CANADIAN CENTRE FOR BUILDING EXCELLENCE

Engineering Health and Efficiency

Exposing the Brain: The cognitive impacts of indoor air pollution

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Acknowledgments

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Conventional Model of Indoor Air Quality

1. Source control
2. Ventilation
3. Air cleaning

Why?

Health

Productivity, protection

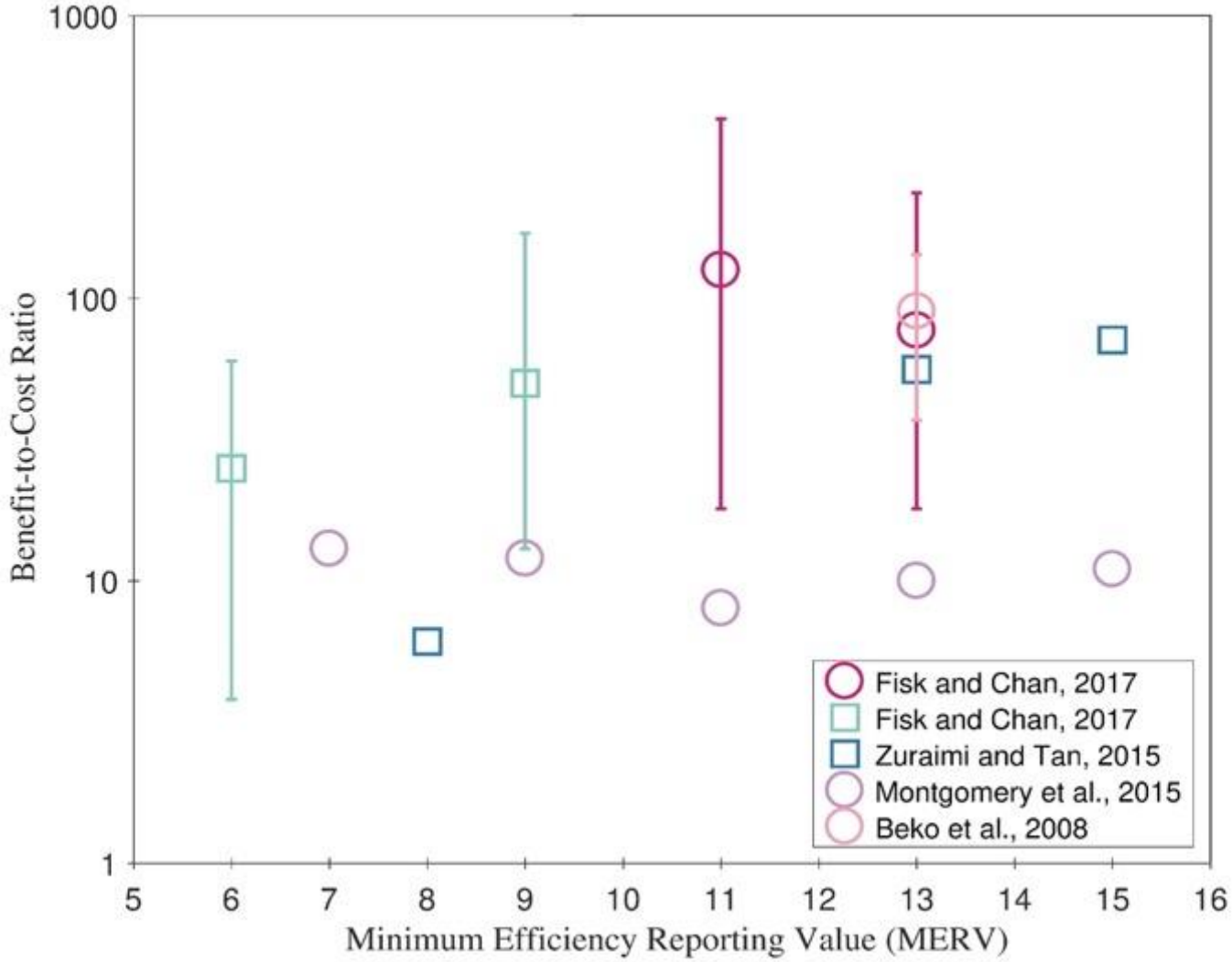
"If there is a pile of manure in a space, do not try to remove the odor by ventilation. Remove the pile of manure."

~ Max von Pettenkofer, 1858

Distance to Major Roadway

2M Canadians: 50 m
4M Canadians: 100 m
10M Canadians: 250 m

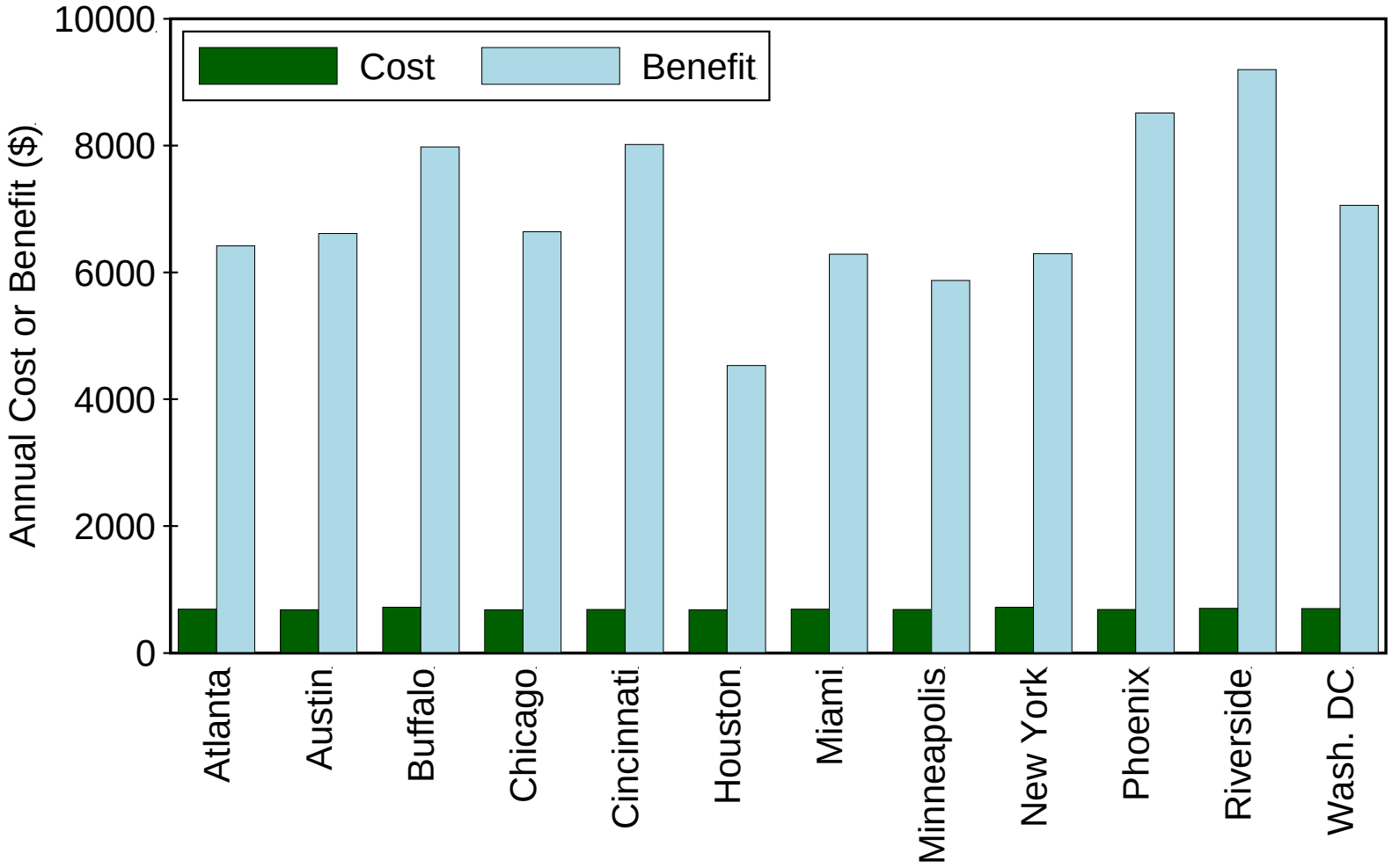
Air cleaning should be an obvious target for investment



Alavy and Siegel (2019) *Sci Tech Built Environ*

Ozone Filtration – Benefits

2 inch activated carbon filters in office buildings



Aldred et al. (2016) *Indoor Air*

COMMENTS OF DONALD R. BAHNFLETH, PRESIDENT
AMERICAN SOCIETY OF HEATING, REFRIGERATING
AND AIR-CONDITIONING ENGINEERS

IAQ 86 OPENING SESSION
APRIL 20, 1986

Good afternoon, and thank you for joining us for this very important conference on Managing Indoor Air for Health and Energy Conservation. During the next four days, we will hear from experts in indoor air quality. A diverse group of talented men and women from around the world will present us with the latest findings in virtually every aspect of the issue.

More than 100 authors will present papers, either orally during the 12 sessions or in poster sessions on Monday and Tuesday. They represent government, corporations, universities and colleges, private laboratories. All of them have worked for months to gather the data for their presentations and they have done it for one purpose: because they believe it important to provide solutions to indoor air quality problems.

ASHRAE has organized and is co-sponsoring with the Department of Energy and the Environmental Protection Agency this conference for the same reason. Because indoor air quality is an important issue. In fact, ASHRAE believes that indoor air quality is and will remain the single most important health issue facing us in the 1980's. Unacceptable indoor air quality can impair our health, affect our sense of well-being, and affect our productivity in terms of both lost time and loss of productive effort.

Years ago, whenever there was a problem regarding the indoor air, we usually tried what I call "granny's solution." We just threw open the door or the window and brought in outside air. Today, we might not always want to bring in unfiltered uncontrolled outside air. In some cities, what's outside could be worse than what's inside. Large amounts of outside air also require expending large amounts of energy for heating and cooling. Concern for the IAQ issue is still growing.

