THE IMPACT OF GREEN BUILDINGS ON COGNITIVE FUNCTION

United Technologies

HARVARD T.H. CHAN SCHOOL OF PUBLIC HEALTH

SYRACUSE UNIVERSITY SYRACUSECOE

UPSTATE MEDICAL UNIVERSITY

THE IMPACT OF GREEN BUILDINGS ON COGNITIVE FUNCTION

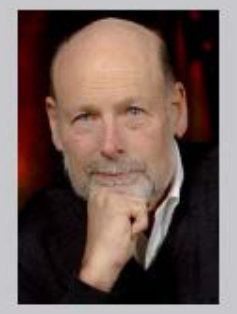
TEAM

Joseph Allen

Piers MacNaughton

Usha Satish

Suresh Santanam



John Spengler

United Technologies

HARVARD T.H. CHAN SCHOOL OF PUBLIC HEALTH

SYRACUSE UNIVERSITY SYRACUSECOE

UPSTATE MEDICAL UNIVERSITY

WHY ARE WE **IGNORING** THE

THE IMPACT OF GREEN BUILDINGS ON COGNITIVE FUNCTION

#THECOGFXSTUDY

WE SPEND

90%

of

OUR TIME INDOORS[1]

10%

OUTDOORS[1]

Allen JG, MacNaughton P, Satish U, Santanam S, Vallarino J, Spengler JD. 2015. Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile Organic Compound Exposures in Office Workers: A Controlled Exposure Study of Green and Conventional Office Environments. Environ Health Perspect DOI: 10.1289/ehp.1510037

1. US EPA Region 1. (2013). Questions About Your Community: Indoor Air. Retrieved from http://www.epa.gov/region1/communities/indoorair.html

THE IMPACT OF GREEN BUILDINGS ON COGNITIVE FUNCTION

#THECOGFXSTUDY

10%
OPERATING COSTS

Just **10%** of a building's operating costs are attributed to **ENERGY, MAINTENANCE, MORTGAGE/RENT,** among others.[3]

90%
SALARIES & BENEFITS

90% of the costs associated with a building come from the people inside the building – **SALARIES AND BENEFITS.**[2]

2. Center for the Built Environment, University of California Berkeley. (2007). The Impact of Ventilation on Productivity. Retrieved from http://www.cbe.berkeley.edu/research/briefs-ventilation.htm
1. US EPA Region 1. (2013). Questions About Your Community: Indoor Air. Retrieved from http://www.epa.gov/region1/communities/indoorair.html
3. Terrapin Bright Green LLC. (2012). The Economics of Biophilia. Retrieved from http://www.interfacereconnect.com/wp-content/uploads/2012/11/The-Economics-of-Biophilia_Terrapin-Bright-Green-2012e_1.pdf

HEALTHY BUILDINGS

A program within the Harvard Center for Health and the Global Environment

HSH

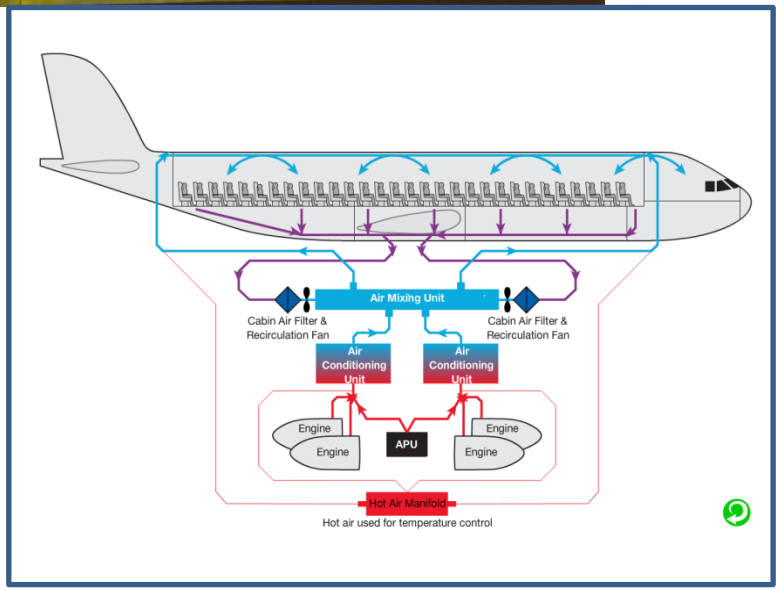
HARVARD SENSORS FOR HEALTH

THE IMPACT OF GREEN BUILDINGS ON

COGNITIVE FUNCTION

HEALTHY BUILDINGS

A program within the Harvard Center for Health and the Global Environment

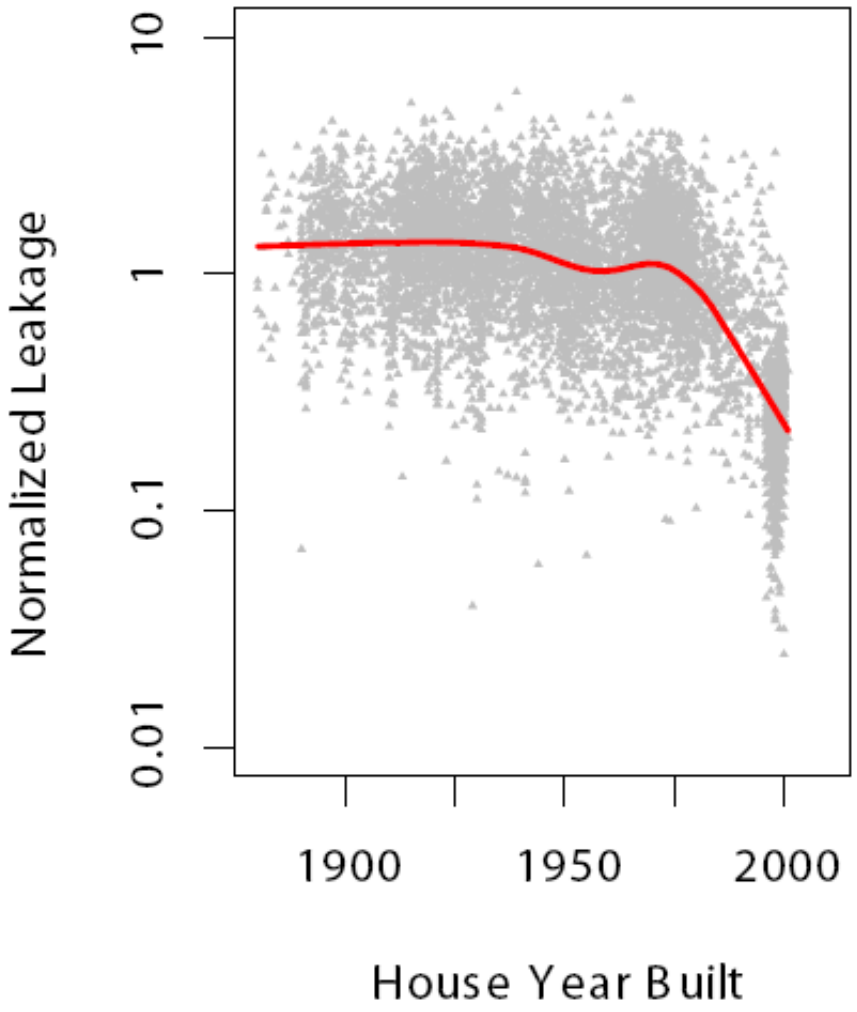


HSH

HARVARD SENSORS FOR HEALTH

Ventilation

#THECOGFXSTUDY



- Balance between acceptable indoor air quality and energy
- Low ventilation and health

(From Chan et al. 2003, LBL)

AT ABOUT THIS TIME…

#THECOGFXSTUDY

SICK BUILDING SYNDROME

TIGHT BUILDINGS — **1979**

1985

BUILDING-RELATED ILLNESS — **1990**

PROBLEM BUILDINGS — **2000**

WHAT ABOUT

GREEN BUILDINGS?

