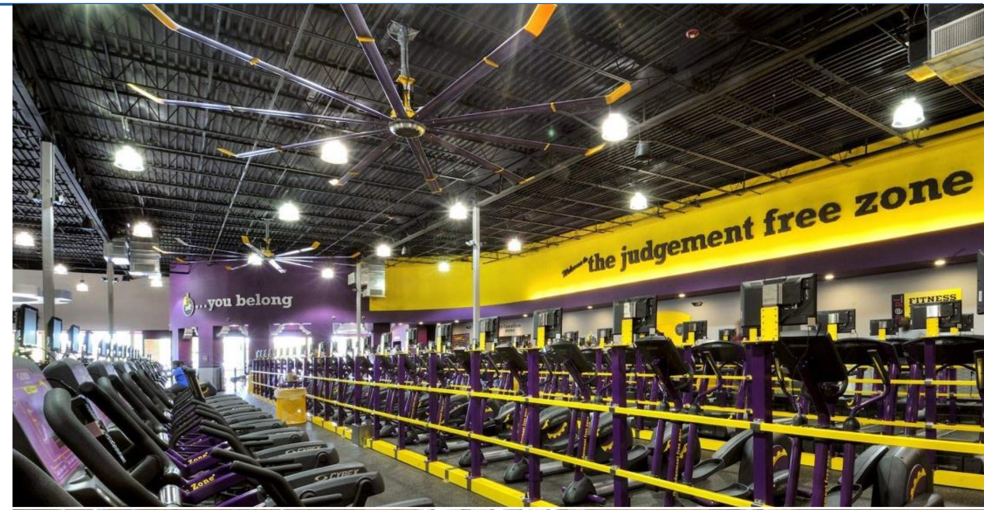
Study 4 – air movement cooling in sport facilities

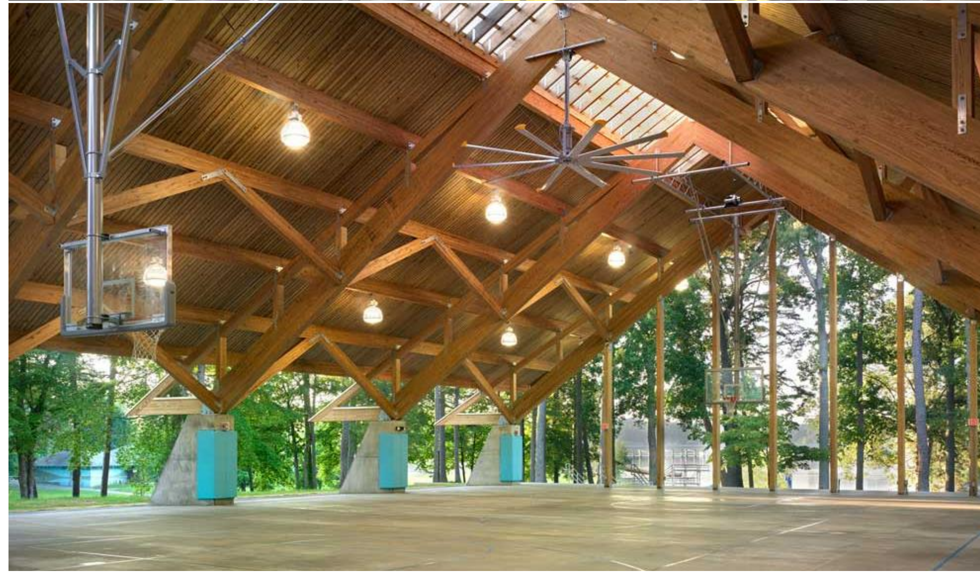
Objectives

- Study air movement cooling at higher than sedentary activity levels (met rates)