The way we live today, spending more than 90 percent of our time indoors, creates the need for a better knowledge of what contaminants are present in the indoor environment and their effect on people. The issue of indoor air quality is a sleeping giant whose time has come, The total number of serious health effects related to IAQ in non-industrial buildings have been miniscule compared to the total building stock. But there have been enough to indicate that a problem exists. Fortunately, addressing the situation this early gives us time to move rationally. The issue does not need to be sensationalized. We do not need knee-jerk reactions.

Why Not?

- The health benefits are real and large, but
  - Very hard to motivate people about chronic health endpoints that occur decades in the future
  - Very hard to monetize health impacts when people inhabit different buildings
  - Industry (and individuals) pay the cost but don’t necessarily accrue the benefits

We need an alternative model

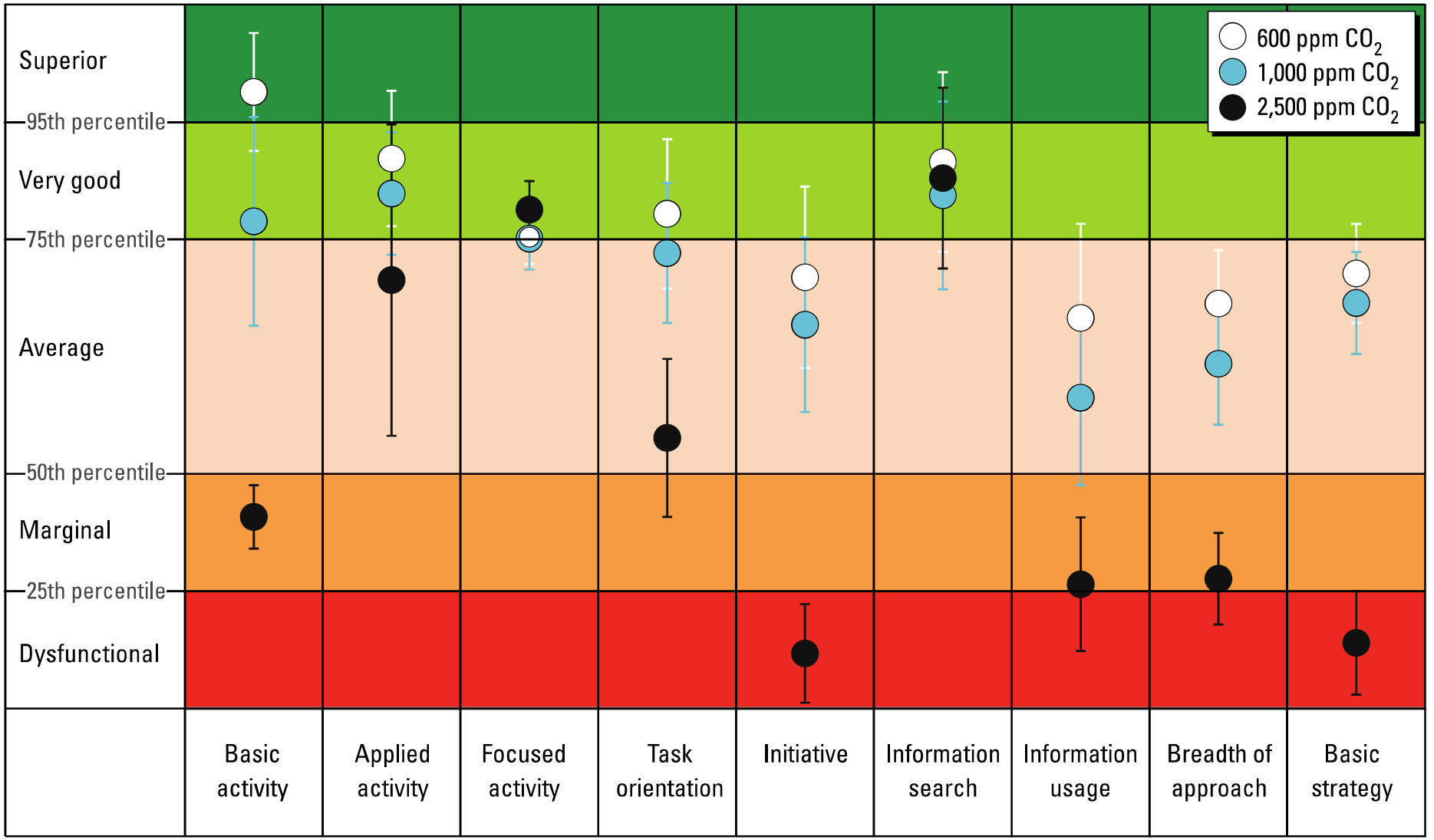


Figure 2. Impact of CO_2 on human decision-making performance. Error bars indicate 1 SD.

Satish et al. (2012) *Environ Health Persp*

Does CO_2 impact cognitive performance?

- Maybe, but these results are pointing to something important
- Variations in environmental variables, including exposures, impact cognitive function
- This is an enormous potential opportunity for IAQ community
  - It is an acute impact
  - It is easily monetizable in some environments

Invest in indoor air to improve cognitive function. Use benefits to pay for improvements. Chronic health outcome improvement are a “side” benefit.

How do we get to this model?

- Role of CO_2/ventilation in cognitive function
- Impact of indoor sources on cognitive function
- Role of indoor stimuli on cognitive function
- Connections between exposures and neurological processes
- Goal: neurocognitive understanding (exposing the brain)

Why CO_2?

- Elevated CO_2 is ubiquitous in indoor environments
- 37 studies in the literature (at time of review)
- Widely varying impacts
  - What explains this variation?

INDOOR AIR
International Journal of Indoor Environment and Health

REVIEW ARTICLE

Indoor CO_2 concentrations and cognitive function: A critical review

Bowen Du, Marlie C. Tandoc, Michael L. Mack, Jeffrey A. Siegel

DOI: 10.1111/ina.12706

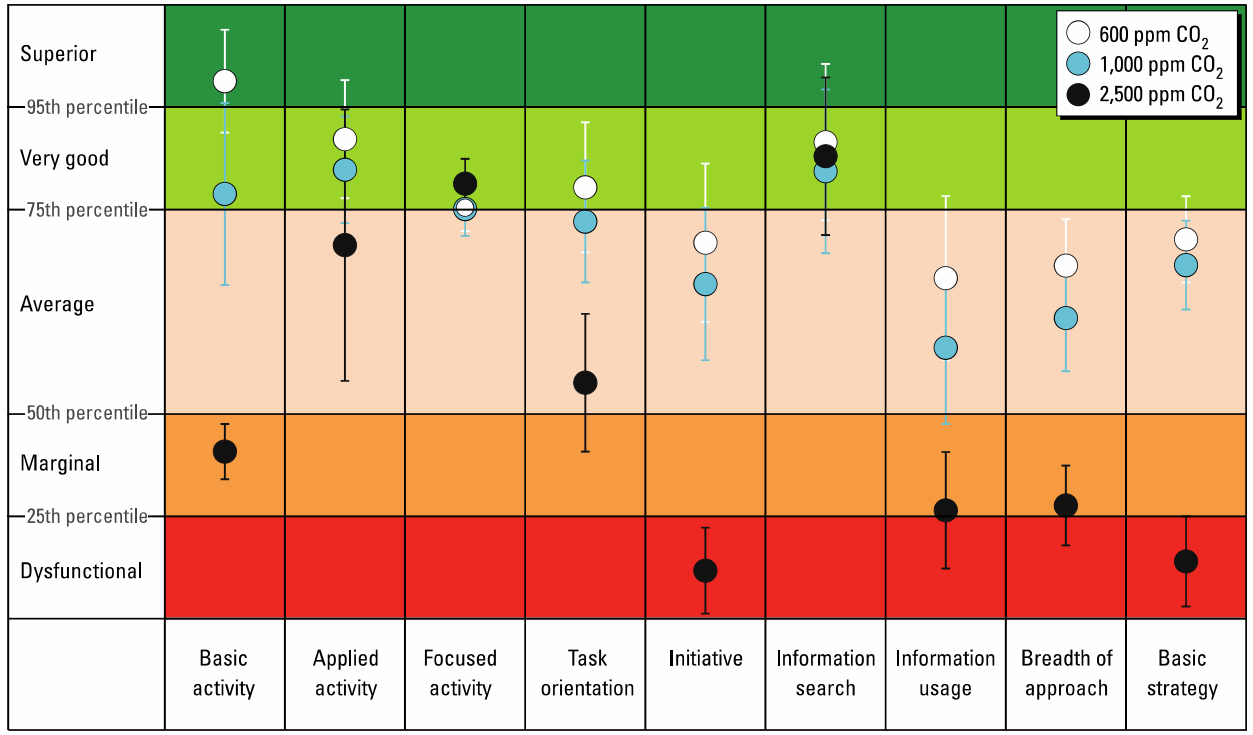


Figure 2. Impact of CO_2 on human decision-making performance. Error bars indicate 1 SD.

Satish et al. (2012) *Environ Health Persp*

Table II. One-Way ANOVA Results.

OUTCOME VARIABLES	CONDITIONS (ppm of CO_2)* 600 ppm	2500 ppm	15,000 ppm	$F(2, 33)$	P	η^2_p
Basic Activity	89.92 6 31.62	83.42 6 28.28	89.58 6 21.47	0.21	0.81	0.013
Applied Activity	54.58 6 24.24	50.33 6 30.43	51.58 6 18.20	0.09	0.91	0.005
Focused Activity	12.33 6 4.48	12.25 6 4.14	11.50 6 3.00	0.16	0.85	0.010
Task Orientation	90.33 6 35.44	75.33 6 31.84	88.50 6 28.86	0.78	0.47	0.045
Basic Initiative	13.92 6 7.19	12.33 6 8.28	17.58 6 12.52	0.94	0.40	0.054
Information Orientation	9.08 6 9.22	5.83 6 6.02	8.92 6 7.46	0.68	0.51	0.040
Information Utilization	8.58 6 5.05	7.58 6 3.87	8.58 6 5.43	0.17	0.84	0.010
Breadth of Approach	7.83 6 1.47	7.75 6 1.06	7.83 6 1.03	0.02	0.98	0.001
Basic Strategy	16.58 6 11.02	16.08 6 12.13	16.00 6 11.22	0.01	0.99	0.001

* Means 6 SD.