WHAT ABOUT GREEN BUILDINGS?

#THECOGFXSTUDY

Curr Envir Health Rpt
DOI 10.1007/s40572-015-0063-y

GLOBAL ENVIRONMENTAL HEALTH AND SUSTAINABILITY (JM SAMET, SECTION EDITOR)

Green Buildings and Health

Joseph G. Allen[1] · Piers MacNaughton[1] · Jose Guillermo Cedeno Laurent[1] · Skye S. Flanigan[1] · Erika Sita Eitland[1] · John D. Spengler[1]

Abstract Green building design is becoming broadly adopted, with one green building standard reporting over 3.5 billion square feet certified to date. By definition, green build… cupants of those buildings. A limitation of much of the research to date is the reliance on indirect, lagging and subjective measures of health. To address this, we propose a frame-

Study	Sample Size (# of people)	Building Type(s)	Results (compared to conventional)
		Studies with Only Occupant Surveys	
Huizenga et al. 2003	Not Provided	Offices -3 green -45 conventional	↑ Air Quality ↑ Cleanliness ↑ Thermal Comfort
Abbaszadeh et al. 2006	33,285	Offices -21 green -160 conventional	↑ Air Quality ↑ Cleanliness ↑ Thermal Comfort
Lee and Kim 2008	40,488	Offices -15 green -200 conventional	↑ Air Quality ↑ Cleanliness ↑ Thermal Comfort ↓ Lighting ↓ Acoustics
Altomonte and Schiavon 2013	21,477	Offices -65 green -79 conventional	↑ Air Quality ↑ Cleanliness ↓ Lighting ↓ Acoustics
Paul and Taylor 2008	93	University -1 green / 2 conventional	↓ Thermal Comfort
Hedge et al. 2014	319	University -2 green -1 conventional	↑ Ventilation ↑ Air Quality
Thatcher and Milner 2014	441	Offices -1 green -2 conventional	↑ Perceived Ventilation ↑ Air Movement ↓ Thermal Comfort ↓ Lighting
U.S. General Services Admin. (GSA) 2011	Not Provided	Offices -22 green	↑ Occupant Satisfaction ↑ Thermal Comfort ↓ Acoustics
Singh et al. 2010	263	Offices -2 green -1 conventional	↑ Self-Reported Well-being ↓ Absenteeism ↓ Asthma & Allergy Symptoms

Study	Sample Size (# of people)	Building Type(s)	Results (compared to conventional)
		Studies with IEQ Measurements + Occupant Surveys	
Liang et al. 2014	233	Offices -3 green -2 conventional	↑ Thermal Comfort ↑ Air Quality ↑ Lighting ↑ Acoustics
Ravindu et al. 2015	70	Factories -1 green -1 conventional	↓ Thermal Comfort ↓ Ventilation
Newsham et al. 2013	2545	Offices -12 green -12 conventional	↑ Air Quality ↓ Acoustics
Jacobs et al. 2014	58	Public Housing -1 green rehabilitation	↑ Self-Reported Well-being ↑ Cleanliness ↓ Allergens
Garland et al. 2013	Not Provided	Public Housing -1 green rehabilitation	↓ Asthma & Allergy Symptoms
Breysse et al. 2013	41	Public Housing -1 green rehabilitation	↓ Respiratory Symptoms
Colton et al. 2014 & 2015	24	Public Housing -1 green rehabilitation -1 conventional	↑ Air Quality ↑ Ventilation ↓ Asthma Symptoms
		Studies with Objective Health Outcome Measures	
Thiel et al. 2014	Not Provided	Hospitals -1 green -1 conventional	↑ Employee Satisfaction ↑ Quality of Care ↓ Length of Open Positions ↓ Patient Mortality

