How indoor climate affects productivity in offices, schools and similar buildings

Lessons learnt (mainly) from research on thermal and air quality effects on performance

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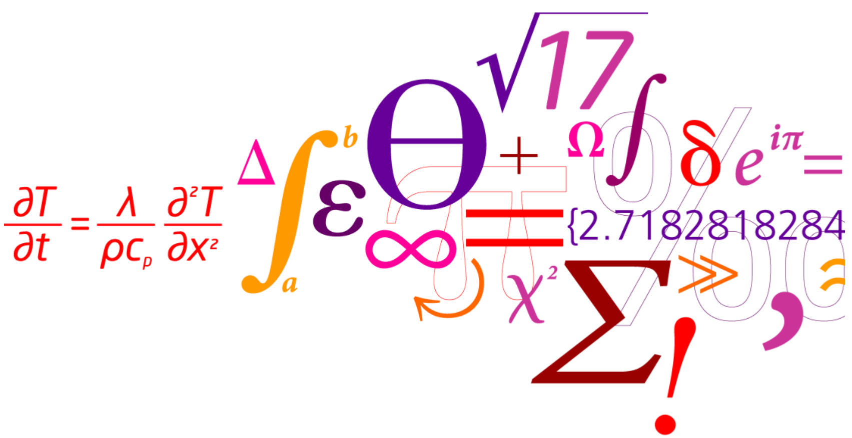
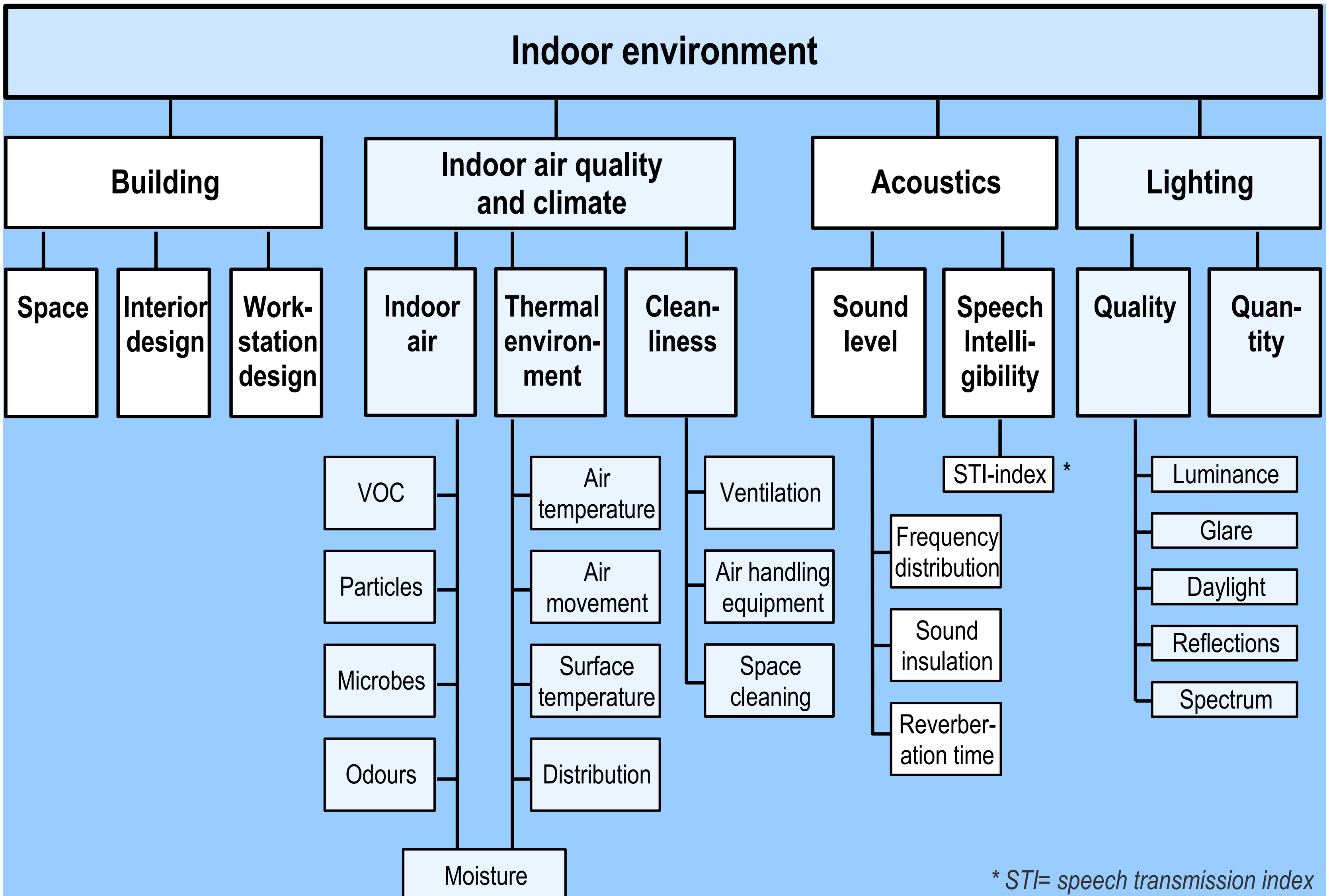
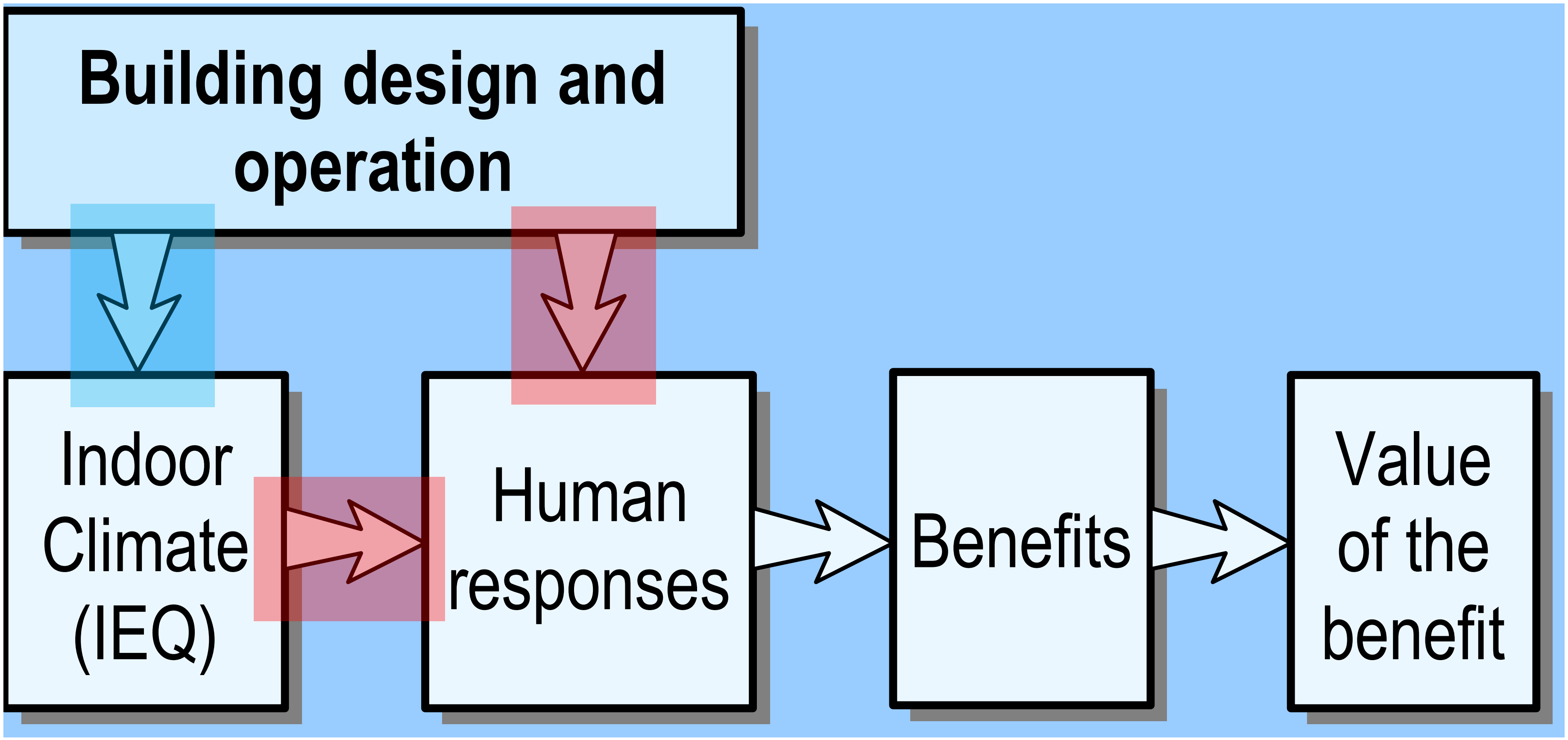