Rodeheffer et al. (2018) *Aero Med Human Perf*

METHODS: **Using a subject-blinded balanced design, 36 submarine-qualified sailors were randomly assigned to receive 1 of 3 CO_2 exposure conditions** (600, 2500, or 15,000 ppm). After a 45-min atmospheric acclimation period, participants completed an 80-min computer-administered SMS test as a measure of decision making.

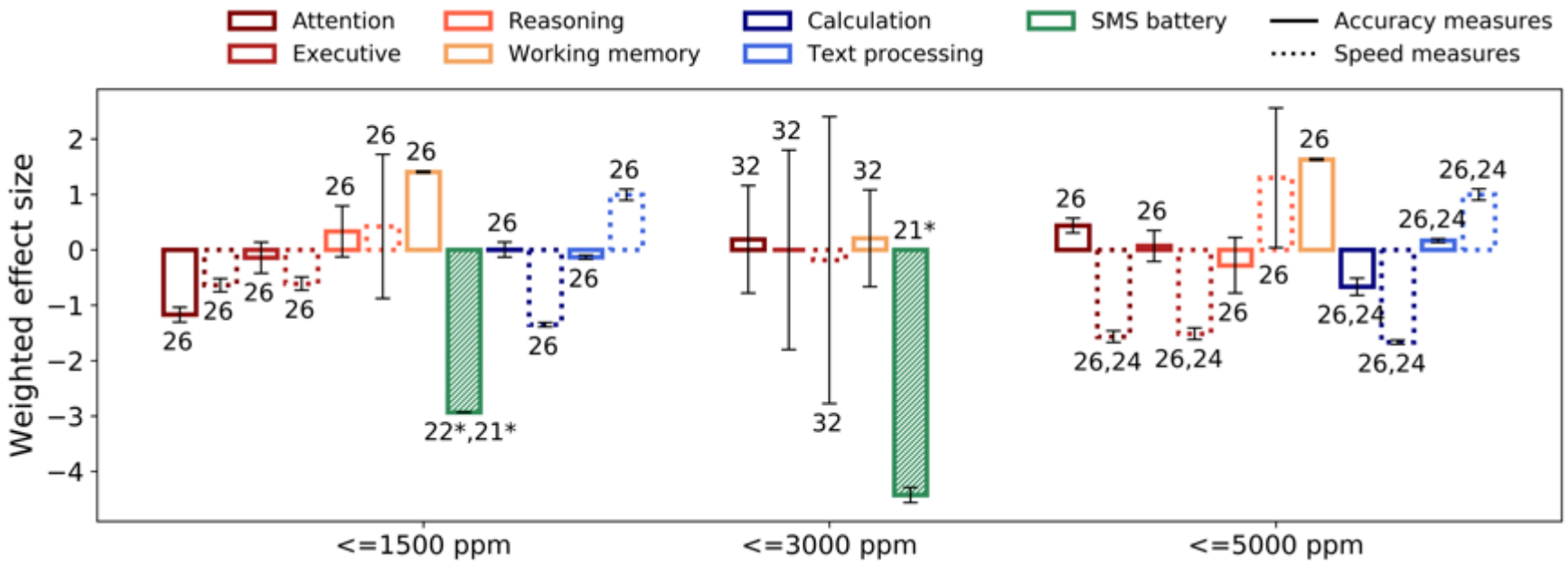
RESULTS: **There were no significant differences for any of the nine SMS measures of decision making between the CO_2 exposure conditions.**

List of selected studies

37 studies

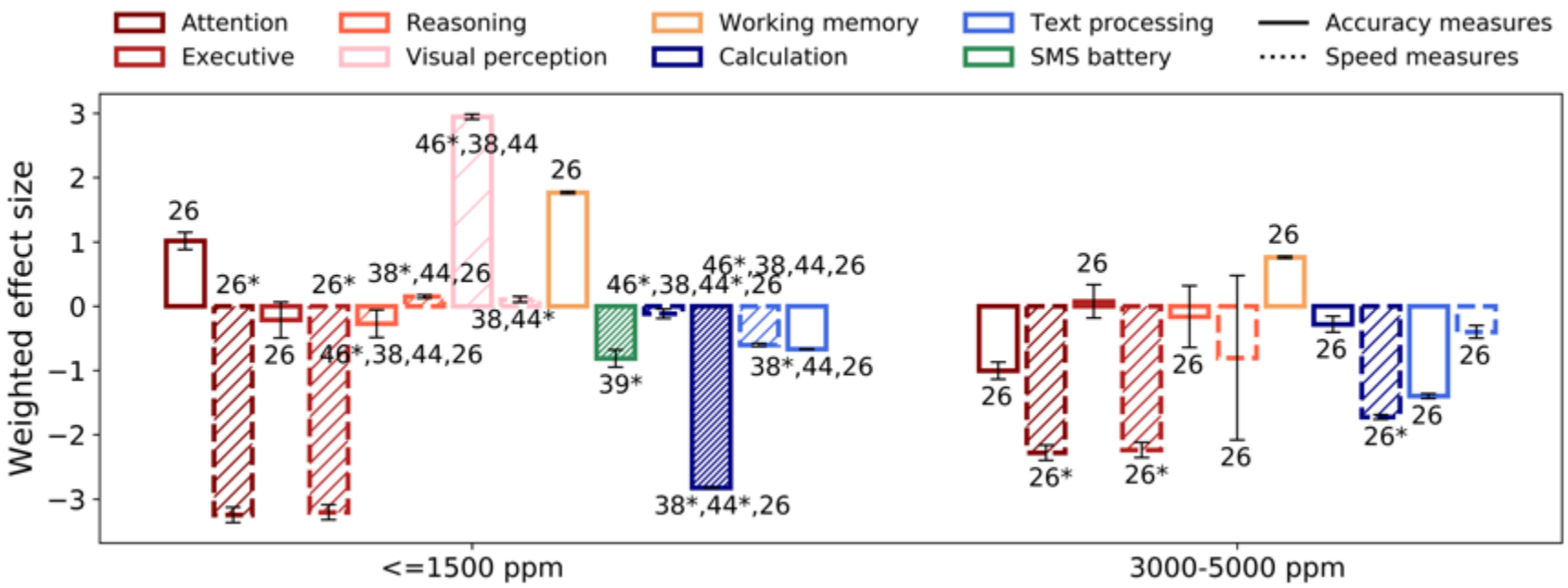
	Source	Ref. CO_2 [ppm]	Test CO_2 [ppm]	Duration [min]	Environment	Occupation (sample size)	Significance
CO_2	Allen et al. 2016	487/586	934	480	Lab	Unknown (24)	**Yes**
			1410				**Yes**
	Satish et al. 2012	600	1000	150	Lab	Unknown (22)	**Yes**
			2500				**Yes**
	Snow et al. 2019	830	2700	<60	Office	Unknown (31)	**Yes**
	Zhang et al. 2017	435	1083	255	Lab	Students (25)	No
			3004				No
	Zhang et al. 2016	409 ± 21	4913 ± 146	153	Lab	Students (10)	No
Vent	Zhang et al. 2017	435	1124	255	Lab	Students (25)	Yes
			3192				Yes
	Tham et al. 2005	571 ± 24	757 ± 37	Multiple	Office	Office workers (26)	No
		575 ± 35	715 ± 35	Days		Office workers (26)	**Yes**
		1032 ± 83	1278 ± 95			Office workers (27)	No
		1008 ± 74	1225 ± 73			Office workers (27)	**Yes**
	Maddalena et al. 2015	800 – 850	1050 – 1750	240	Lab	Unknown (32)	**Yes**
	Wargocki et al. 2007	744 ± 176	952 ± 232	Multiple	Classroom	Children (32 – 45)	**Yes**
		809 ± 148	1049 ± 154	Days		Children (32 – 45)	**Yes**
	Petersen et al. 2016	800 – 970	1310 – 1610	36 – 258	Classroom	Children (70 – 79)	**Yes**

Results from Selected Pure CO_2 Studies



- Pure CO_2 found only to affect high-level decision-making performance measured by the strategic management simulation (SMS) battery

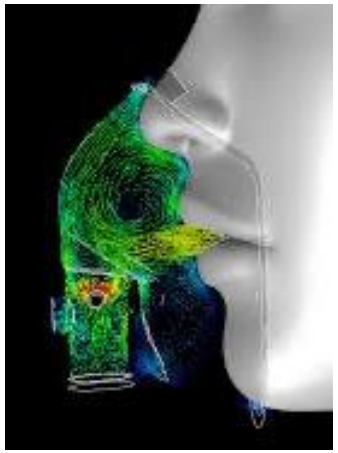
Results from Selected Ventilation Studies



- Low ventilation found to cause declines in the speed measurement of various cognitive functions but not accuracy.

Summary

- Lots of variation
  - Cognitive battery
  - Study design
  - CO_2 reinhalation



Zhu et al. (2005) *Build Environ*
Laverge et al. (2013*) Build Environ*
Ghahramani et al. (2019) *J Build Eng*

Physiological responses during exposure to carbon dioxide and bioeffluents at levels typically occurring indoors

"Exposure to bioeffluents, when metabolically generated CO_2 was at 3000 ppm, significantly increased diastolic blood pressure and salivary a-amylase level compared with pre-exposure levels, and reduced the performance of a cue-utilization test: These effects may suggest higher arousal/stress."