LIMITATIONS

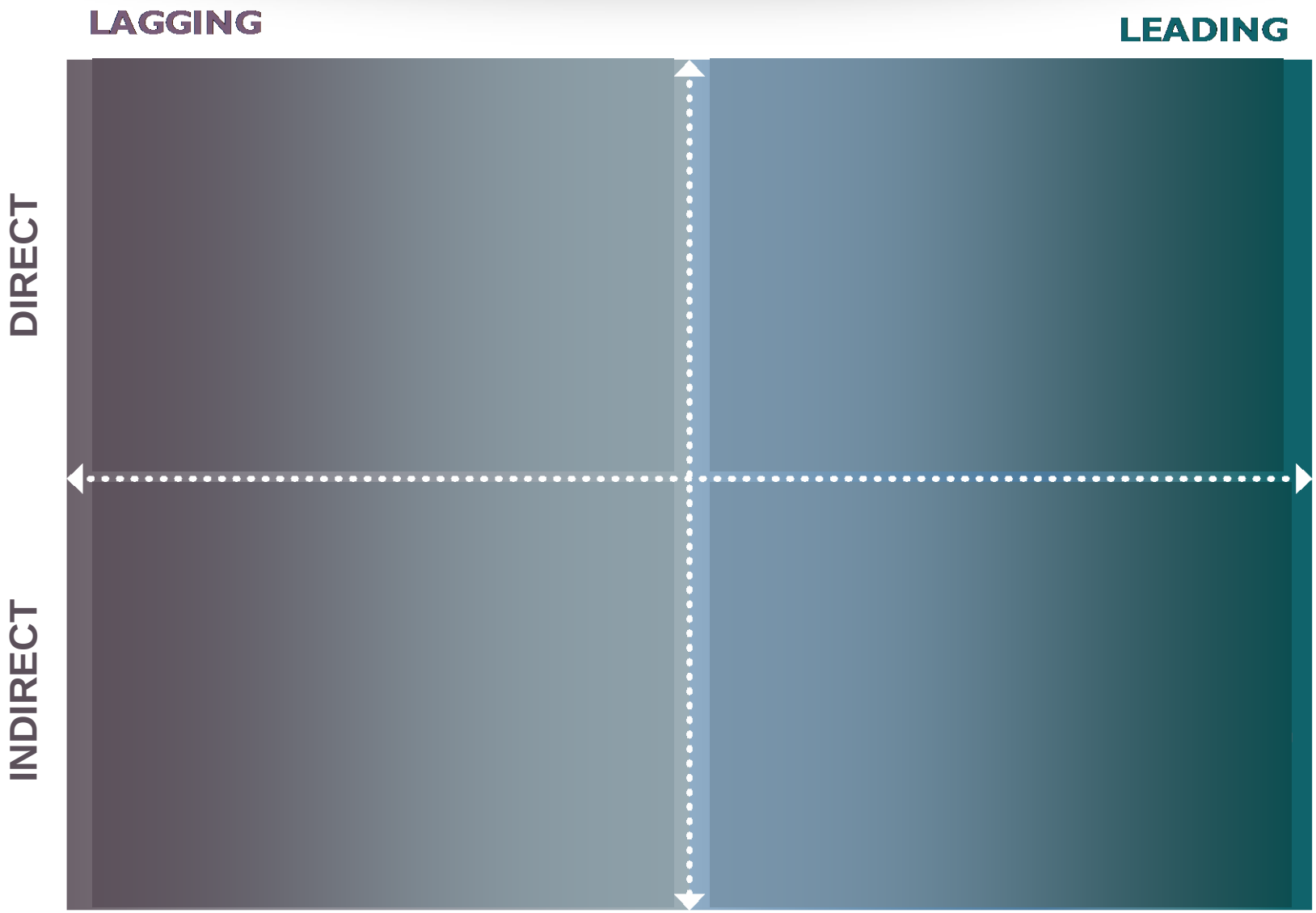
OF “GREEN” BUILDING STUDIES


OBJECTIVES
statistics
achievement
bet
TEAM
INDIVIDUAL
targets
mo
DEFINE
ASSESSMENT
leading SALES
goals
metrics
SUCCESS
KPI
key performance indicators
ectations
FFECT
indicator
practica
strategi
finance
measurement
repeated
PROCESS
output
identification
outsta
ations
understanda
usiness
SERVICE

Allen J, MacNaughton P, Cedeno Laurent J, Flanigan S, Eitland E, Spengler J. Green Buildings and Health. *Current Environmental Health Reports*. 2015.

HEALTH PERFORMANCE INDICATORS

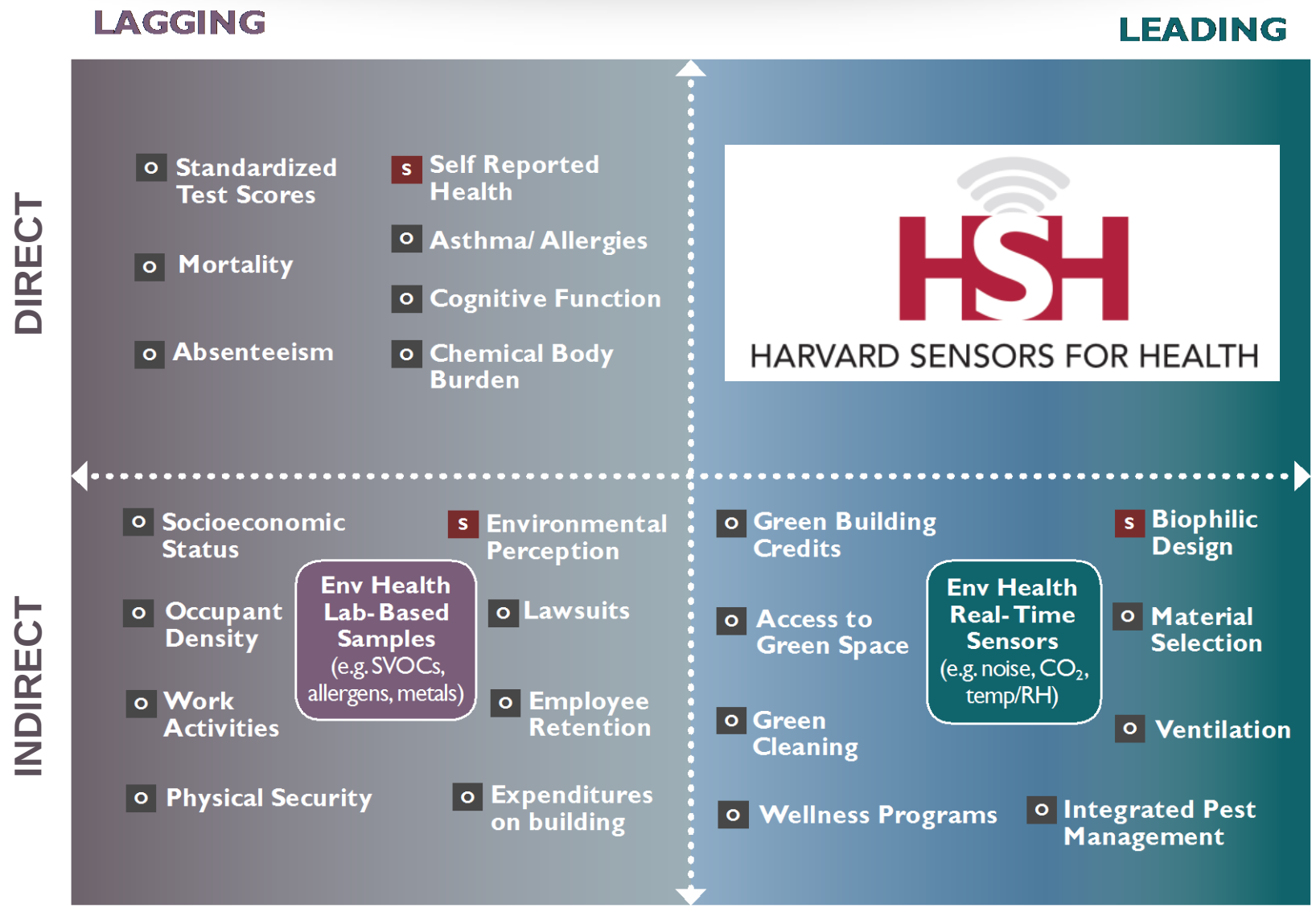
#THECOGFXSTUDY



Allen J, MacNaughton P, Cedeno Laurent J, Flanigan S, Eitland E, Spengler J. Green Buildings and Health. *Current Environmental Health Reports*. 2015.

HEALTH PERFORMANCE INDICATORS

#THECOGFXSTUDY



Allen J, MacNaughton P, Cedeno Laurent J, Flanigan S, Eitland E, Spengler J. Green Buildings and Health. *Current Environmental Health Reports*. 2015.

THE IMPACT OF GREEN BUILDINGS ON COGNITIVE FUNCTION

OBJECTIVE:

PHASE I

To **simulate** IEQ conditions found in Green and Conventional buildings and evaluate the impacts on an objective measure of human performance – cognitive function.