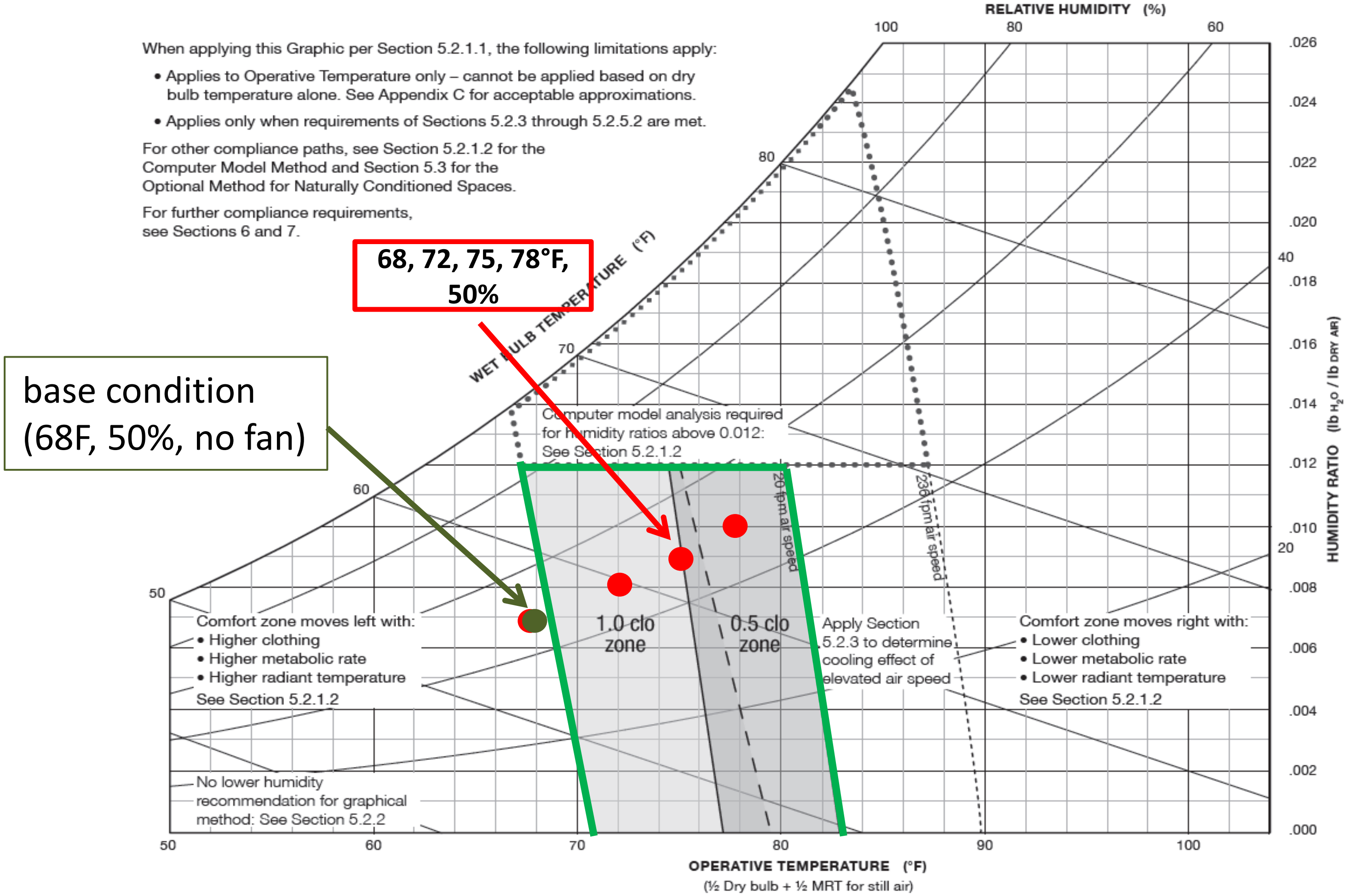
Approach

- Physiological tests
- Comfort surveys





Test conditions



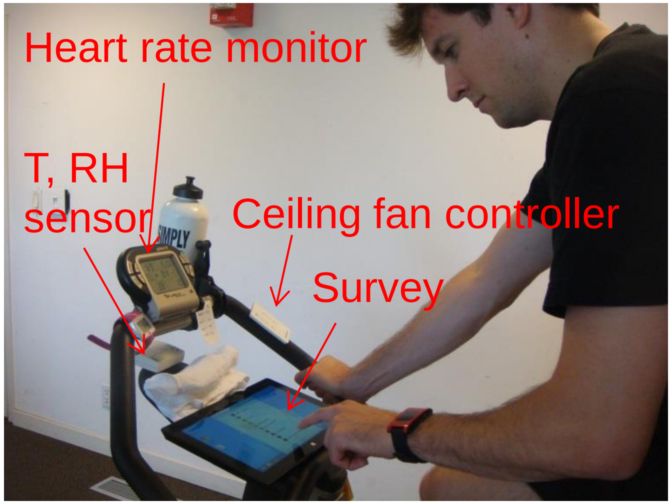
ASHRAE Standard 55

Study design

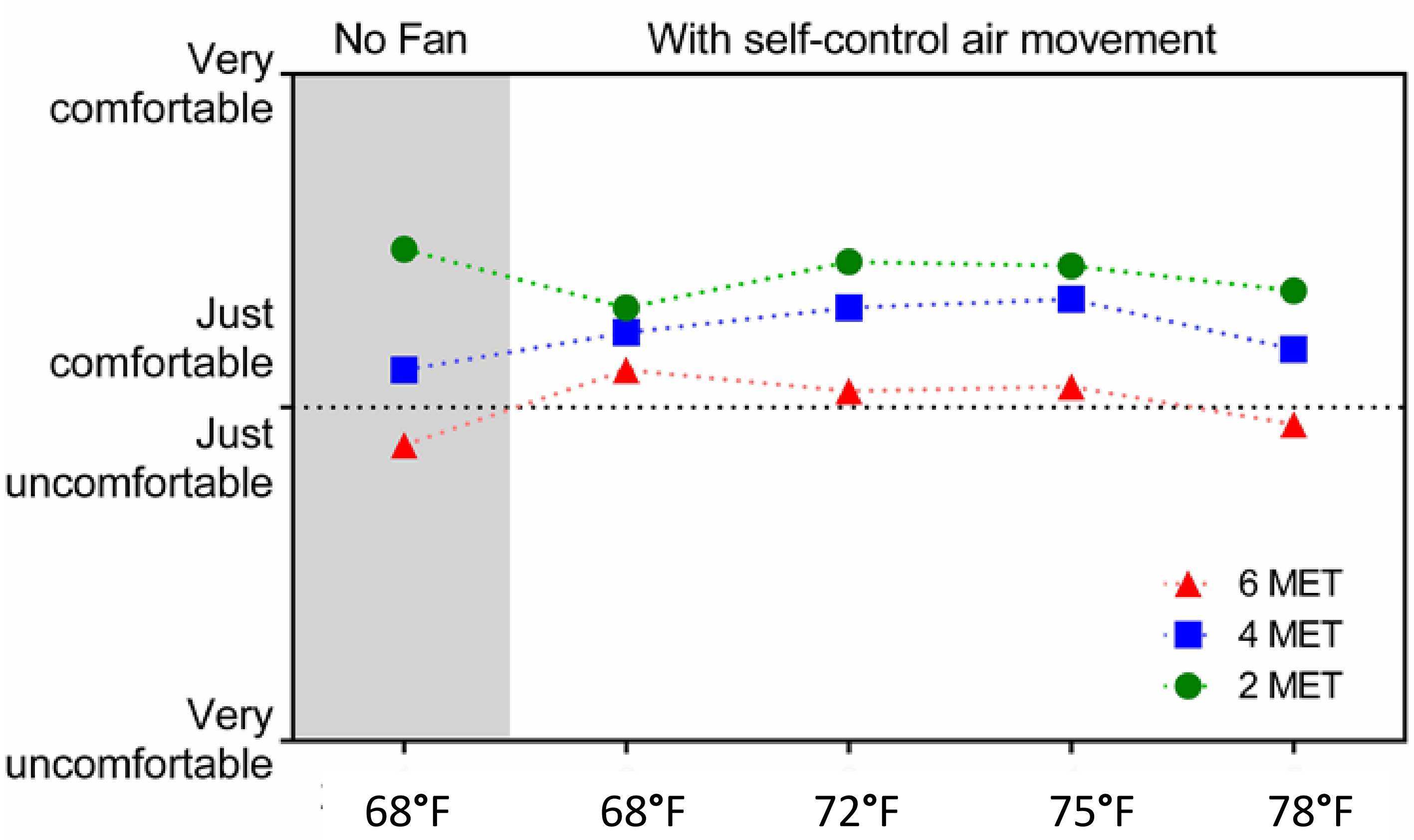
Metabolic level: 2, 4, 6 met

Subjects: 10 males, 10 females

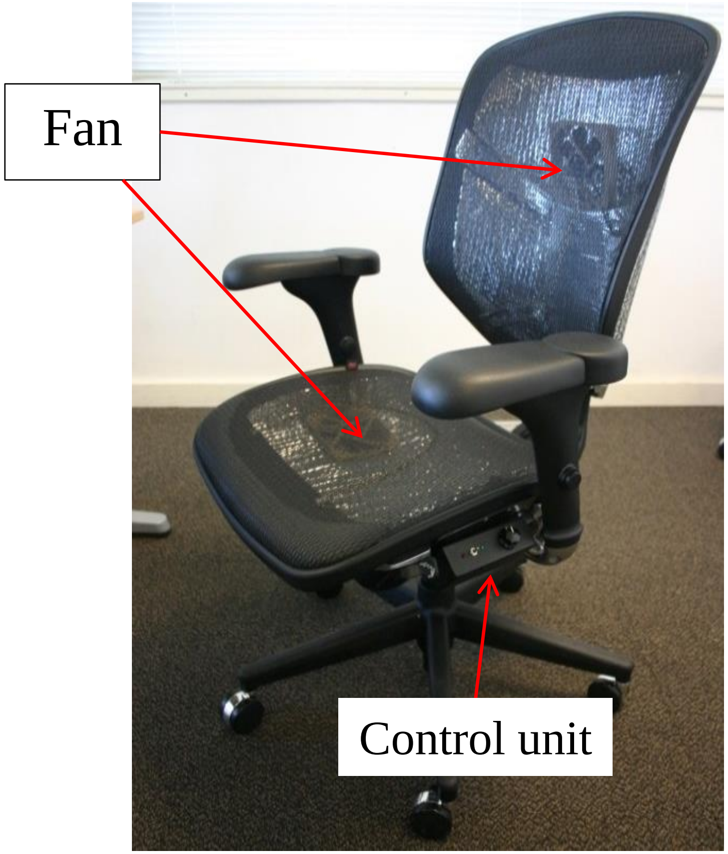
20 minute rides for each met level

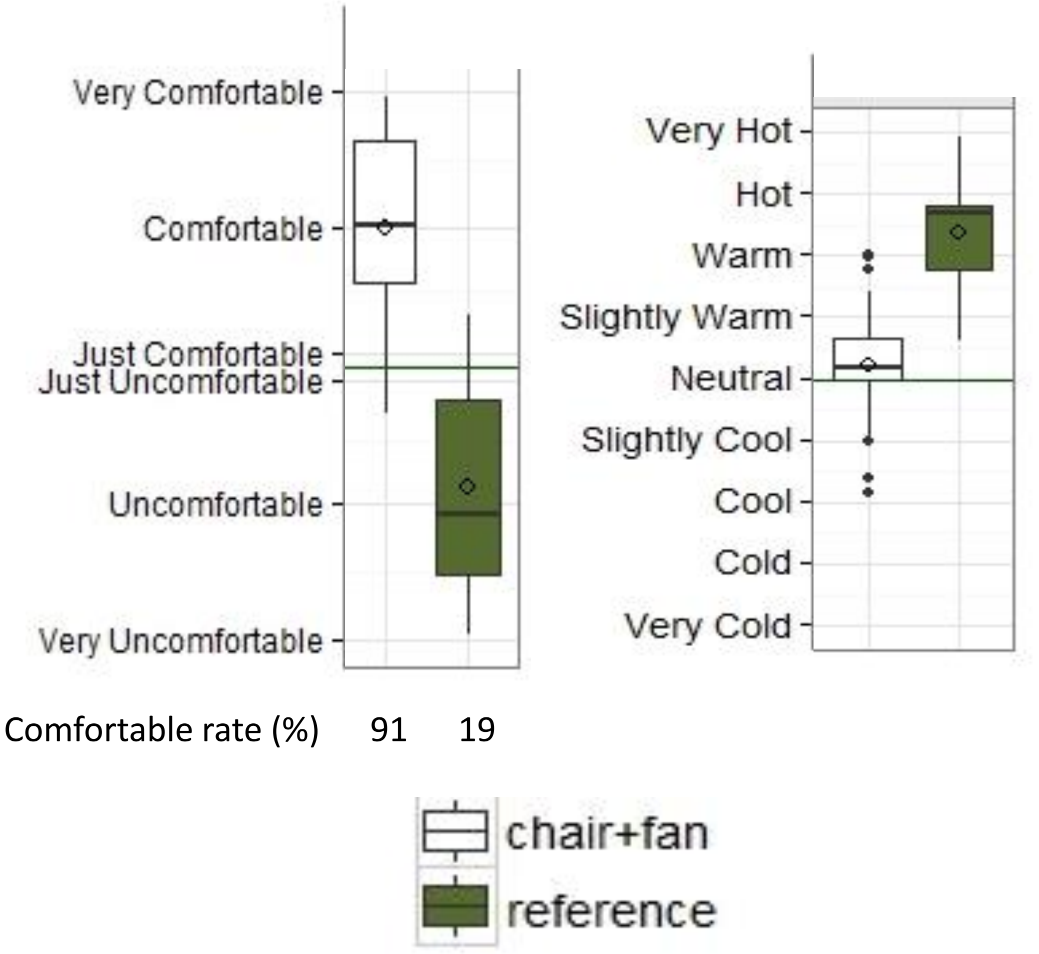


Fans provided comfort at high temperatures