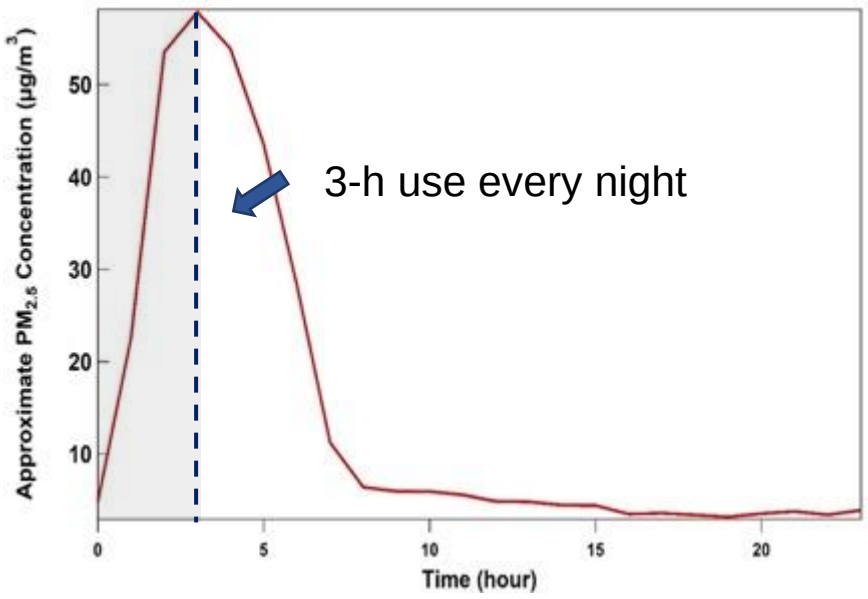
Zhang et al. (2017) *Indoor Air*

Respiratory performance of humans exposed to moderate levels of carbon dioxide

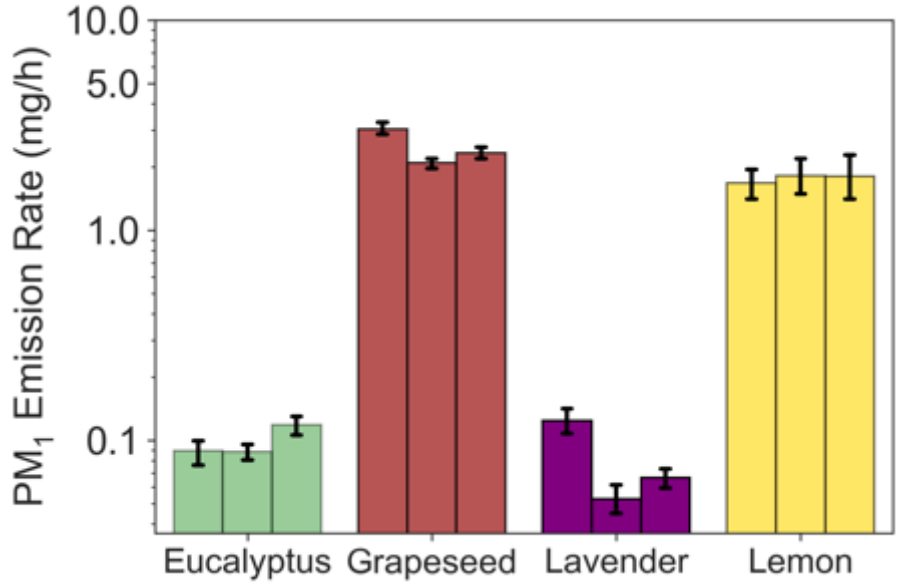
"Parameters measured using FVC decreased significantly from the start to the end of exposure only at the reduced ventilation condition ($p < 0.04$, large effect size). Hence, poor ventilation likely affects respiratory parameters. This effect is probably not caused by increased CO_2 alone and rather by other pollutants—predominantly human bioeffluents in this work—whose concentrations increased as a result.

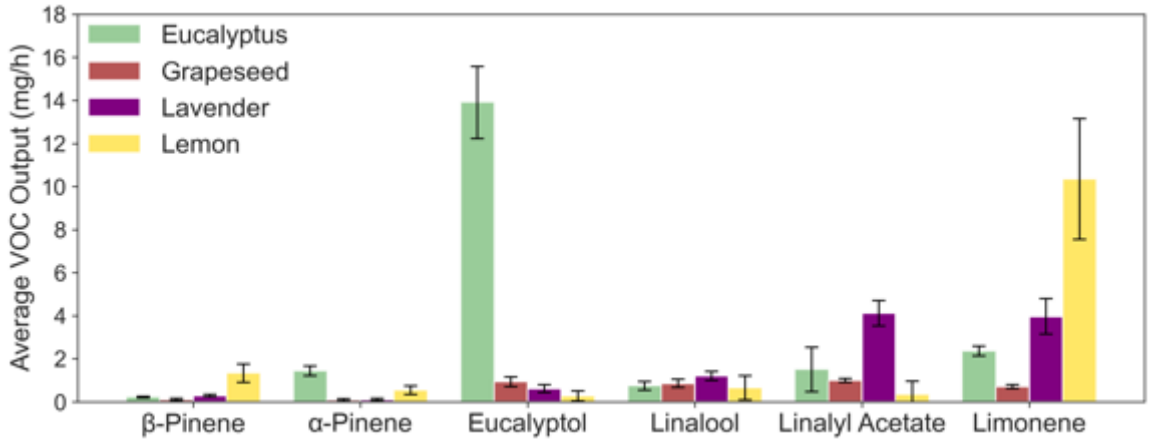
Mishra et al. (2021) *Indoor Air*

What about other pollutants?



Zhang et al. (2020) *Sci Tech Built Environ*



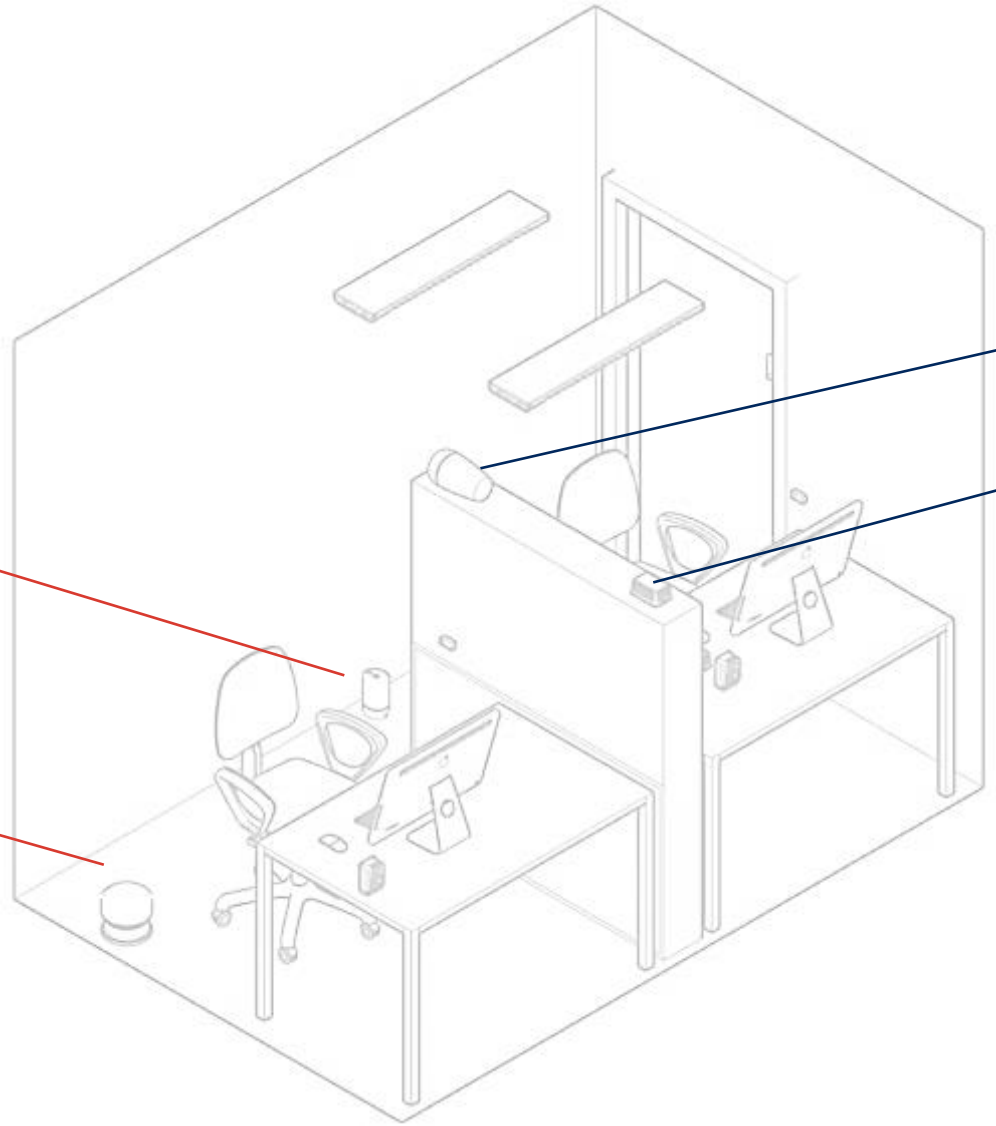


Schwartz-Narbonne et al. (2021) *Indoor Air*

Experimental Setup

Scenarios

- Diffuser with lemon oil / grapeseed oil/ water
- Portable air cleaner with / without a filter
- Phase 1 (lemon oil/distilled water; n=42, 22/20)
- Phase 2 (grapeseed oil/ filter; n=17, 8/9)



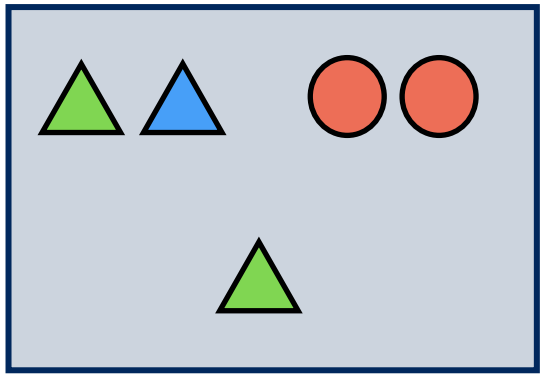
Environmental measurements

- VOCs (limonene & *β*-pinene)
- PM_1, $PM_{2.5}$, PM_{10}
- CO_2
- Ozone
- Formaldehyde
- Air temperature, relative humidity

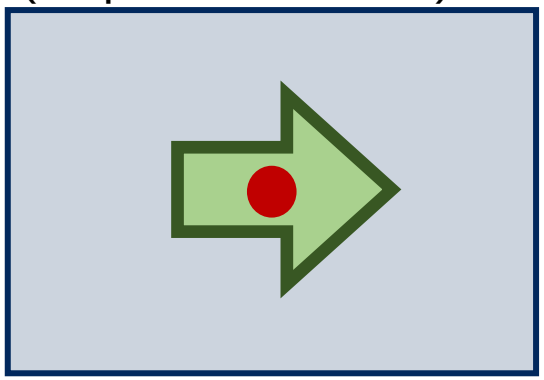
Du et al. (2021) *Indoor Air*

Cognitive Test Battery

Abstract Matching
(executive functioning)