METHODS

THE IMPACT OF GREEN BUILDINGS ON COGNITIVE FUNCTION

#THECOGFXSTUDY

24 PARTICIPANTS

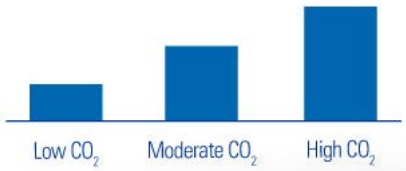
6 DAYS OVER **2 WEEKS**

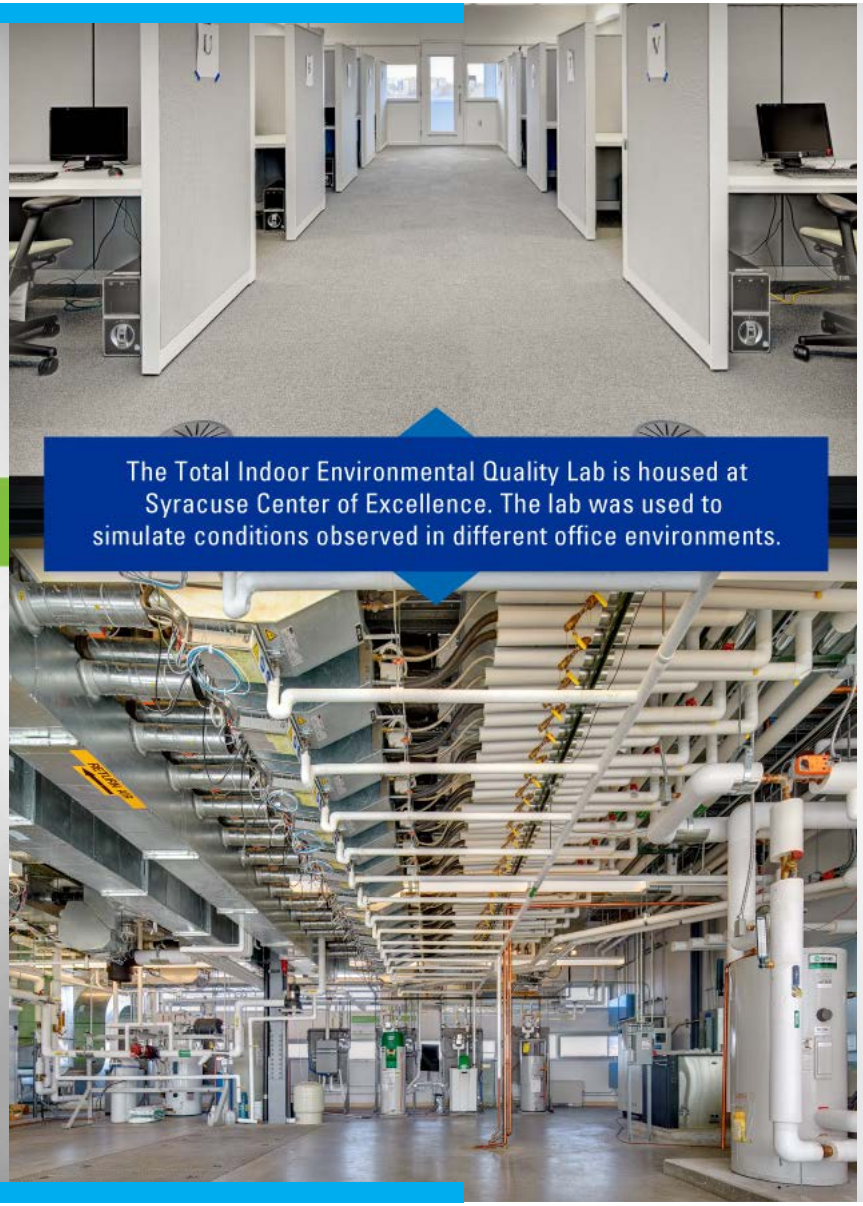
2 TESTS

1 **Multivariable test for building types:**

Conventional	Green	Enhanced Green
i.e., Typical Office	Low VOC	Low VOC and High Ventilation

2 **Single-variable test for carbon dioxide:**





The Total Indoor Environmental Quality Lab is housed at Syracuse Center of Excellence. The lab was used to simulate conditions observed in different office environments.

Allen JG, MacNaughton P, Satish U, Santanam S, Vallarino J, Spengler JD. 2015. Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile Organic Compound Exposures in Office Workers: A Controlled Exposure Study of Green and Conventional Office Environments. Environ Health Perspect DOI: 10.1289/ehp.1510037

DAY	1	2	3	4	5	1&6
CO_2 (ppm)	550	950	1400	950	950	550
Ventilation (cfm/person)	40	40	40	20	20	40
VOCs ($\mu g/m^3$)	50	50	50	50	550	50
CONDITION	GREEN+	MEDIUM CO_2	HIGH CO_2	GREEN	CONVENTIONAL	GREEN+