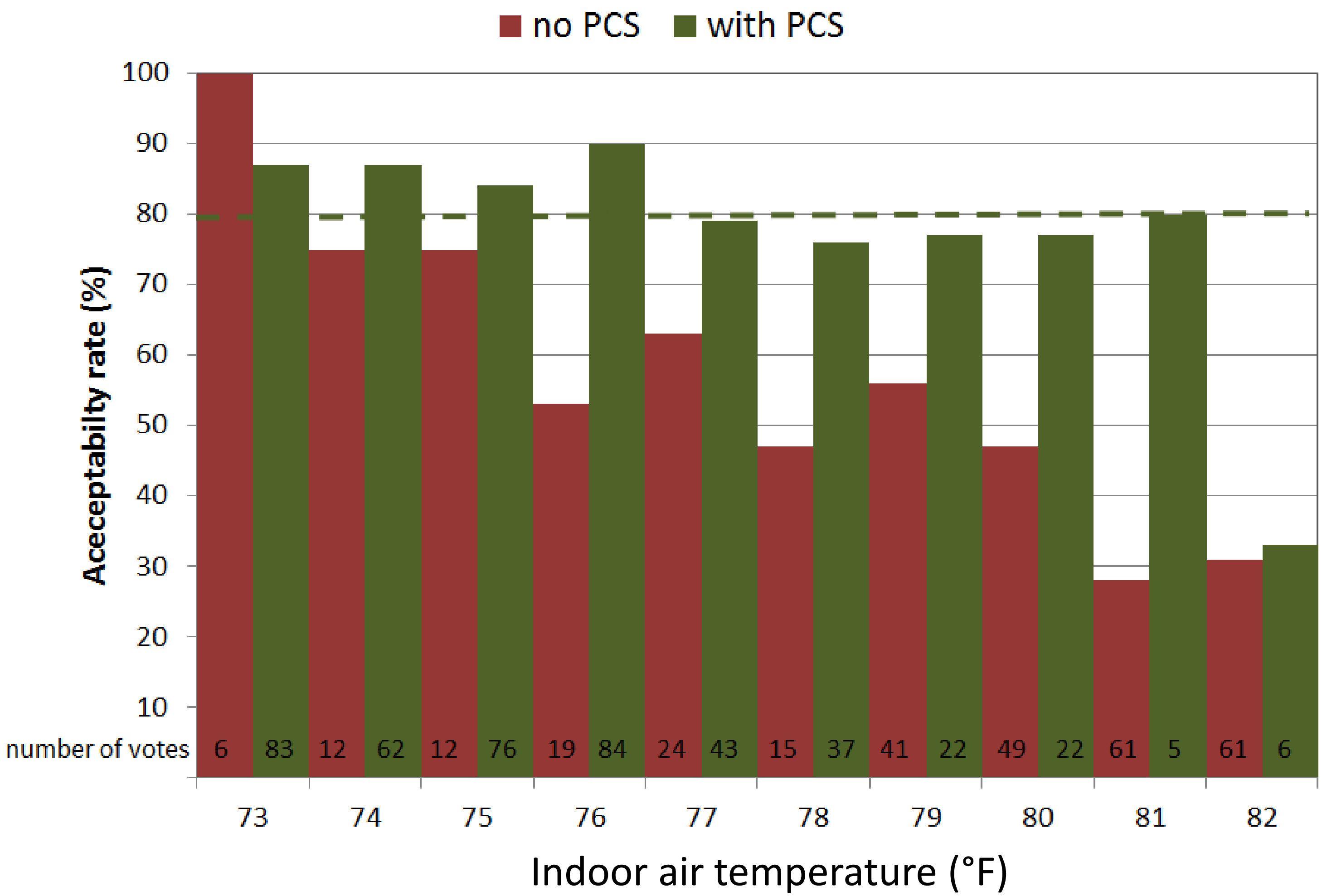
Summary of related work: near-body air movement within a heated/cooled chair (lab study at 84°F 50% RH)





Field study of chair in a campus building

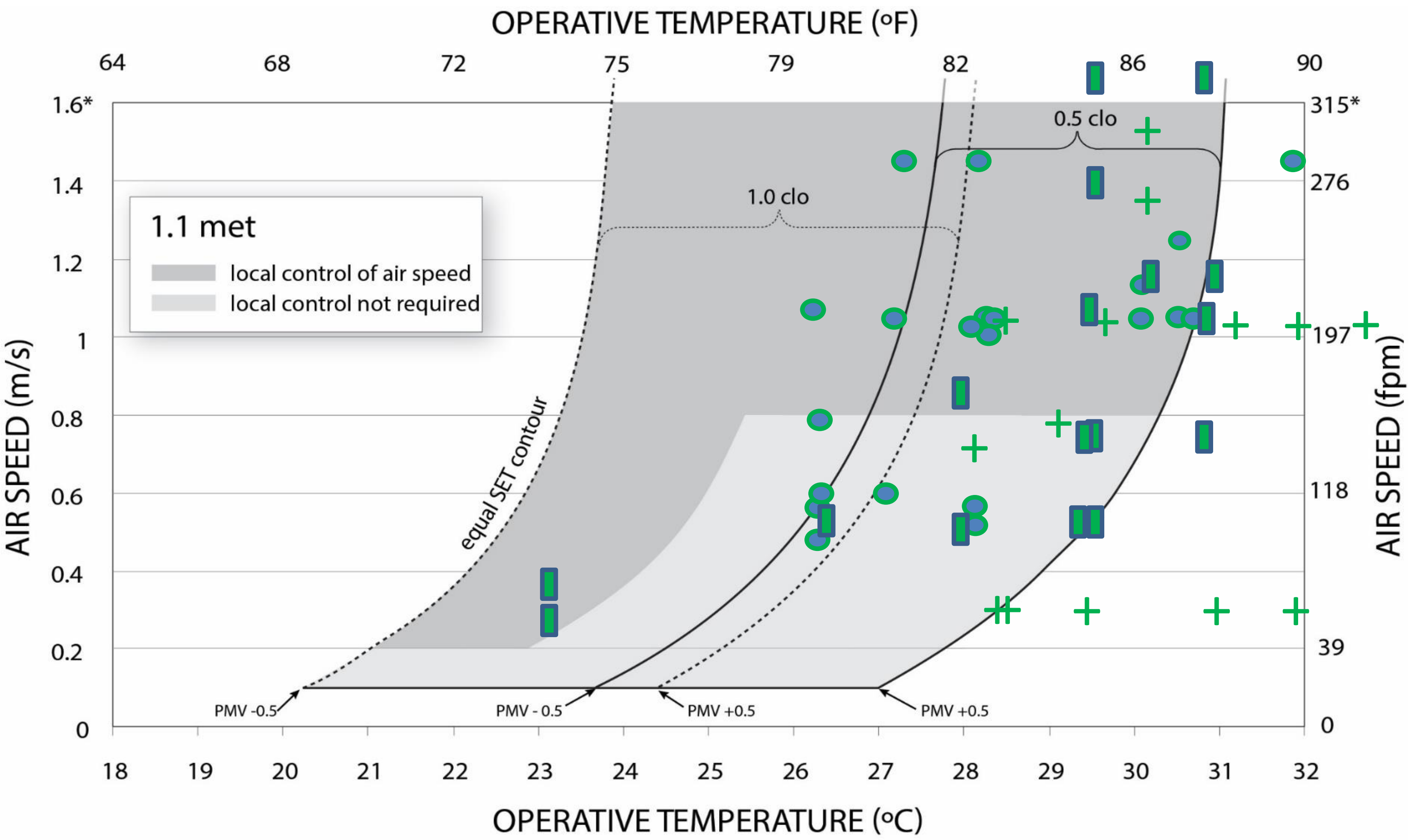
Acceptability rates with and without chairs (summer)



Without PCS, acceptability rate is about 50 – 75%

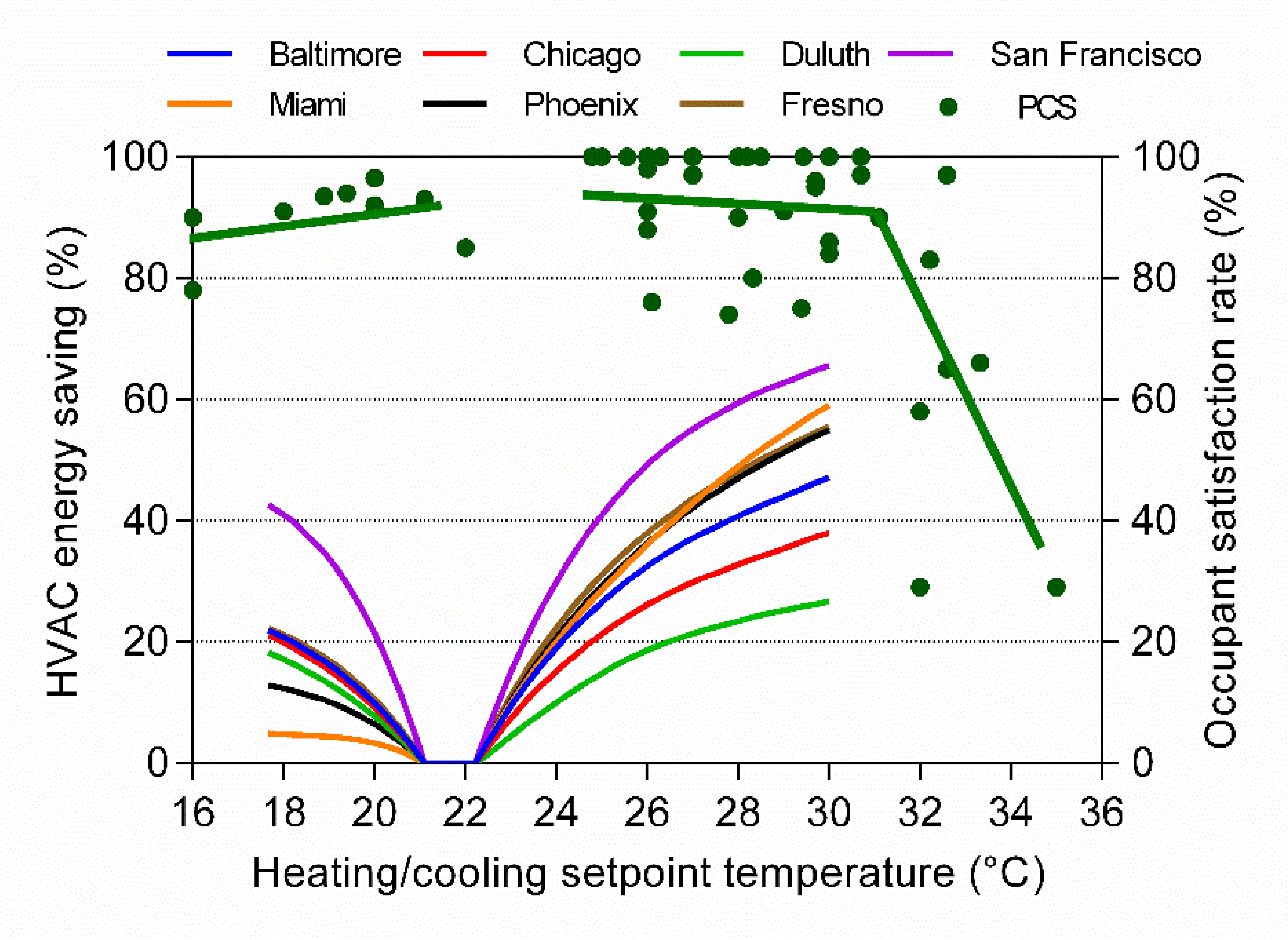
With PCS, acceptability rate is about 75 – 90%