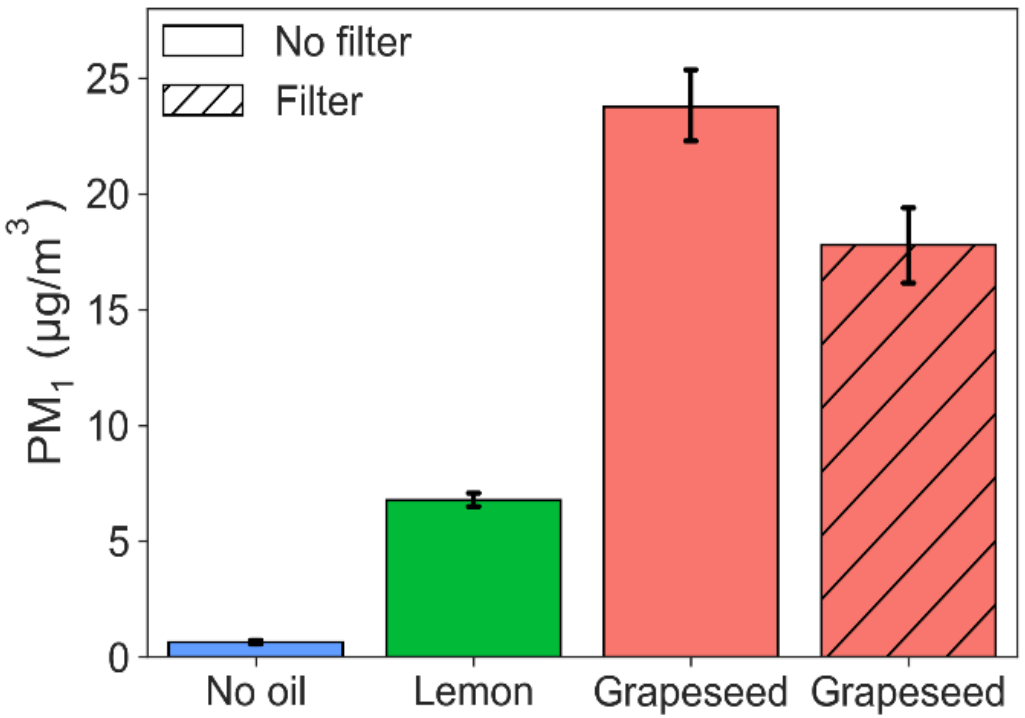
Stop Signal Reaction Time
(response inhibition)

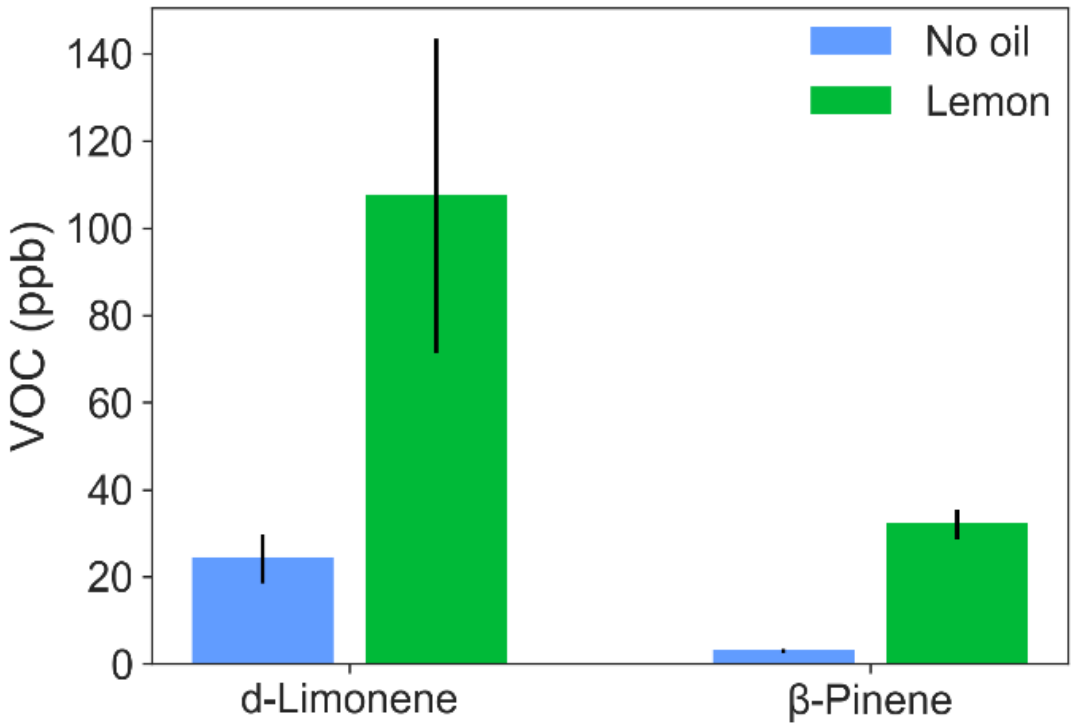


Continuous Recognition Memory
(memory over time)

Balloon Analog Risk Taking
& Four-Armed Bandit (risk taking)

Du et al. (2021) *Indoor Air*





Du et al. (2021) *Indoor Air*

Stop Signal Reaction Time
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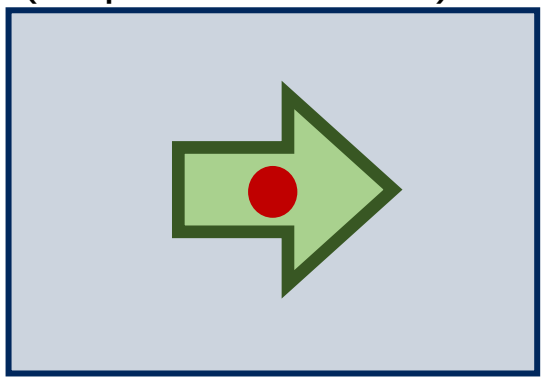
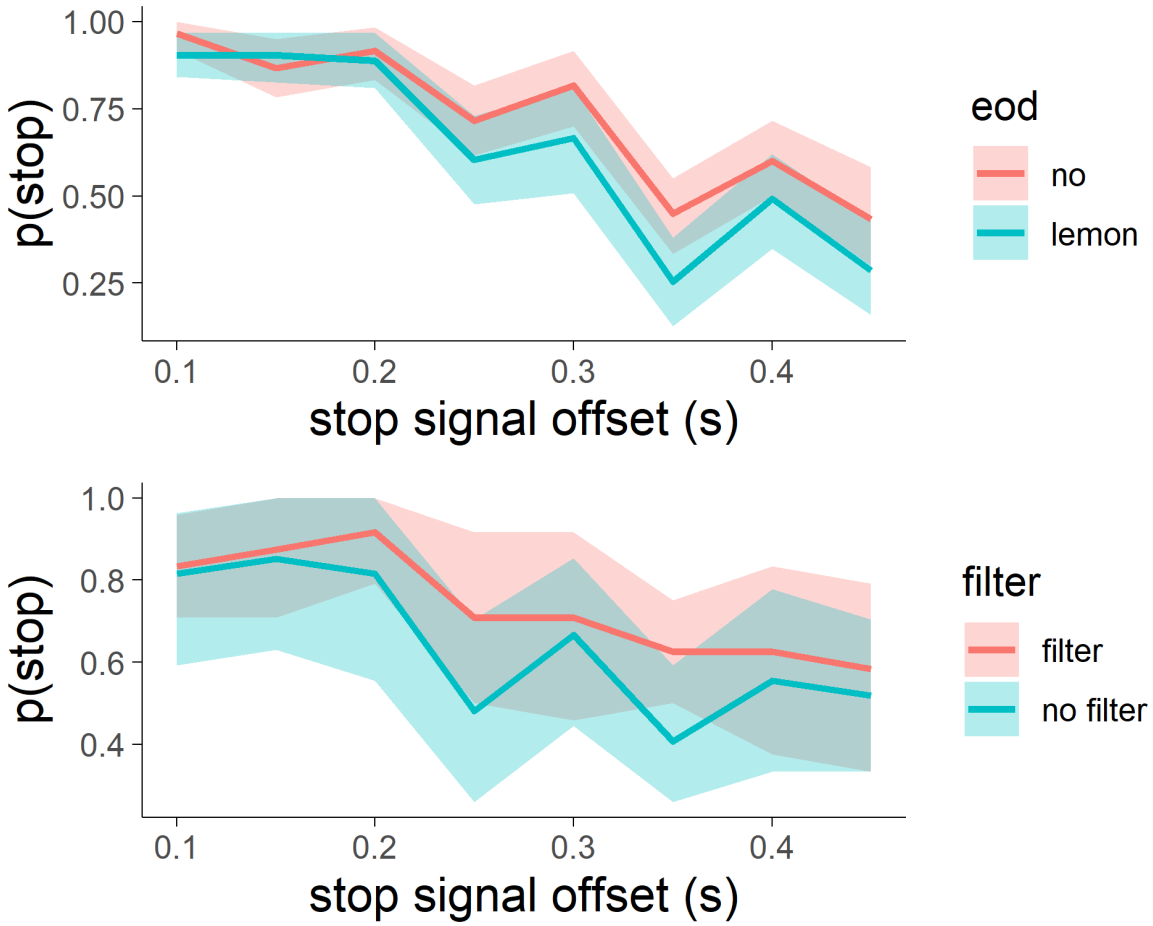
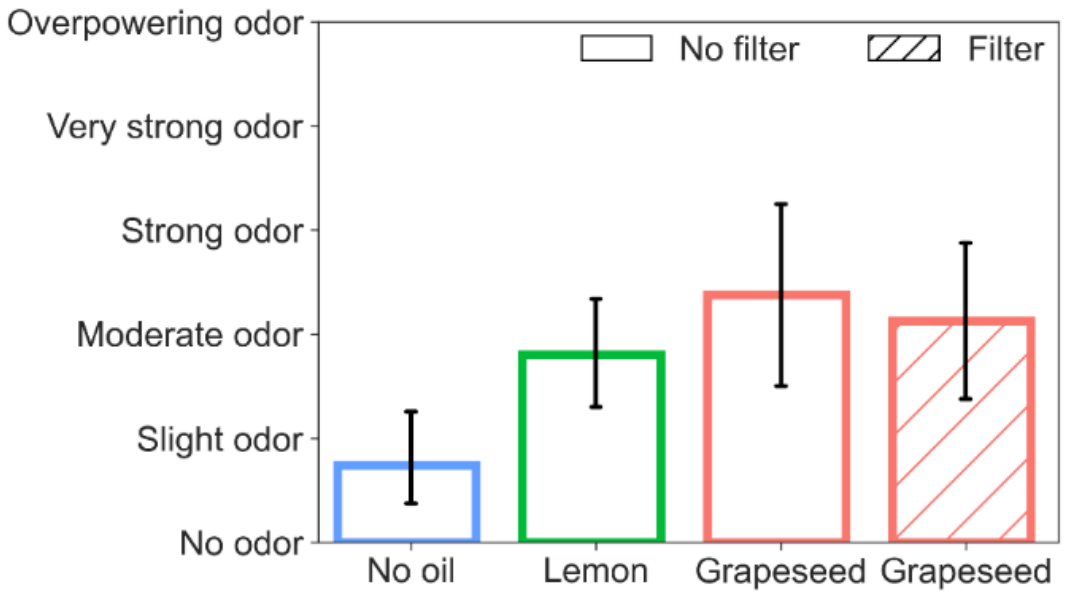
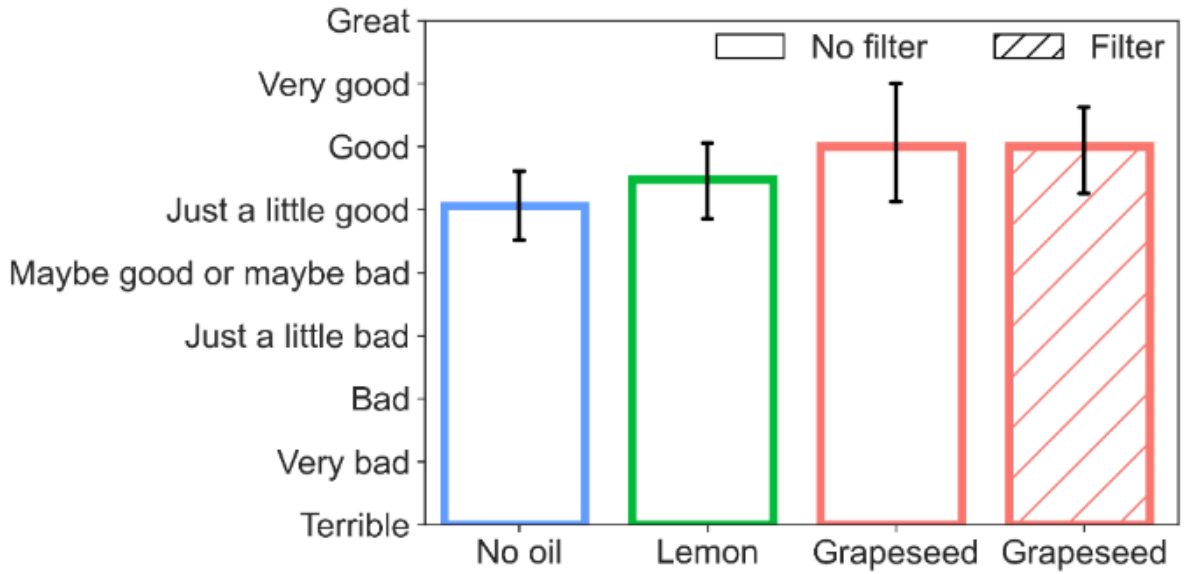