CO_2

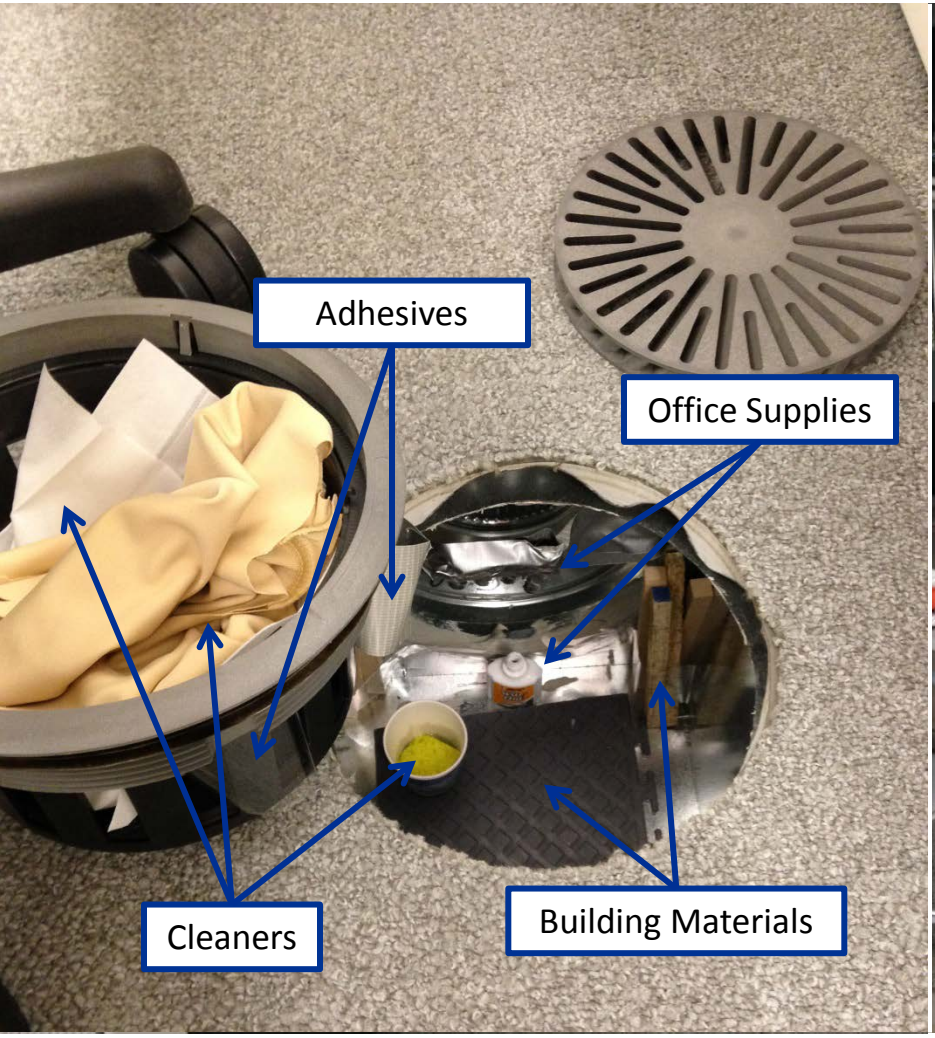
VENTILATION

VOC

VOC
VENTILATION
CO_2

Measured but held constant: temperature, RH, $PM_{2.5}$, noise, illuminance, irradiance, NO_2, O_3, and metals

VOCs



Ventilation and CO_2

ELEMENTS OF PRODUCTIVITY

#THECOGFXSTUDY

Normal everyday tasks require processing of different types of information

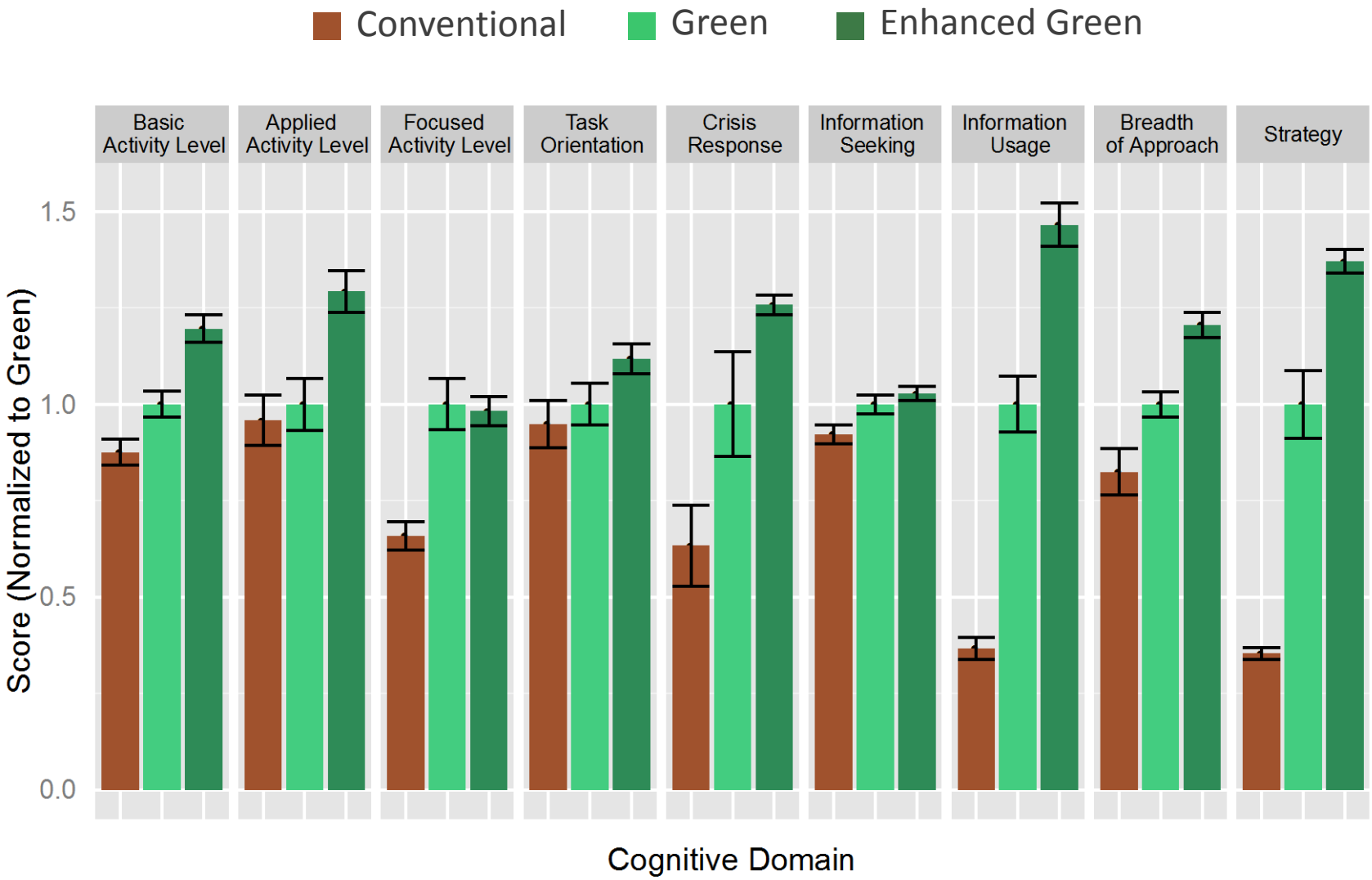
- Receiving information
- Analyzing information
- Utilization of information in a relevant context
- Ability to relate this information to experience
- Ability to retain this information for future