Summary of air movement studies in the literature



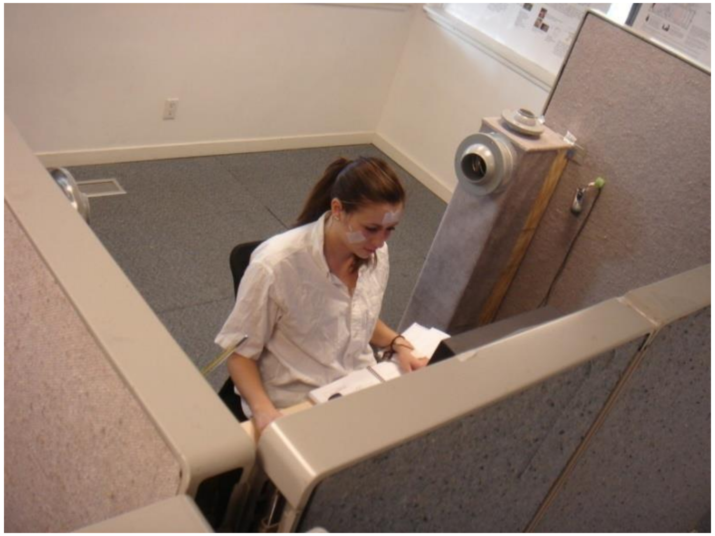
Zhang, H., E. Arens, Y. Zhai 2015, "Review of the corrective power of personal comfort systems in non-neutral ambient environments" *Building and Environment,* April