Du et al. (2021) *Indoor Air*



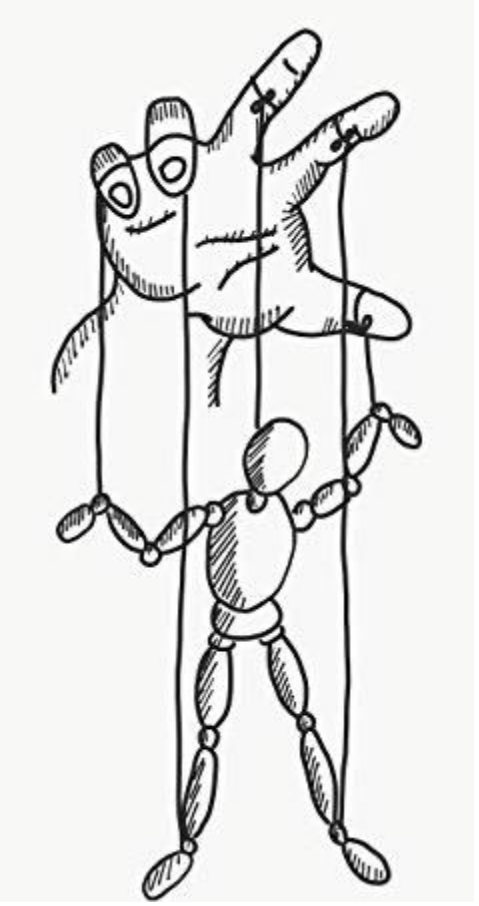


Du et al. (2021) *Indoor Air*

Overall Results

"Results show that exposure to essential oil emissions caused shortened reaction time at the cost of significantly worse response inhabitation control and memory sensitivity, indicating potentially more impulsive decision-making."

Du et al. (2021) *Indoor Air*



https://www.amazon.com/Romeo-and-Juliet/dp/B07GG1NHHB

- Rosemary essential oil improved short-term memory of images and numbers [1]
- Scent congruity influenced perceptions of retail stores and actual sales [2]
- Smell of citrus-scented cleaner enhances the behavior concept of cleaning [3]

[1] Filiptsova et al. (2017). *Egyptian journal of basic and applied sciences*.
[2] Spangenberg et al. (2006). *Journal of Business Research.*
[3] Holland et al. (2005). *Psychological science.*

David Suzuki Foundation

SOLUTIONS ARE IN OUR NATURE

Ref: http://www.davidsuzuki.org/what-you-can-do/queen-of-green/faqs/cleaning/can-indoor-plants-improve-air-quality-inside-my-home/

Can indoor plants improve air quality?

Believe it or not, NASA created a list of the best air-filtering plants!

The plants listed below are some of the most popular house plants, so they'll be easy to find, and they're also easy to care for.

Decorate your home or office with a combination of indoor plants

- Spider plants
- Peace lilies
- Snake plants (aka mother-in-law's tongue)
- Elephant ears
- Weeping figs
- Rubber plants
- Bamboo palms (aka reed palm)

Back in the 1980s, NASA did a study to look at which plants were best able to filter the air of the space station! And if it's good enough for the space station...

You don't have to be an astronaut to know that plants produce oxygen. But what you might not realize is that indoor plants can also absorb contaminants like benzene and formaldehyde (a known carcinogen). Dr. B.C. Wolverton's research also showed that plant-filtered rooms have 50 to 60 per cent less airborne microbes, like mold spores and bacteria.

Get rid of any fake, silk plants—they only collect dust—and harness the environment's natural ability to clean itself. You can also check the library for a more exhaustive list in Dr. B. C. Wolverton's book, *How to Grow Fresh Air: 50 houseplants that purify your home or office*.

A Brief History of Plants and Indoor Air

- Many investigations of the impact of plants on IAQ

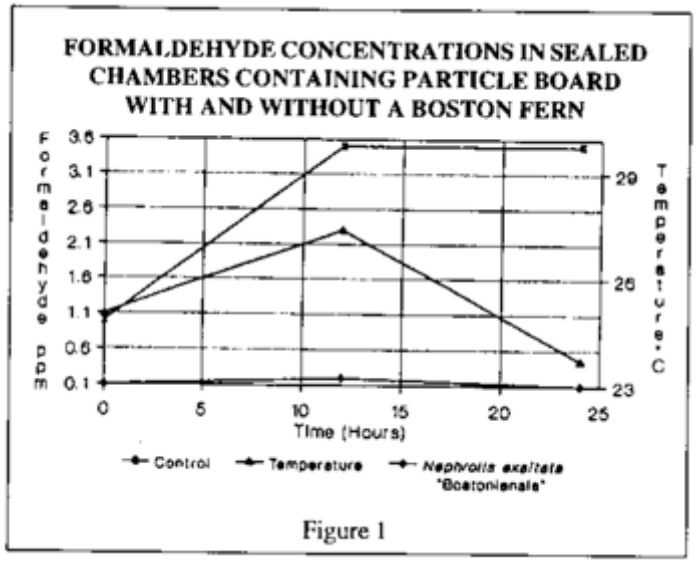
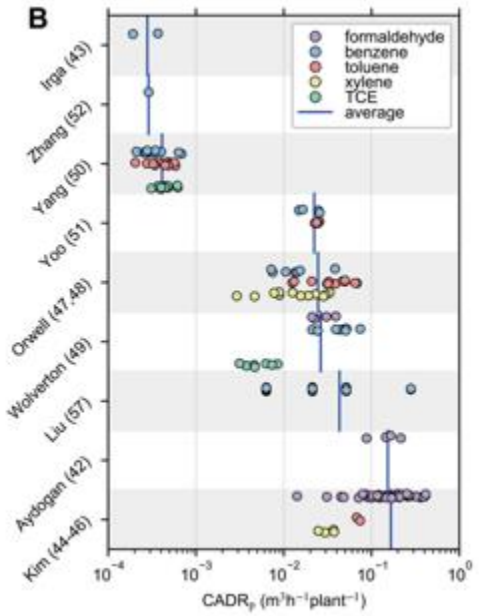


Figure 1

Plants And Soil Microorganisms: Removal of Formaldehyde, Xylene, and Ammonia from the Indoor Environment

B. C. Wolverton and John D. Wolverton
Wolverton Environmental Services
514 Pine Grove Road
Picayune, Mississippi 39466

Journal of Mississippi Academy of Sciences (1993)



Potted plants do not improve indoor air quality: a review and analysis of reported VOC removal efficiencies

Bryan E. Cummings[1] · Michael S. Waring[1]

Journal of Exposure Science & Environmental Epidemiology (2020) 30:253–261
https://doi.org/10.1038/s41370-019-0175-9

Table 7
Changes of Employees' Satisfaction, Concentration, Perceived Air Quality, and Productivity in Lean and Green Office Environments Across all Studies

	Study 1		Study 2		Study 3
Dependent variable	L	G	L	G	L vs. G
Workplace satisfaction	+	+ +	0	+ +	Not tested
Concentration	0	+ +	0	+	Not tested
Perceived air quality	0	+	0	+ +	Not tested
Productivity[a]	(−)	(+)	0	0	+[b]

Note. L = lean condition; G = green condition. + + = positive change at $p < .01$. + = positive change at $p < .05$. (+) = positive change at $p < .10$. (−) = negative change at $p < .10$. 0 = no change ($p > .10$). This table was based on simple effect analyses in Studies 1 (T1 vs. T2) and 2 (T1 vs T2, T3) and the MANCOVA in Study 3.
[a] Productivity was measured in different ways across the studies. [b] This effect refers to the difference between the lean and the green condition.