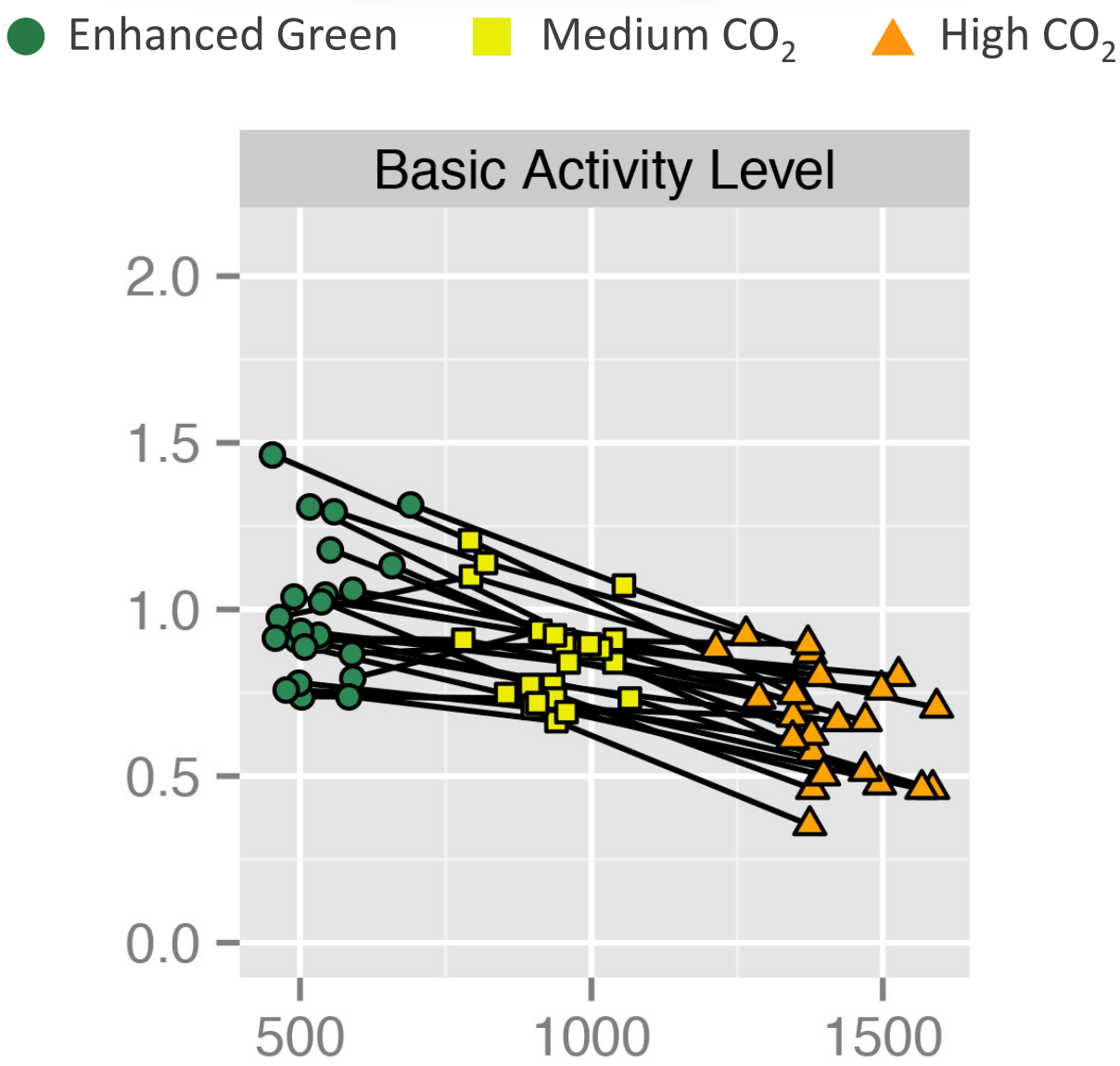
COGNITIVE DOMAINS

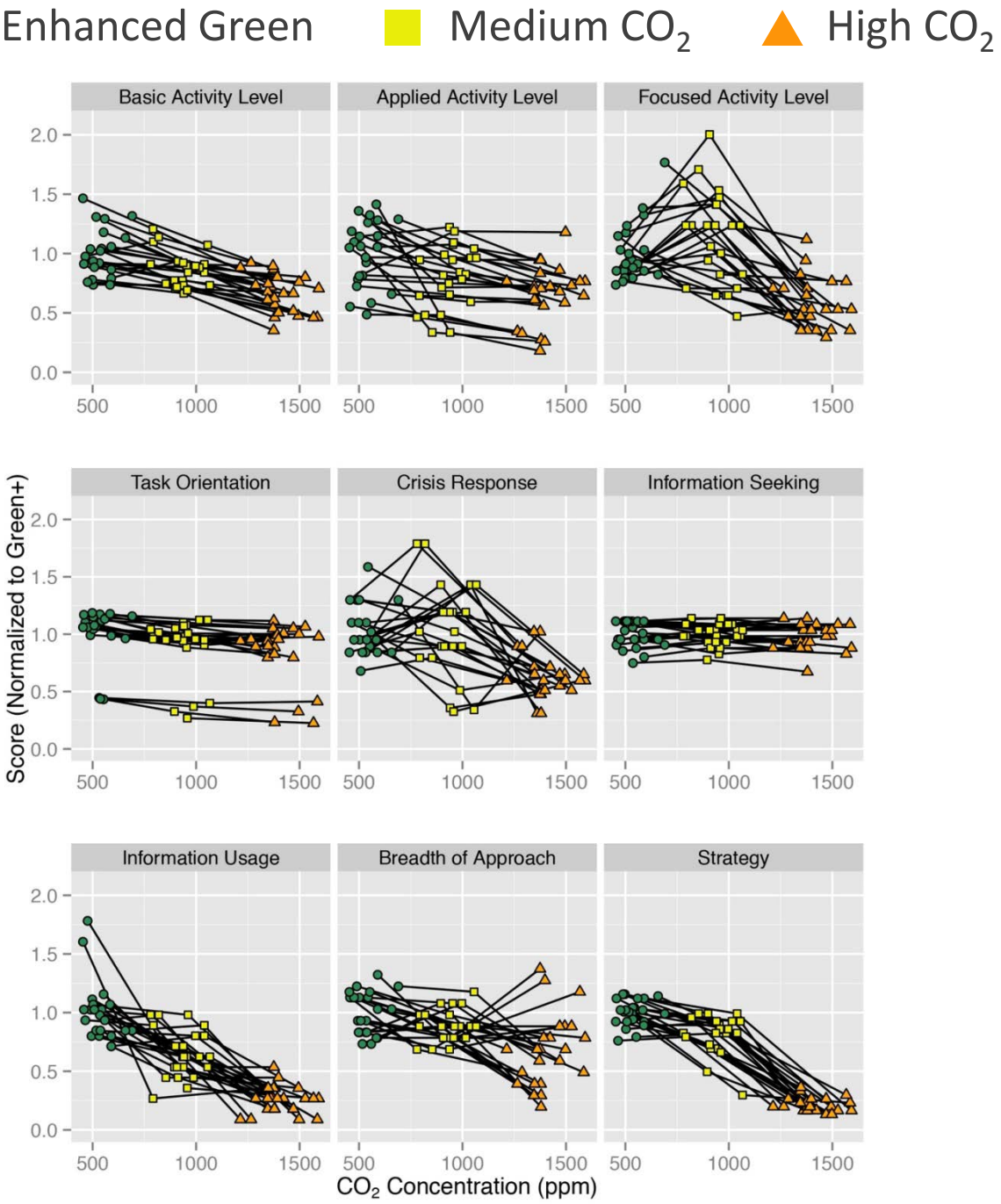
#THECOGFXSTUDY

Domains	Definitions
1) Basic Activity Level	Overall activity
2) Applied Activity Level	Activity directed towards overarching goals
3) Focused Activity Level	Activity directed towards task at hand
4) Task Orientation	Focus on concurrent task demands
5) Crisis Response	Critical thinking under crisis
6) Information Seeking	Openness to, and search for, information
7) Information Usage	Ability to utilize information effectively
8) Breadth of approach	Multi-dimensional thinking
9) Strategy	Optimally prioritized and sequenced plans and actions