Indoor climate parameters (IEQ)



IEQ and human performance



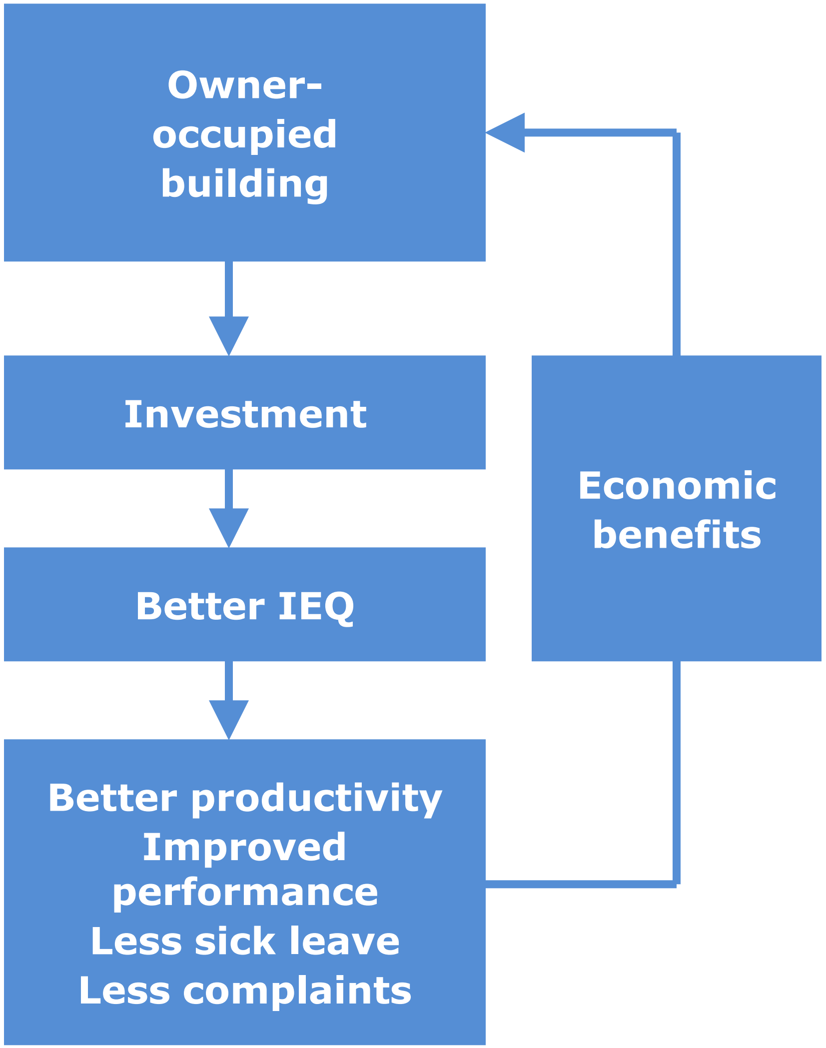
Recipients of benefits

- Individuals (better working conditions, higher wages, less medical costs, longer at work, etc.)
- Building owner (increased building value, higher rent, less maintenance costs, etc.)
- Employer (increased revenue, less staff turnover, less absence rate)
- Society (higher GDP, lower costs of compensation/litigation)