Occupant satisfaction rates under air movement cooling



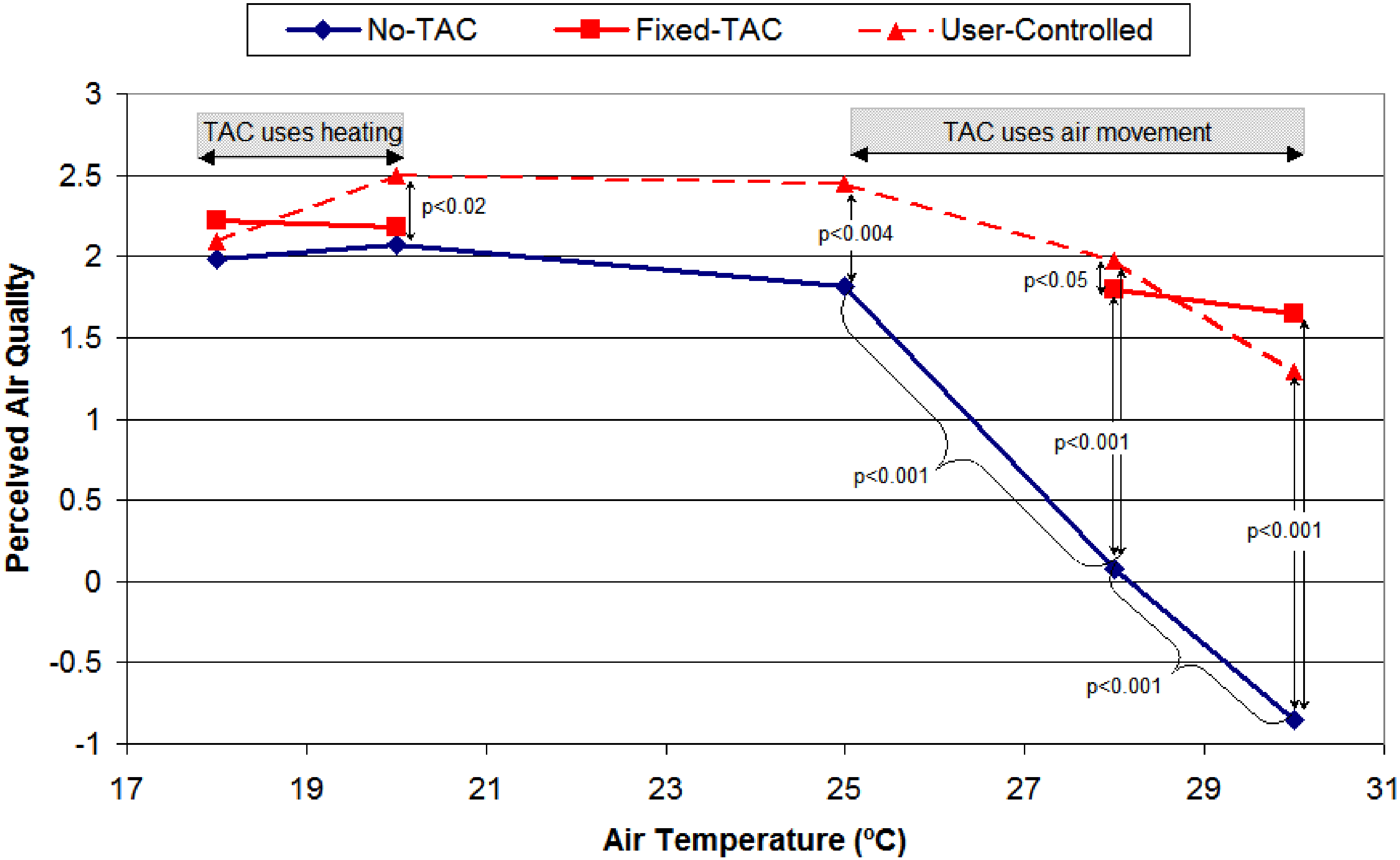
Air movement and perceived air quality

Study of air movement cooling

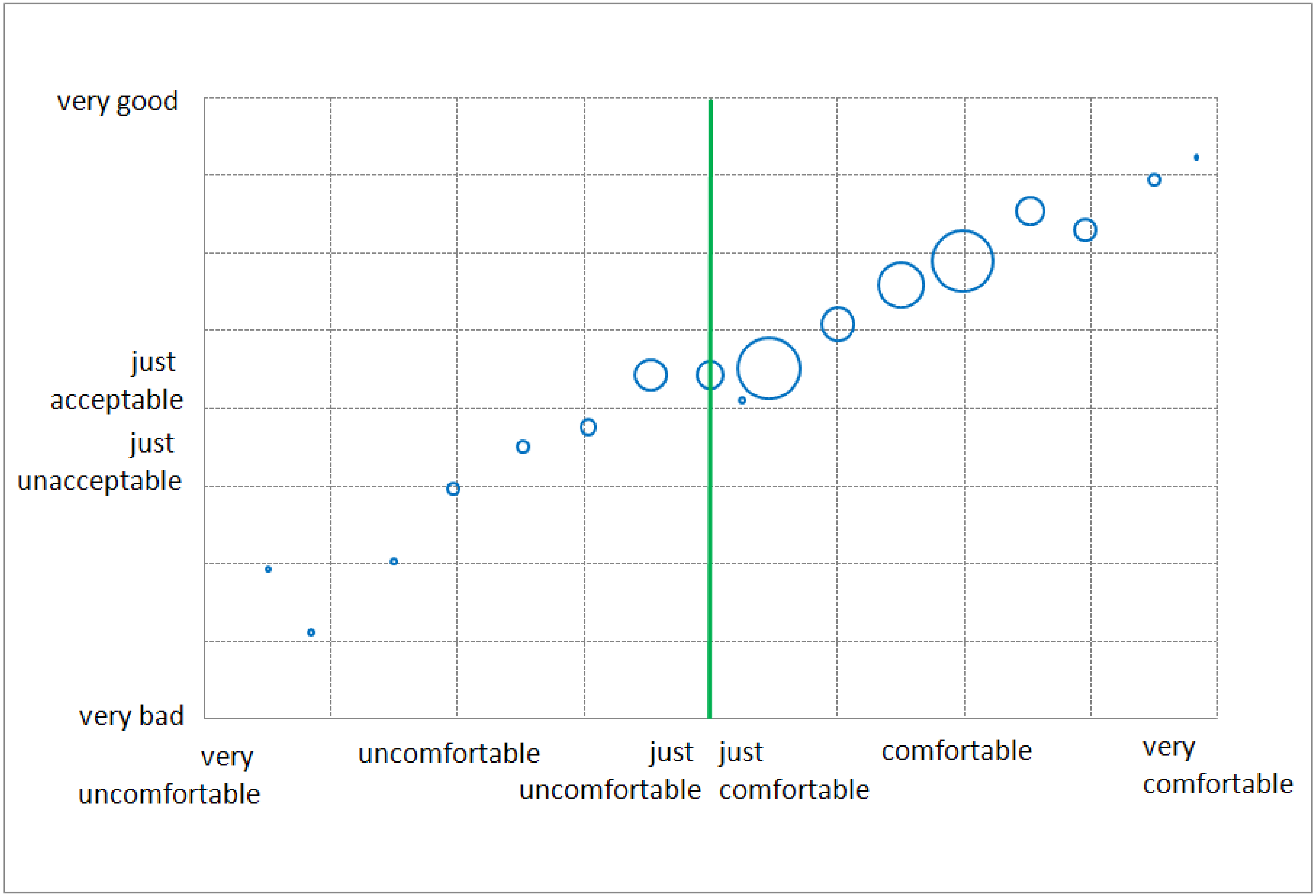


- **2 tests/day**
- **2 people/test**
- **28^{o}C (82.4F), 50%RH**

Impact of airspeed on perceived air quality

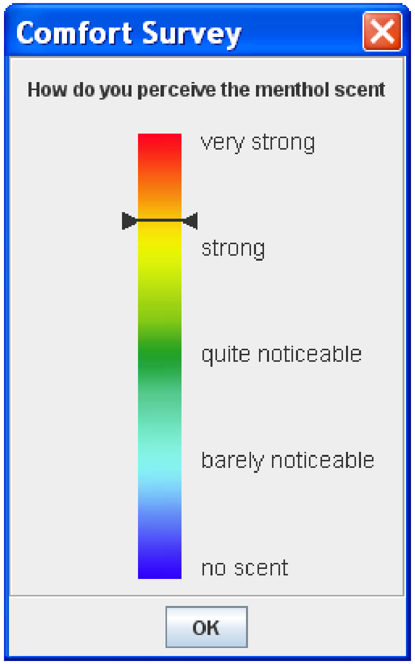


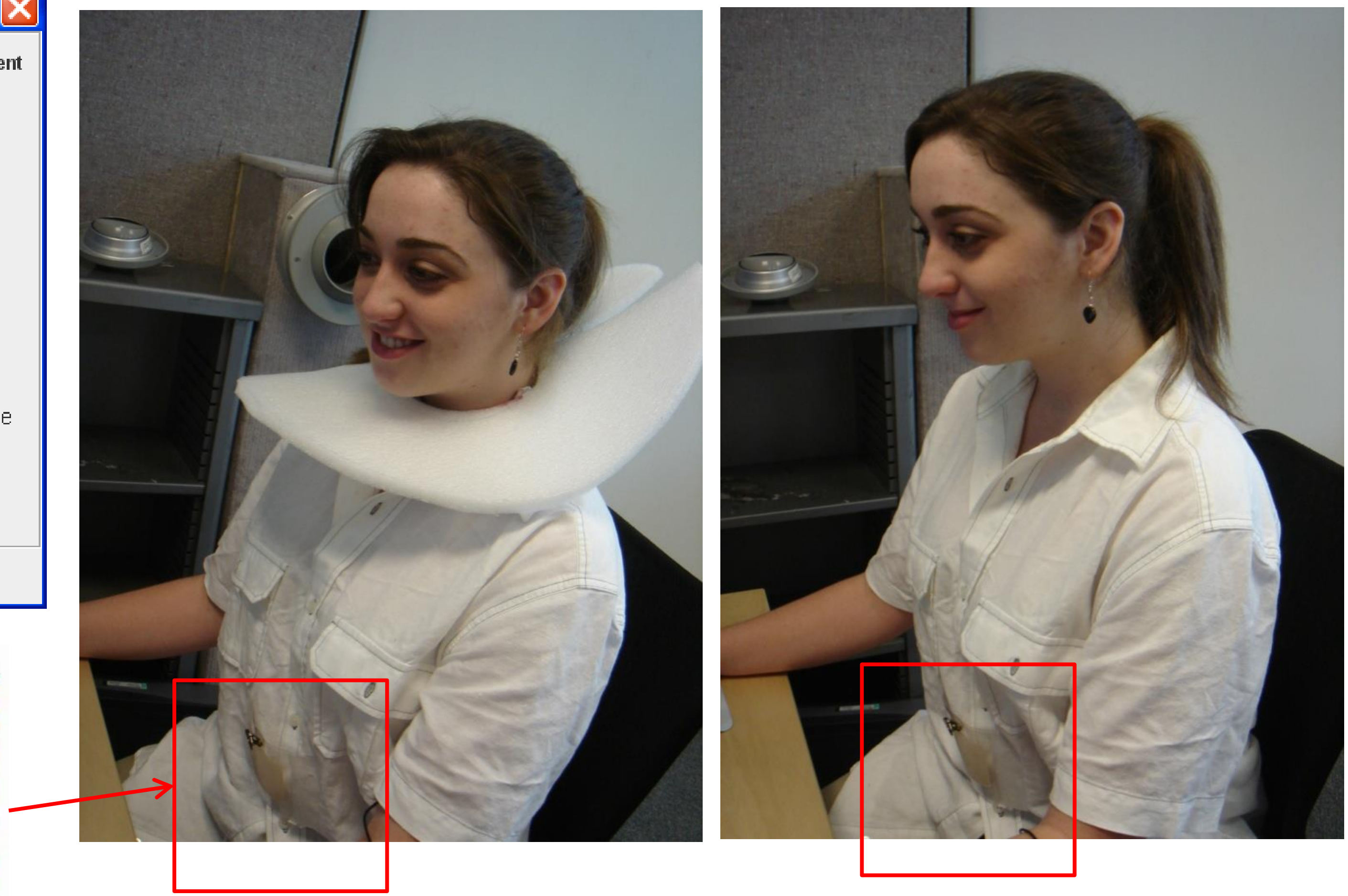
Thermal comfort versus acceptability of perceived air quality



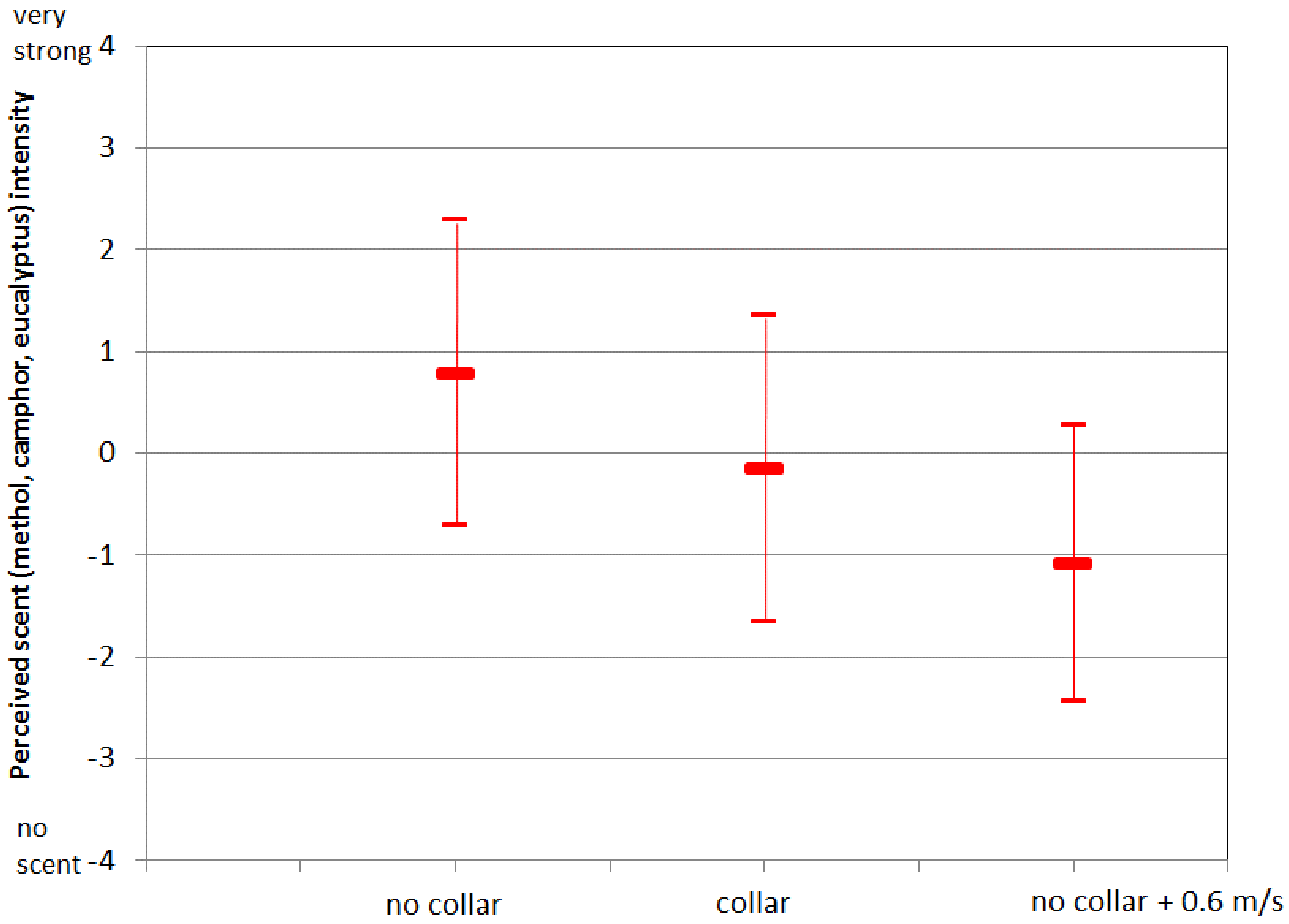
Investigating body plume effects

Creating body odor; isolating body plume





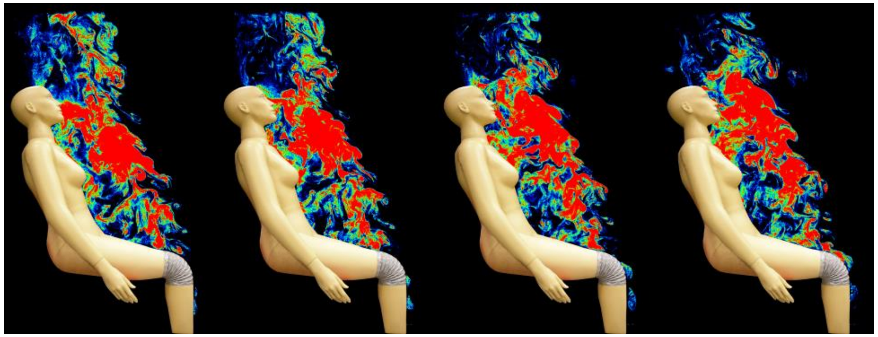
Scent intensity: collar versus airspeed disruption