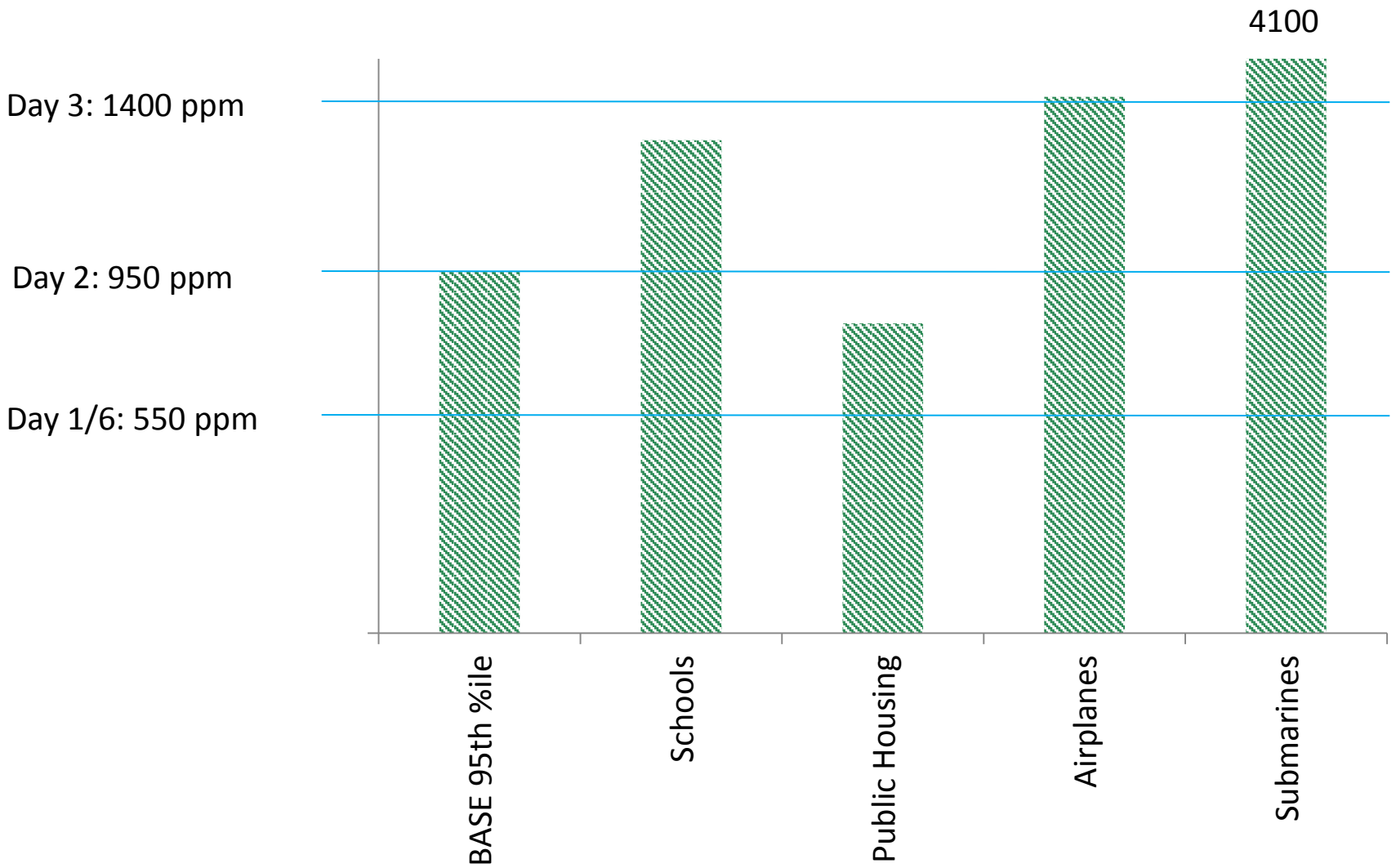
RESULTS


Conventional
Green
Enhanced Green
Basic Activity Level
Applied Activity Level
Focused Activity Level
Task Orientation
Crisis Response
Information Seeking
Information Usage
Breadth of Approach
Strategy
Score (Normalized to Green)
0.0
0.5
1.0
1.5
Cognitive Domain


Enhanced Green
Medium CO_2
High CO_2
Basic Activity Level
2.0
1.5
1.0
0.5
0.0
500
1000
1500


Enhanced Green
Medium CO_2
High CO_2
Basic Activity Level
Applied Activity Level
Focused Activity Level
Task Orientation
Crisis Response
Information Seeking
Information Usage
Breadth of Approach
Strategy
Score (Normalized to Green+)
CO_2 Concentration (ppm)
0.0
0.5
1.0
1.5
2.0
500
1000
1500

CO_2 levels in practice



Statistical Methods

IEQ Condition ⋯⋯⋯⋯⋯⋯⋯⋯⋯⋯⋯⋯> Cognitive Function

$$y_{ij} = \beta_1 + \beta_2*\text{Green+(1)} + \beta_3*\text{Mid-CO}_2 + \beta_4*\text{High-CO}_2 + \beta_5*\text{Green} + \beta_6*\text{Green+(2)} + b_{1i} + e_{ij}$$

Where:

y_{ij}= normalized cognitive score on cognitive domain y for subject i on day j

i= 1,…,24 subjects

j=1,…,6 days

β_1= fixed intercept

β_2= fixed effect of Green+(1) condition vs. Conventional condition

β_3= fixed effect of Mid-CO_2 condition vs. Conventional condition

β_4= fixed effect of High-CO_2 condition vs. Conventional condition

β_5= fixed effect of Green condition vs. Conventional condition

β_6= fixed effect of Green+(2) condition vs. Conventional condition

b_{1i}= random effect of intercept for subject i

Impact of Environmental Conditions on Cognitive Function

Condition	Cognitive Domain: Estimate (p-value)									
	Basic Activity Level	Applied Activity Level	Focused Activity Level	Task Orientation	Crisis Response	Information Seeking	Information Usage	Breadth of Approach	Strategy	Average
Green+ (1)	1.35 (<0.0001)	1.39 (<0.0001)	1.44 (<0.0001)	1.14 (<0.0001)	2.35 (<0.0001)	1.10 (<0.0001)	3.94 (<0.0001)	1.43 (<0.0001)	3.77 (<0.0001)	1.99 (<0.0001)
Moderate CO_2	1.20 (<0.0001)	1.08 (0.23)	1.68 (<0.0001)	1.05 (0.0009)	2.05 (<0.0001)	1.11 (0.61)	2.61 (<0.0001)	1.29 (0.0013)	3.17 (<0.0001)	1.69 (<0.0001)
High CO_2	0.91 (0.015)	0.88 (0.081)	0.85 (0.087)	1.00 (0.76)	1.33 (0.14)	1.08 (0.35)	1.01 (<0.0001)	0.98 (0.78)	0.83 (0.36)	0.99 (0.78)
Green	1.14 (0.0003)	1.04 (0.51)	1.51 (<0.0001)	1.03 (0.065)	1.97 (<0.0001)	1.09 (0.45)	2.72 (<0.0001)	1.21 (0.018)	2.83 (<0.0001)	1.61 (<0.0001)
Conventional*	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Green+ (2)	1.37 (<0.0001)	1.33 (<0.0001)	1.52 (<0.0001)	1.15 (<0.0001)	2.27 (<0.0001)	1.11 (<0.0001)	4.04 (<0.0001)	1.50 (<0.0001)	3.98 (<0.0001)	2.03 (<0.0001)
R^2	0.34	0.17	0.33	0.03	0.28	0.06	0.69	0.27	0.79	0.81