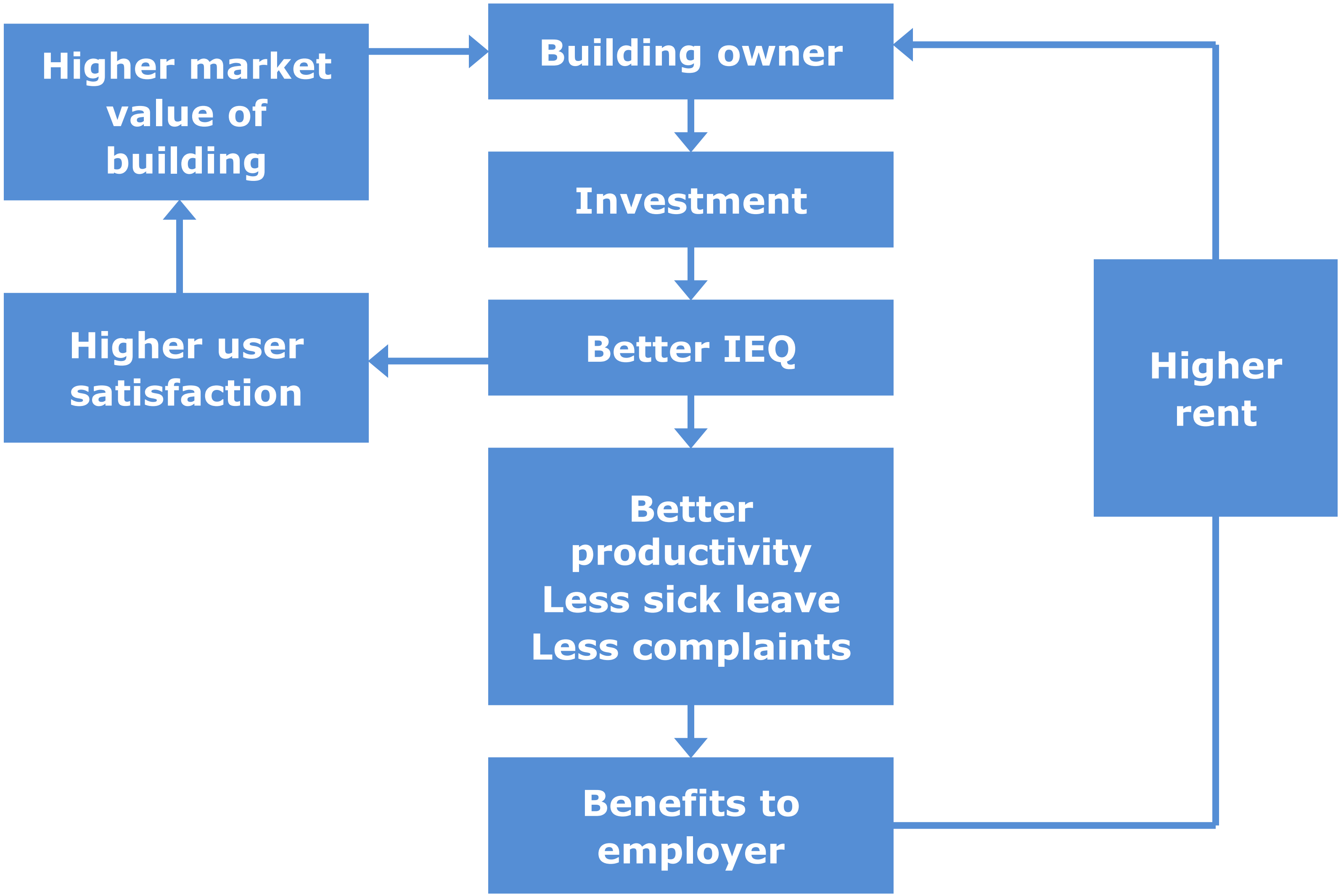
Offices

- The majority of all working places are office-type; the proportion is continuously growing
- In Europe, office buildings are the second largest section of the non-residential market for new construction (ca. 20% of the market)
- A growing demand for continuously increasing competence and productivity
- Occupants suffer too often from an inferior indoor environment and report comfort/health problems