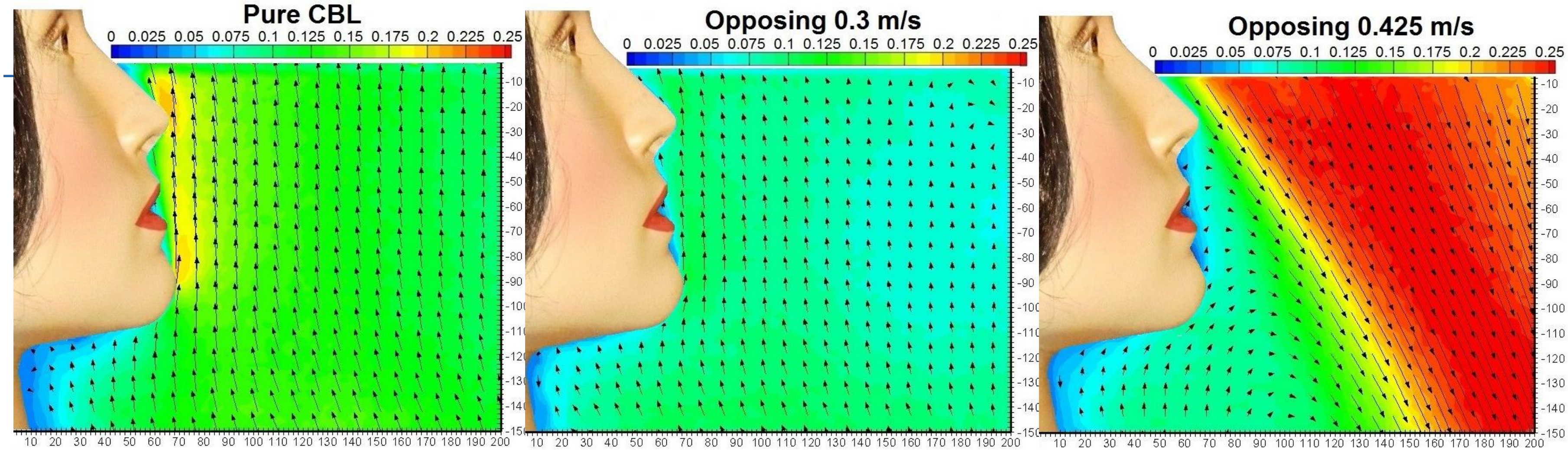
Human convective boundary layer and its impact on personal exposure

Body plume affects inhaled air quality

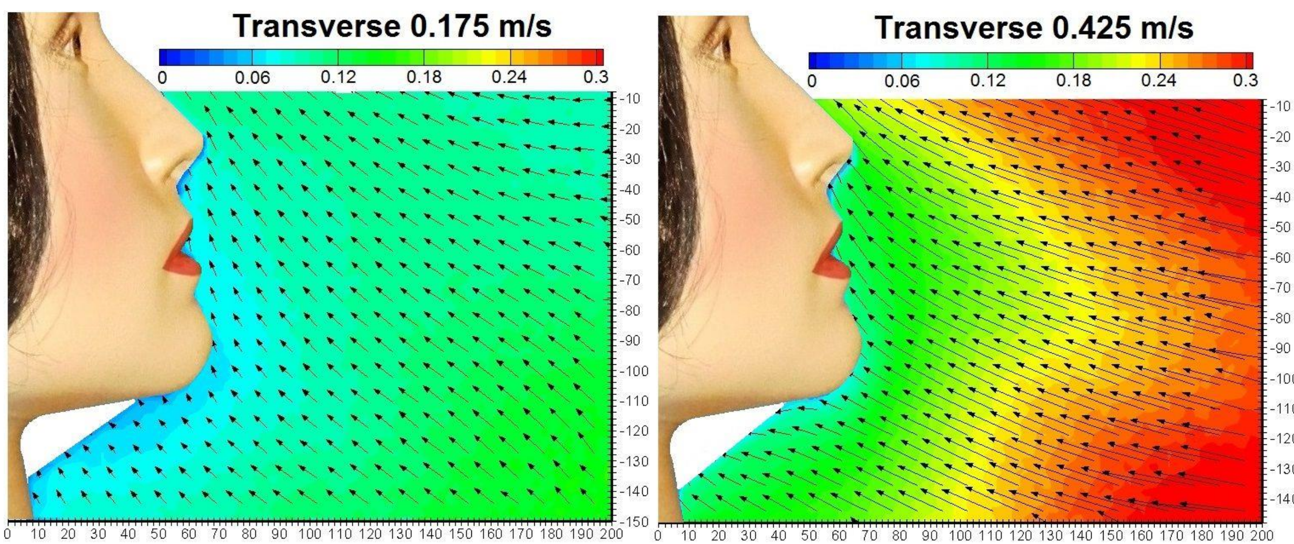
Boundary layer air is 1 – 2°F higher than the ambient air tempearture



The CBL in ventilated environment - Study by Dusan Licina

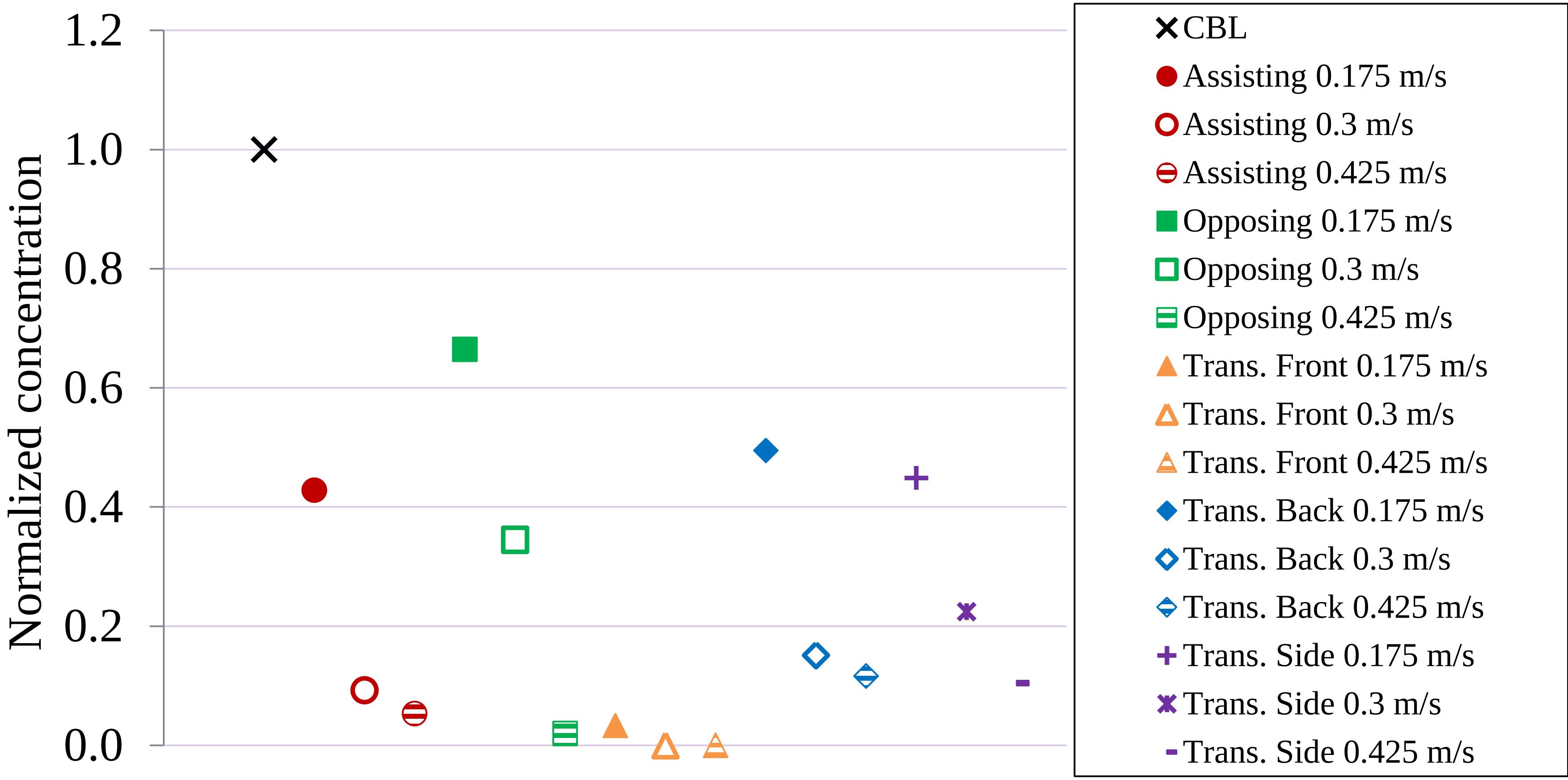


Interaction of the human CBL with the downward ventilation flow from above



Interaction of the human CBL with the ventilation flow from front

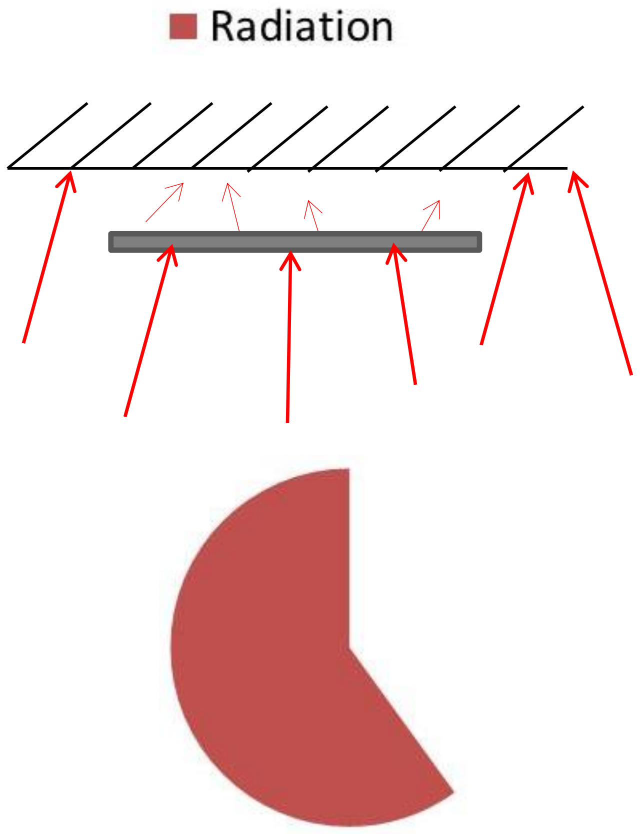
Personal exposure in ventilated environment