* Reference

Strengths

- Case-cross over design which eliminates the concern of confounding due to between-subject variability because each person acts as their own control
- Repeat 1st and last day as control
- No Monday or Friday effect
- Participants blinded
- Full work day exposure
- Simulated 'typical' office environment
- Variables were selected to represent conditions that are not uncommon
- Complete characterization of IEQ factors that could be confounders

Conclusions

- Significantly better cognitive function in green buildings compared to conventional buildings
- CO_2 and VOCs cause significant independent cognitive deficits at levels found in conventional buildings
- Increasing supply of outdoor air in green buildings lowers exposure to CO_2, VOCs and other pollutants, and was associated with better cognitive function

Implications

- The vast majority of U.S. office workforce spends time in these environments that were outperformed by Green building conditions
- Applicable to other environments (schools, airplanes, air traffic control, military)
- Green buildings impact health on 2 scales
  - Individual (in green buildings)
  - Population (reduction in energy use)
- **Green building design with enhanced ventilation requires adopting energy efficient systems**

United Technologies

#THECOGFXSTUDY

THE IMPACT OF GREEN BUILDINGS ON COGNITIVE FUNCTION

IMPROVED PRODUCTIVITY QUANTIFIED

7 U.S. CITIES SELECTED

IN VARIOUS CLIMATE ZONES

4 HVAC SYSTEM STRATEGIES

VARIABLE AIR VOLUME

VARIABLE AIR VOLUME with energy recovery ventilator

FAN COIL UNIT

FAN COIL UNIT with energy recovery ventilator

DOUBLING THE VENTILATION

FOR **IMPROVED PRODUCTIVITY** COSTS BETWEEN

$14-40 / / YEAR

IN ALL CLIMATE ZONES INVESTIGATED

Allen JG, MacNaughton P, Satish U, Santanam S, Vallarino J, Spengler JD. 2015. Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile Organic Compound Exposures in Office Workers: A Controlled Exposure Study of Green and Conventional Office Environments. Environ Health Perspect DOI: 10.1289/ehp.1510037

THE IMPACT OF GREEN BUILDINGS ON COGNITIVE FUNCTION

#THECOGFXSTUDY

WHEN

ENERGY-EFFICIENT TECHNOLOGIES

ARE UTILIZED, THE COST IS BETWEEN

$1-18/ / YEAR

IN ALL CLIMATE ZONES INVESTIGATED

Allen JG, MacNaughton P, Satish U, Santanam S, Vallarino J, Spengler JD. 2015. Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile Organic Compound Exposures in Office Workers: A Controlled Exposure Study of Green and Conventional Office Environments. Environ Health Perspect DOI: 10.1289/ehp.1510037

THE IMPACT OF GREEN BUILDINGS ON COGNITIVE FUNCTION

#THECOGFXSTUDY

WHEN **VENTILATION** IS **INCREASED** FROM

20 CFM PER PERSON

40 CFM PER PERSON

EMPLOYEE **DECISION-MAKING PERFORMANCE**

A? B?

8 PERCENTILE INCREASE

=

CORRESPONDING **SALARY DIFFERENCE** EACH YEAR

$6,500

Allen JG, MacNaughton P, Satish U, Santanam S, Vallarino J, Spengler JD. 2015. Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile Organic Compound Exposures in Office Workers: A Controlled Exposure Study of Green and Conventional Office Environments. Environ Health Perspect DOI: 10.1289/ehp.1510037

Curr Envir Health Rpt
DOI 10.1007/s40572-015-0063-y

GLOBAL ENVIRONMENTAL HEALTH AND SUSTAINABILITY (JM SAMET, SECTION EDITOR)

Green Buildings and Health

Joseph G. Allen[1] · [illegible][1] · Jose Guillermo Cedeno Laurent[1] ·
Skye S. Flanigan[1] · John D. Spengler[1]

ehp ENVIRONMENTAL HEALTH PERSP[illegible]
http://ehp.niehs.nih.gov

Environmental Perceptions and Health before and after Relocation to a Green Building

Piers MacNaughton[1], John Spengler[1], Jose Vallarino[1], Suresh Santanam[2],
Usha Satish[3], and Joseph Allen[1]

Int. J. Environ. Res. Public Health **2015**, *12*, 1-x manuscripts; doi:10.3390/ijerph120x0000x
OPEN ACCESS
International Journal of
Environmental Research and
Public Health
ISSN 1660-4601
www.mdpi.com/journal/ijerph

and Health Implications of Enhanced ngs

Usha Satish [3], Suresh Santanam [4], John Spengler [1] and

arvard T.H. Chan School of Public Health,
ston, MA 02115, USA;

THE IMPACT OF GREEN BUILDINGS ON COGNITIVE FUNCTION

#THECOGFXSTUDY

WE SPEND

90%

of

OUR TIME INDOORS[1]

10%

OUTDOORS[1]

Allen JG, MacNaughton P, Satish U, Santanam S, Vallarino J, Spengler JD. 2015. Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile Organic Compound Exposures in Office Workers: A Controlled Exposure Study of Green and Conventional Office Environments. Environ Health Perspect DOI: 10.1289/ehp.1510037

1. US EPA Region 1. (2013). Questions About Your Community: Indoor Air. Retrieved from http://www.epa.gov/region1/communities/indoorair.html

THE IMPACT OF GREEN BUILDINGS ON COGNITIVE FUNCTION

#THECOGFXSTUDY

10%
OPERATING COSTS

Just **10%** of a building's operating costs are attributed to **ENERGY, MAINTENANCE, MORTGAGE/RENT,** among others.[3]

90%
SALARIES & BENEFITS

90% of the costs associated with a building come from the people inside the building – **SALARIES AND BENEFITS.**[2]

2. Center for the Built Environment, University of California Berkeley. (2007). The Impact of Ventilation on Productivity. Retrieved from http://www.cbe.berkeley.edu/research/briefs-ventilation.htm
1. US EPA Region 1. (2013). Questions About Your Community: Indoor Air. Retrieved from http://www.epa.gov/region1/communities/indoorair.html
3. Terrapin Bright Green LLC. (2012). The Economics of Biophilia. Retrieved from http://www.interfacereconnect.com/wp-content/uploads/2012/11/The-Economics-of-Biophilia_Terrapin-Bright-Green-2012e_1.pdf

QUESTIONS?

Joseph G. Allen
Assistant Professor
jgallen@hsph.harvard.edu
@j_g_allen

Usha Satish
Professor
satishu@upstate.edu

Piers MacNaughton
Doctoral Candidate
pom422@mail.harvard.edu

THE IMPACT OF GREEN BUILDINGS ON COGNITIVE FUNCTION