The Relative Benefits of Green Versus Lean Office Space: Three Field Experiments

Marlon Nieuwenhuis
Cardiff University

Craig Knight
University of Exeter

Tom Postmes
University of Groningen

S. Alexander Haslam
University of Queensland

Journal of Experimental Psychology: Applied
2014, Vol. 20, No. 3, 199–214

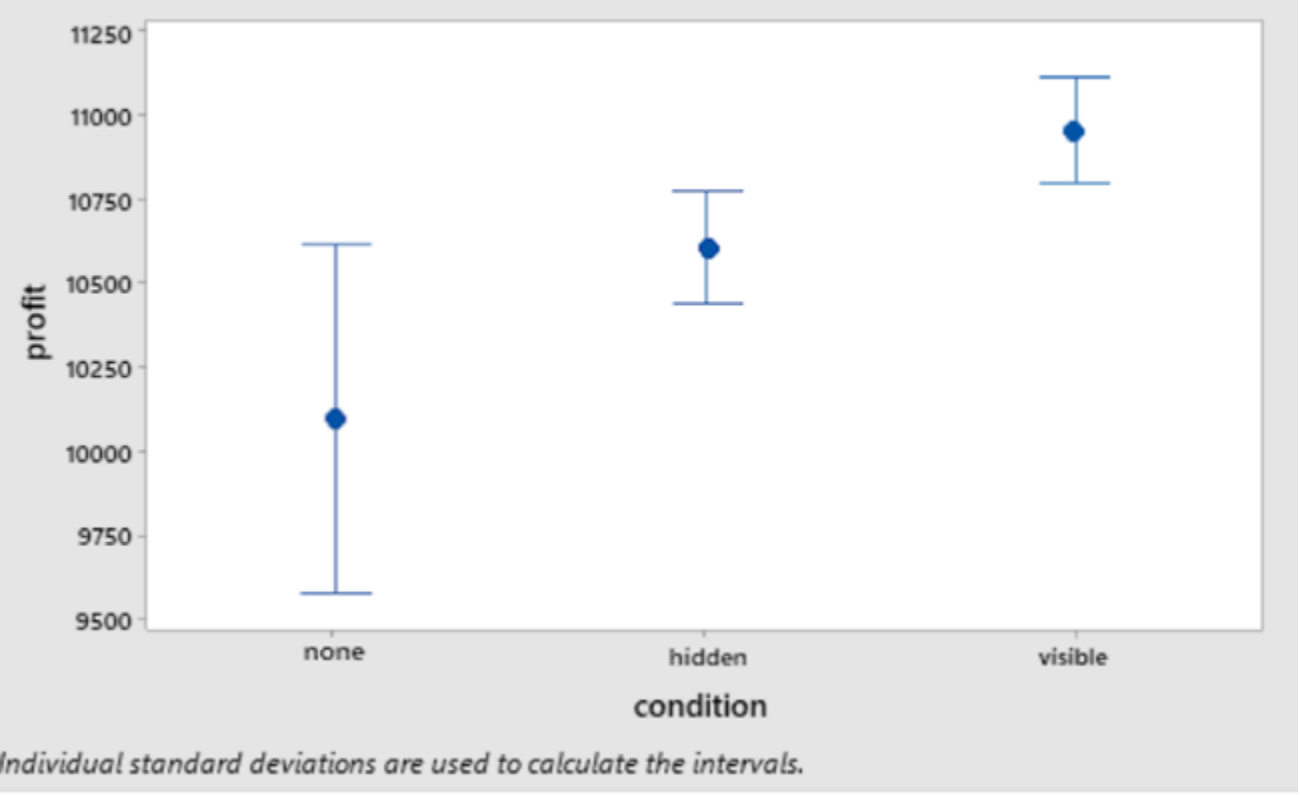
Experimental Design

- N= 19, Within-subject design (but not randomized order, potential learning effects)
- Three experimental conditions:
  - Ordinary classroom (November 18, 2019)
  - Hidden plants (November 25, 2019)
  - Visible plants (November 25, 2019)
- Each test subject did cognitive battery (~20 minutes)
- Measurements of PM, HCHO, temp., RH, CO_2
- Brief survey of IAQ perceptions and perceptions of plants