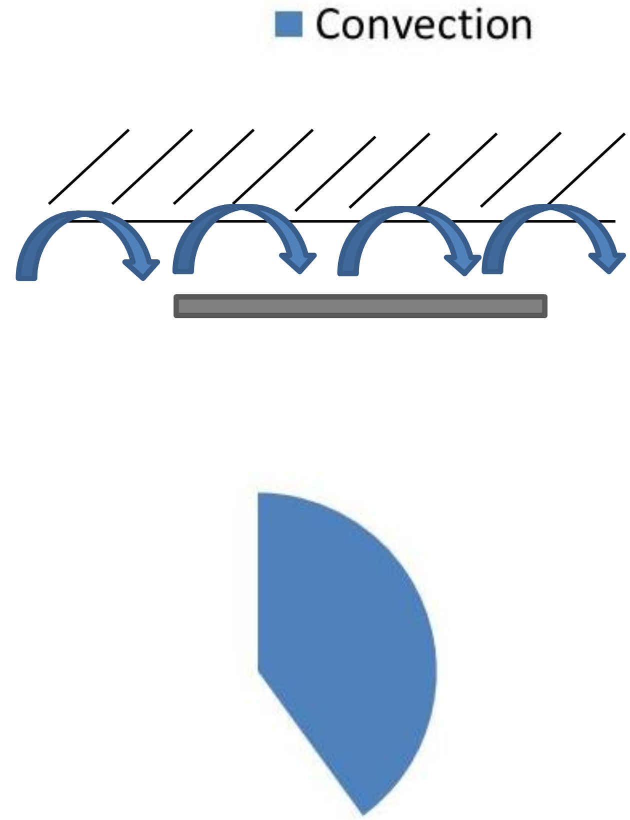
Normalized concentration of cough released from 3 m distance from the manikin – Influence of the CBL, the direction and magnitude of invading airflow

Radiant cooling + acoustical panels + fans

Problem: heat transfer is blocked by suspended panels



60% Radiant heat exchange



40% Convective heat exchange

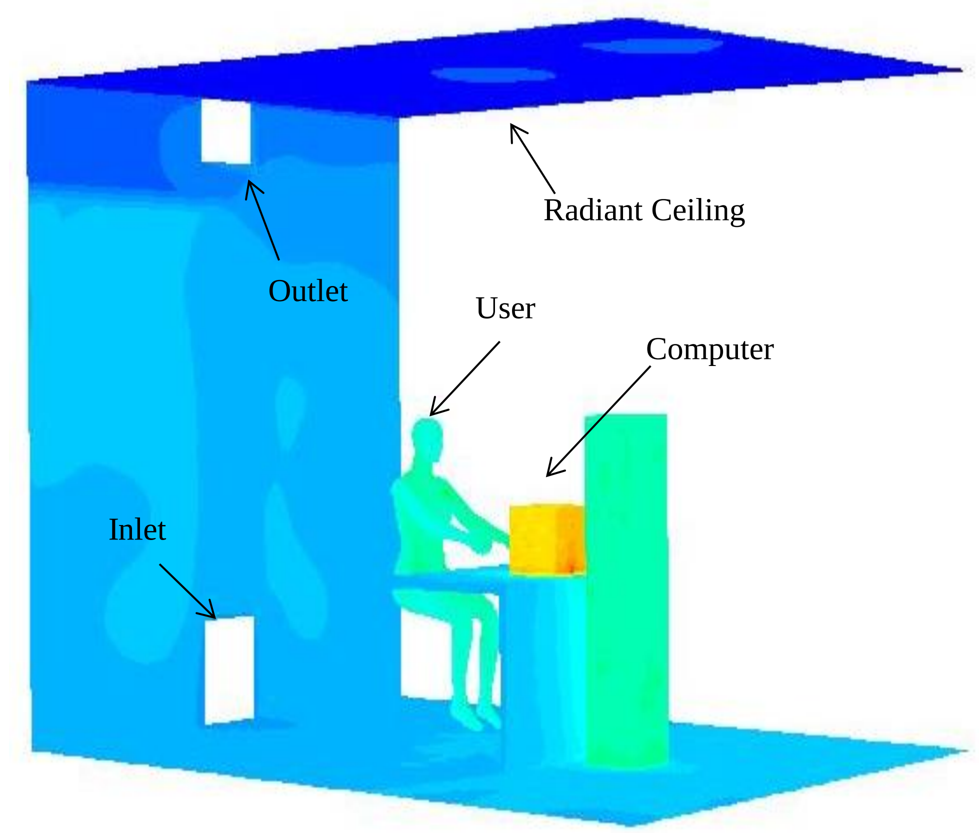
Goals and method

Goals

- Investigate the impacts of acoustical ceiling panels on radiant slab systems
- Study the ability of ceiling integrated fan to increase the ceiling convection coefficient

Method

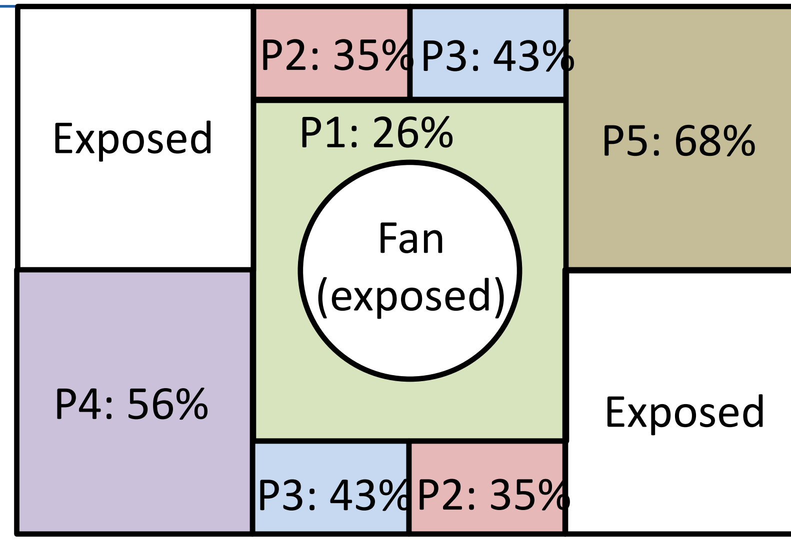
- CFD model of a portion of office equipped with radiant ceiling
- 16 configurations



Funded by CBE and CARB in collaboration with Armstrong

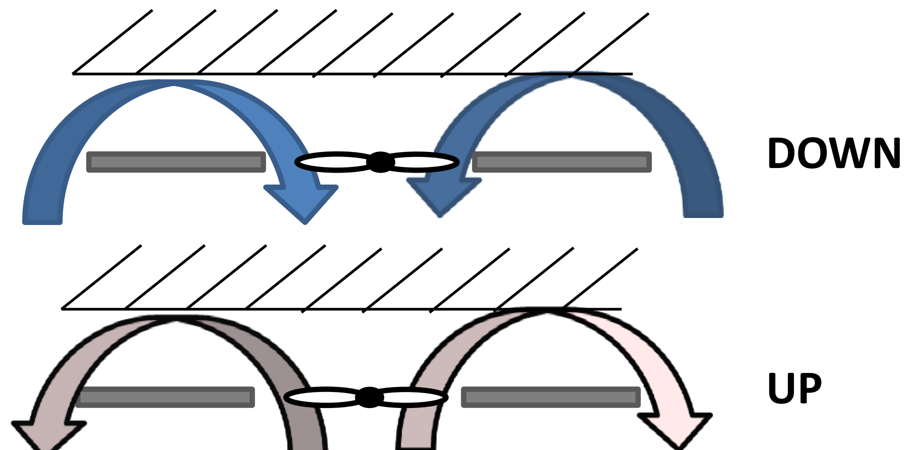
Configurations tested

- Baseline with no fan and no panels
- Five different levels of acoustical panel coverage (26%, 35%, 43%, 56%, 68%)



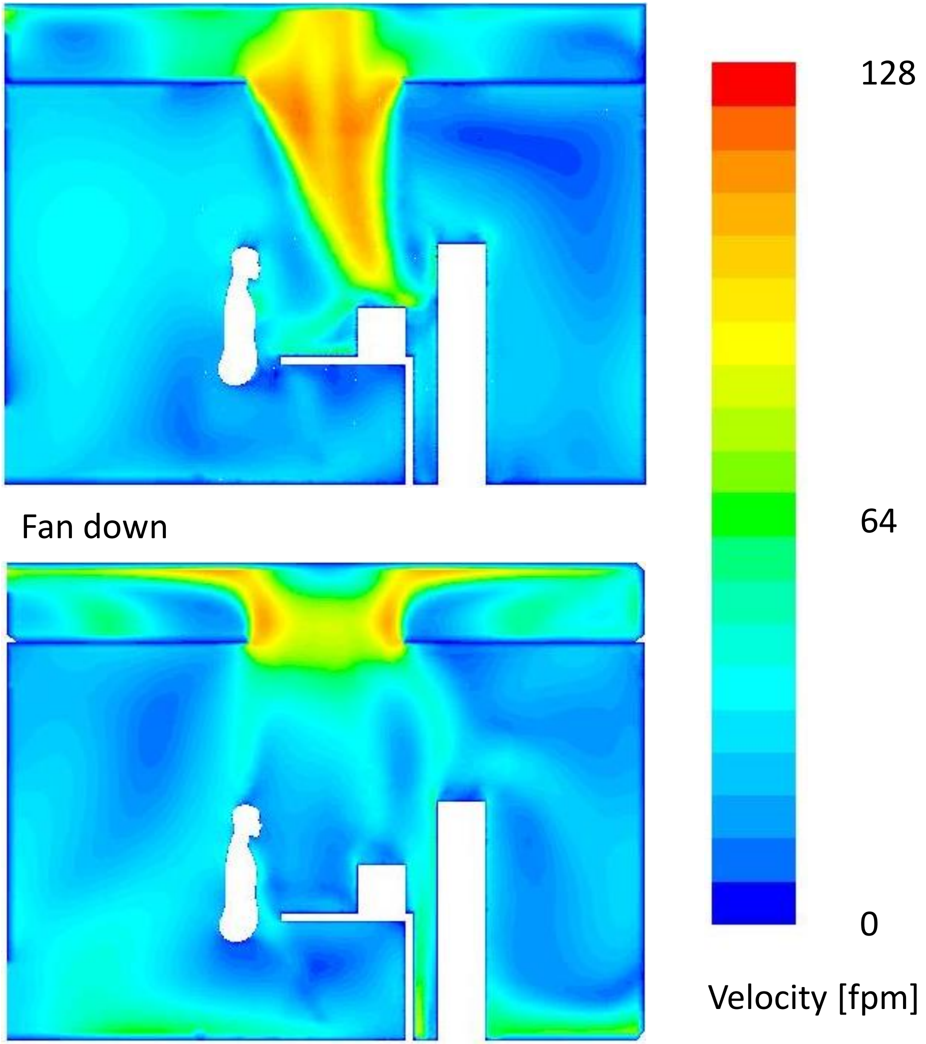
Acoustic ceiling panels configuration

- Two fan configurations (fan blowing up or down). Air speed at the blade level equal to 98.4 fpm



Results

Panels coverage	No fan	Fan down	Fan up
0% (baseline)	100%	ND	ND
26%	96%	144%	144%
35%	91%	139%	153%
43%	88%	139%	154%
56%	88%	139%	151%
68%	89%	132%	152%



Fan down

Fan up

Overcoming barriers to fan use; future prospects

Contributions to ceiling fan design and evaluation

Objective

- Work with industry to produce a standard ceiling fan performance index
- Guidance for designers about fan placement and the effects of workstation furniture

Test facilities

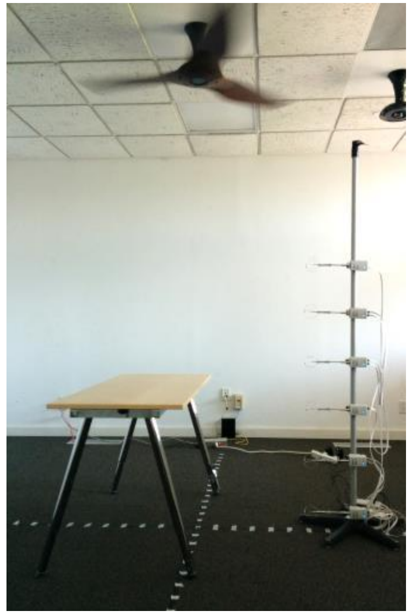
- CBE environmental chamber
- Thermal manikin

Funding

CEC/PIER *Changing the Rules* project, CBE

Quantifying airflow interaction with furniture

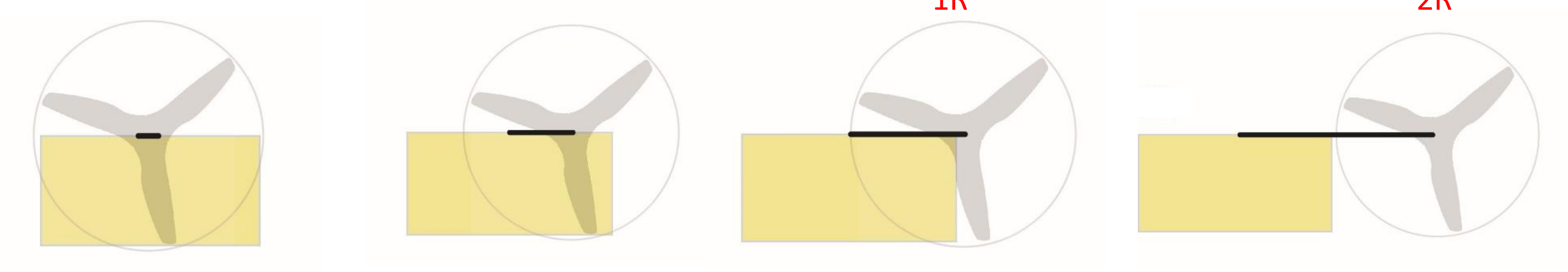
No furniture



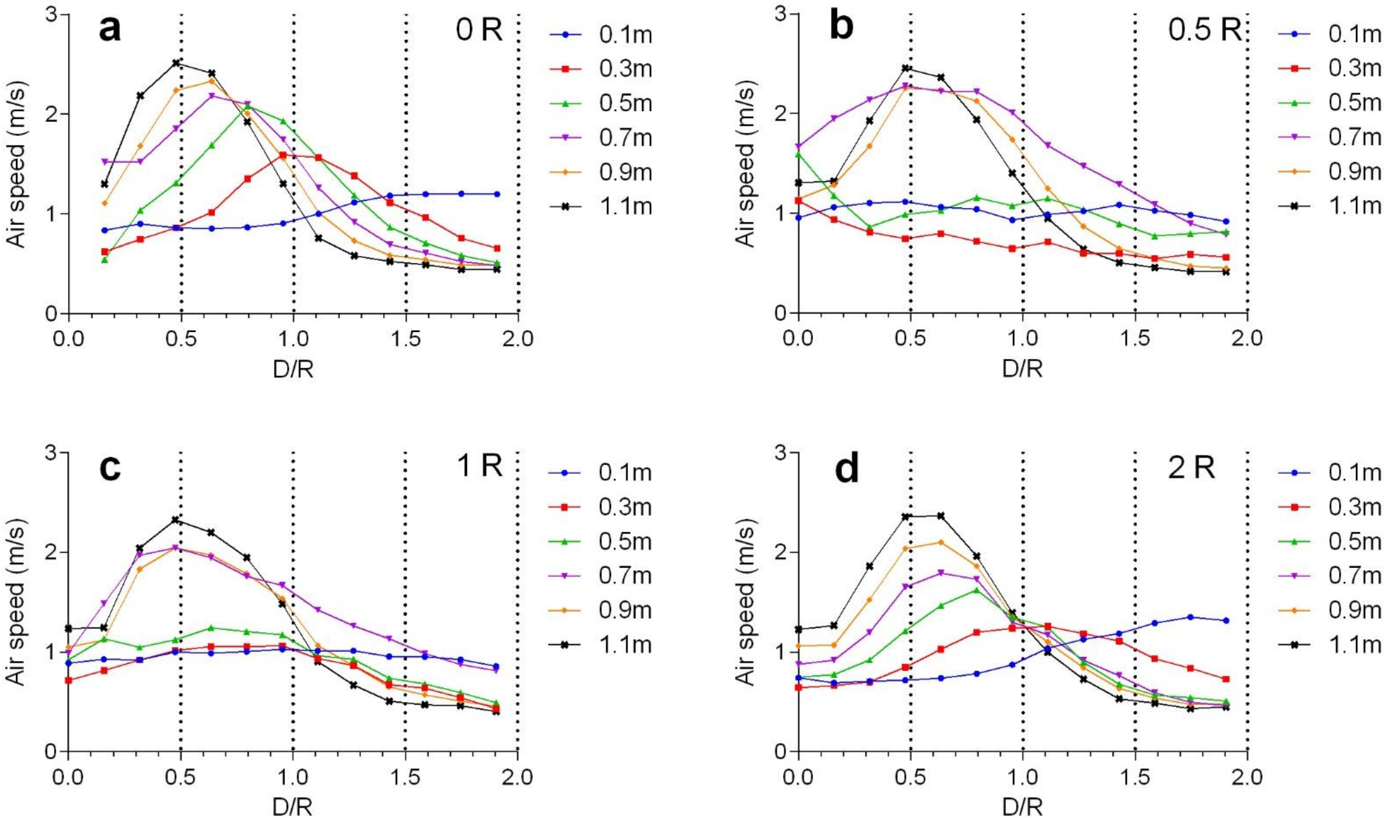
With table

With partition

0R 0.5R 1R 2R



Airspeed distributions with furniture



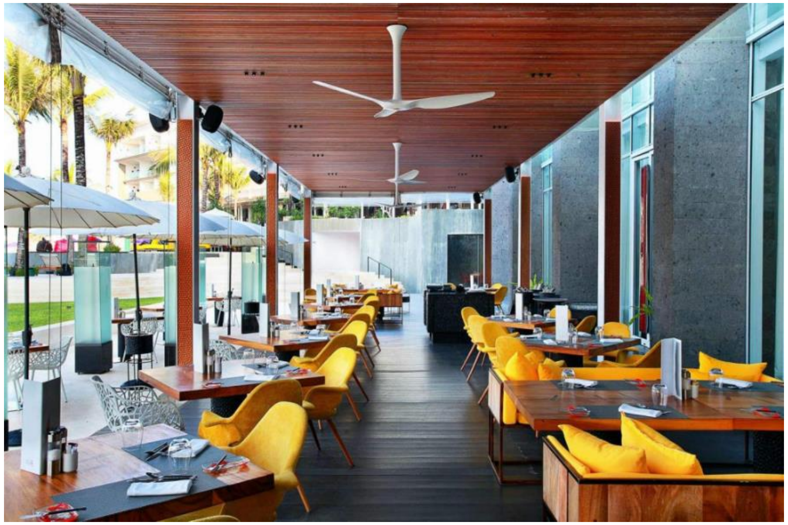
Focusing fans within the workstation

Progress in the industry and future prospects

- Appearance—major progress in the fan industry
- Power efficiency improved with DC motors
- Intelligent controls for comfort and energy effectiveness—links with internet building automation

- We believe the momentum is underway for cooling with air movement
- An elevated air speed should be the base condition before compressor cooling is initiated—this requires a fundamental change to the practice of the last 50 years, but is not beyond reach

Creating architectural acceptance



Thank you!