Jarvis et al. 2020 *Indoor Air Conf. Paper 830*

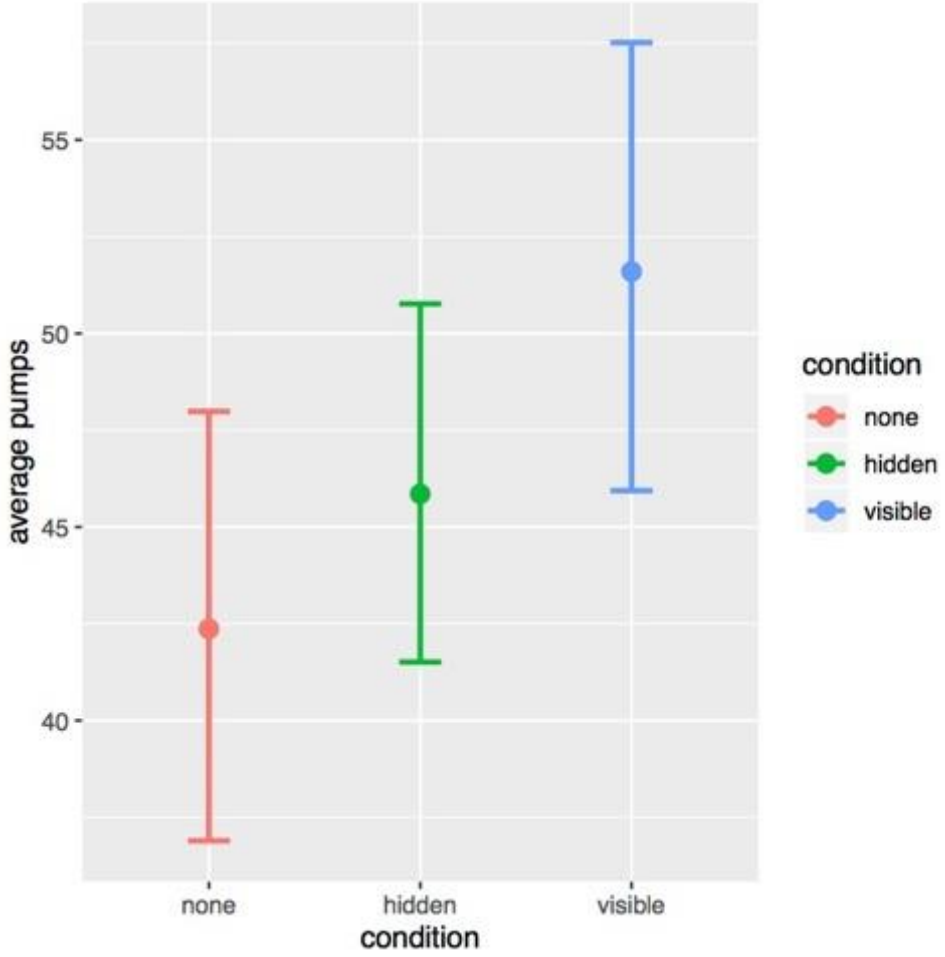
Four Armed Bandit Test

Condition vs. Average Cumulative Profit
95% Confidence interval



Balloon Analogue Test

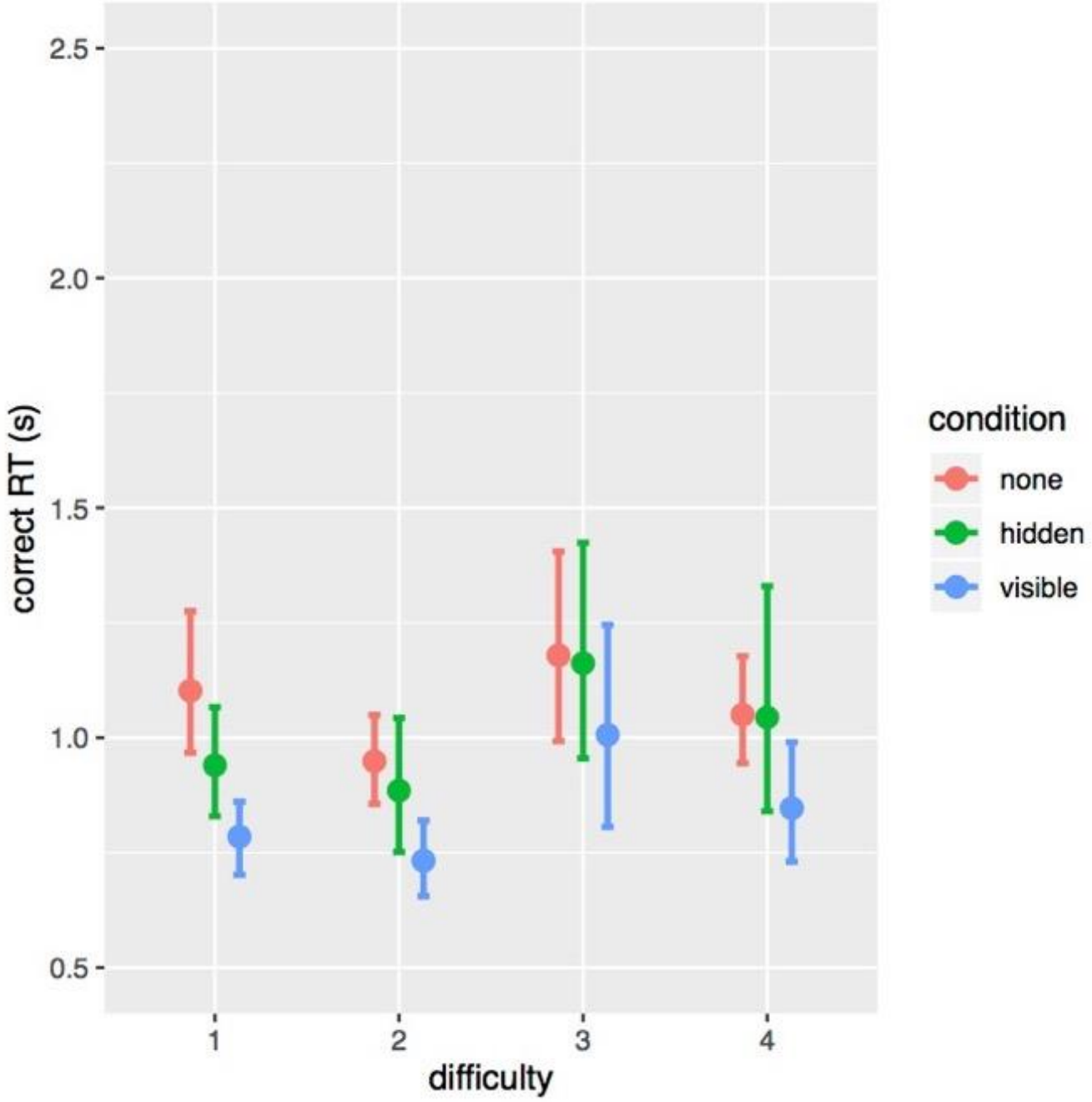
Condition vs. Average Number of Successful Balloon Pumps
95% Confidence interval



Jarvis et al. 2020 *Indoor Air Conf. Paper 830*

Difficulty vs. Mean Response Time for Correct Abstract Matching Results

95% Confidence



Test 1,2, and 3:

Overall, do the current classroom conditions enhance or interfere with your mental ability to complete tasks?

Interfere			*Neutral*			*Enhance*
1	*2*	*3*	*4*	*5*	*6*	*7*

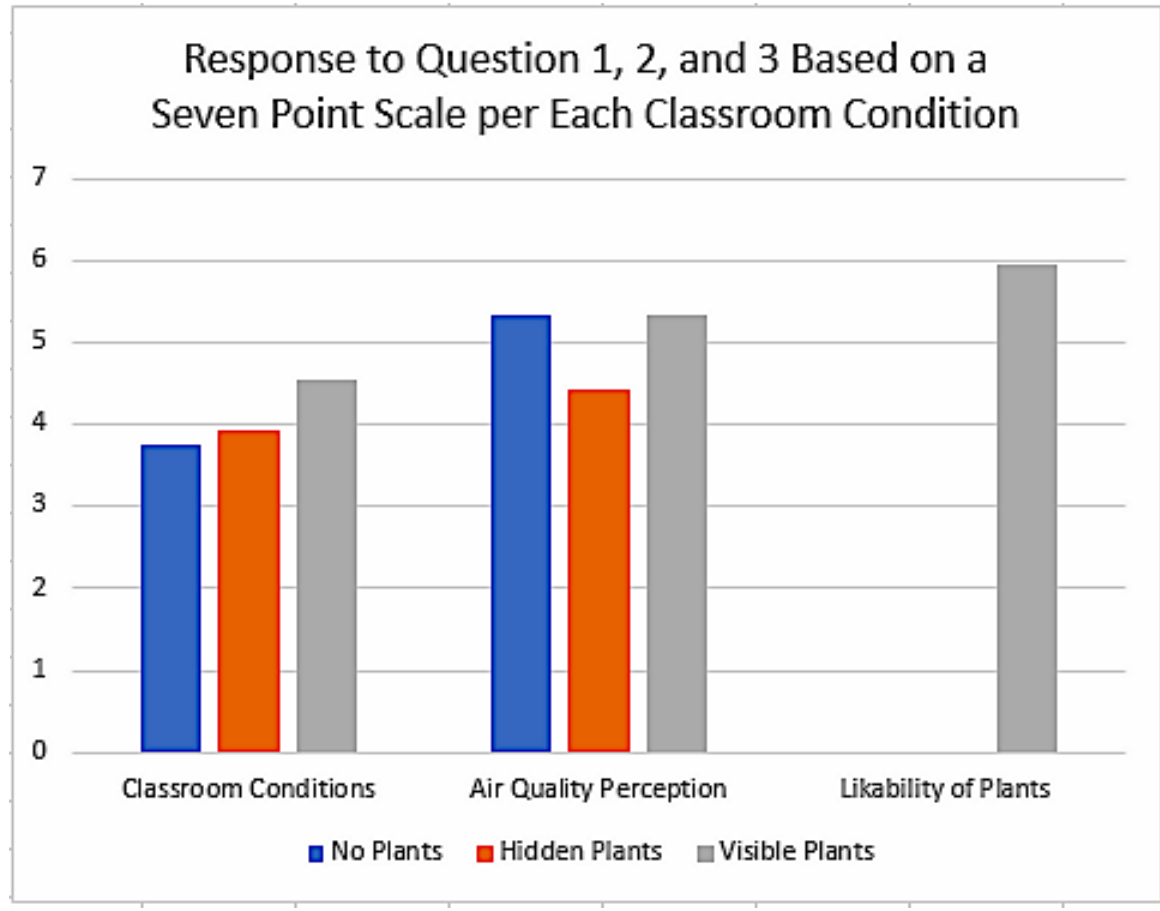
How do you assess the air quality level? *(Simone, Levorato, Olesen & Zhu,2014)*

clearly unacceptable		*not acceptable*		*just acceptable*		*clearly acceptable*
1	*2*	*3*	*4*	*5*	*6*	*7*

Only after Test 3:

Do you like working with plants in your indoor environment? (1—>7)

No plants			*Hidden Plants*			*Visual Plants*
1	*2*	*3*	*4*	*5*	*6*	*7*

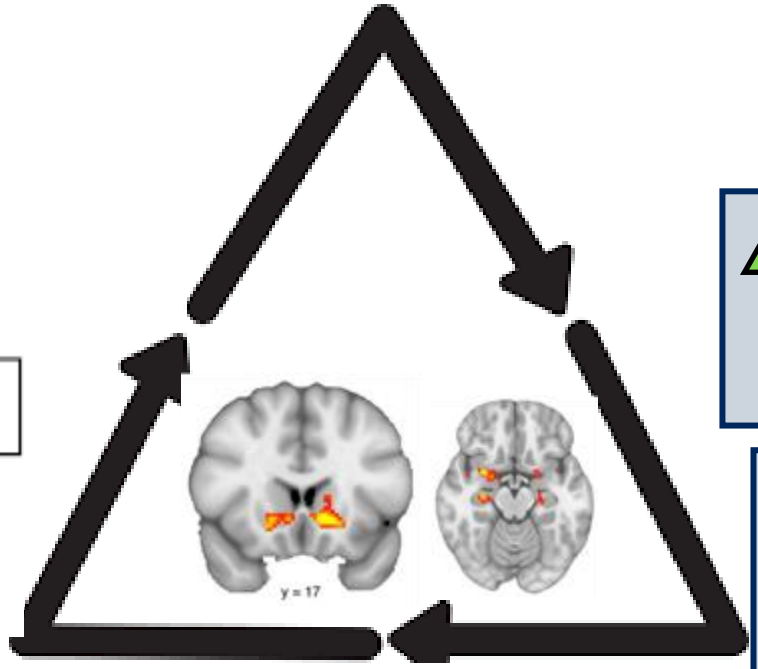


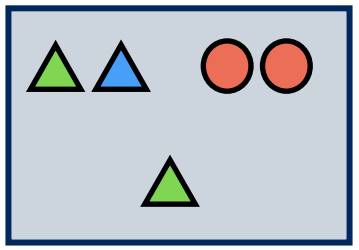
Jarvis et al. 2020 *Indoor Air Conf. Paper 830*

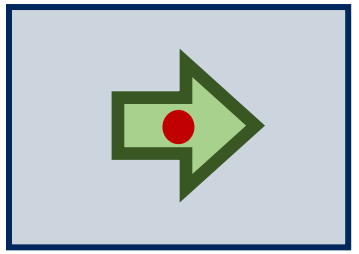
Implications

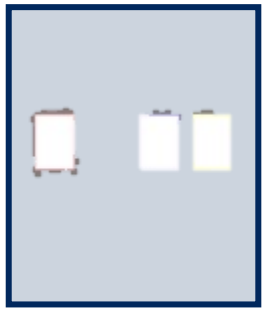
- Perceptions are also potentially important to cognitive function
- Within subjects: Learning effects/confusion between trials
- Between subjects: Individual variability

Overall Summary and Ongoing Work









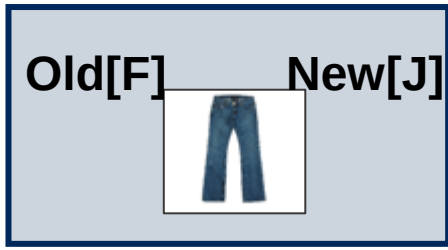


Image: Hipskind et al. (2011) *Nut Clin Prac*

Invest in indoor air to improve cognitive function. Use benefits to pay for improvements. Chronic health outcome improvement are a “side” benefit.

Parting Comments

- COVID-19 has increased attention on indoor air measures
- Can we maintain this attention as the pandemic recedes?
  - Performance on standardized tests
  - Reduced absenteeism from school and work
  - Increased productivity
  - Reduced asthma frequency and severity