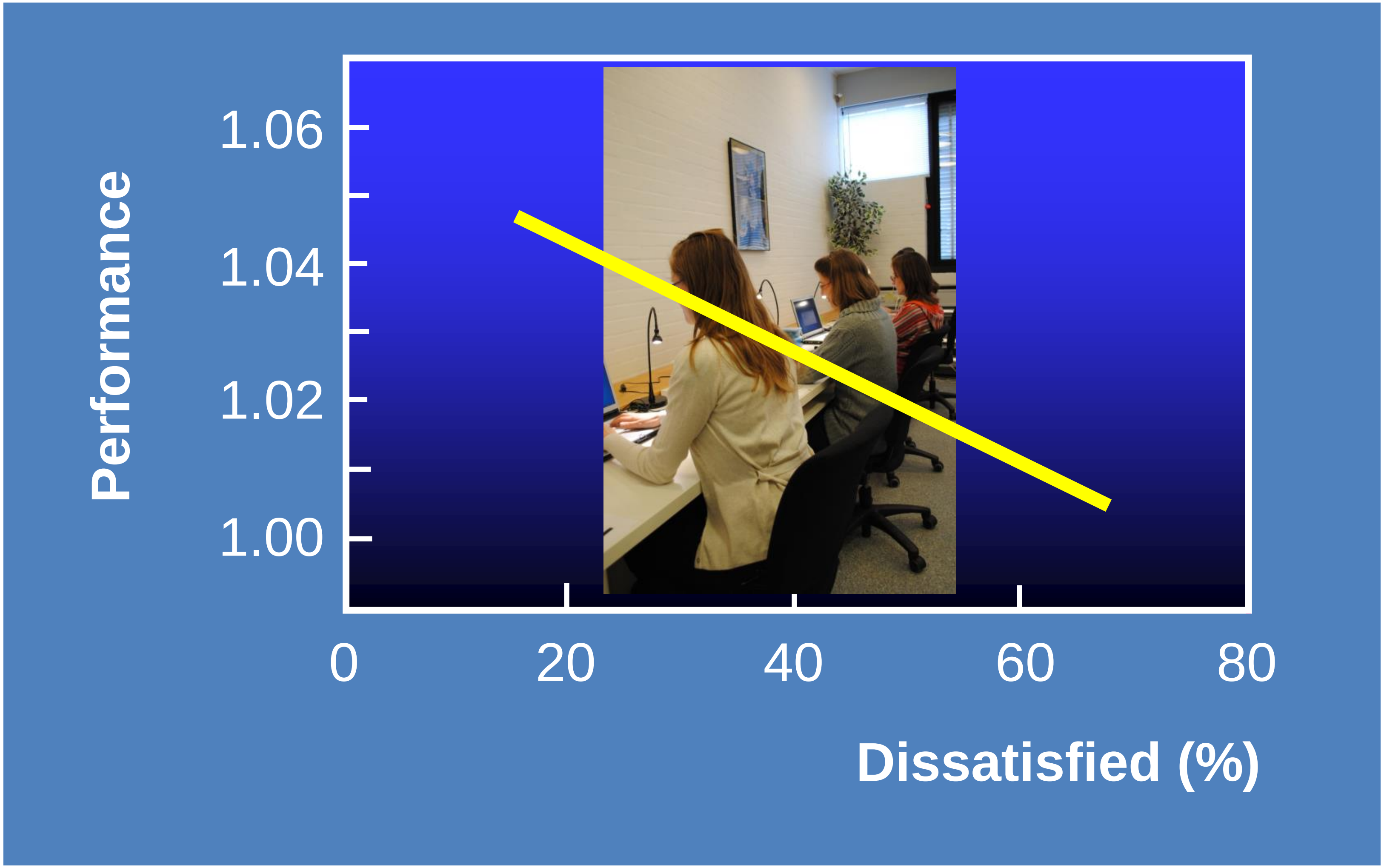
Driving force for the investment in high IEQ in office buildings



Driving force for the investment in high IEQ in office buildings

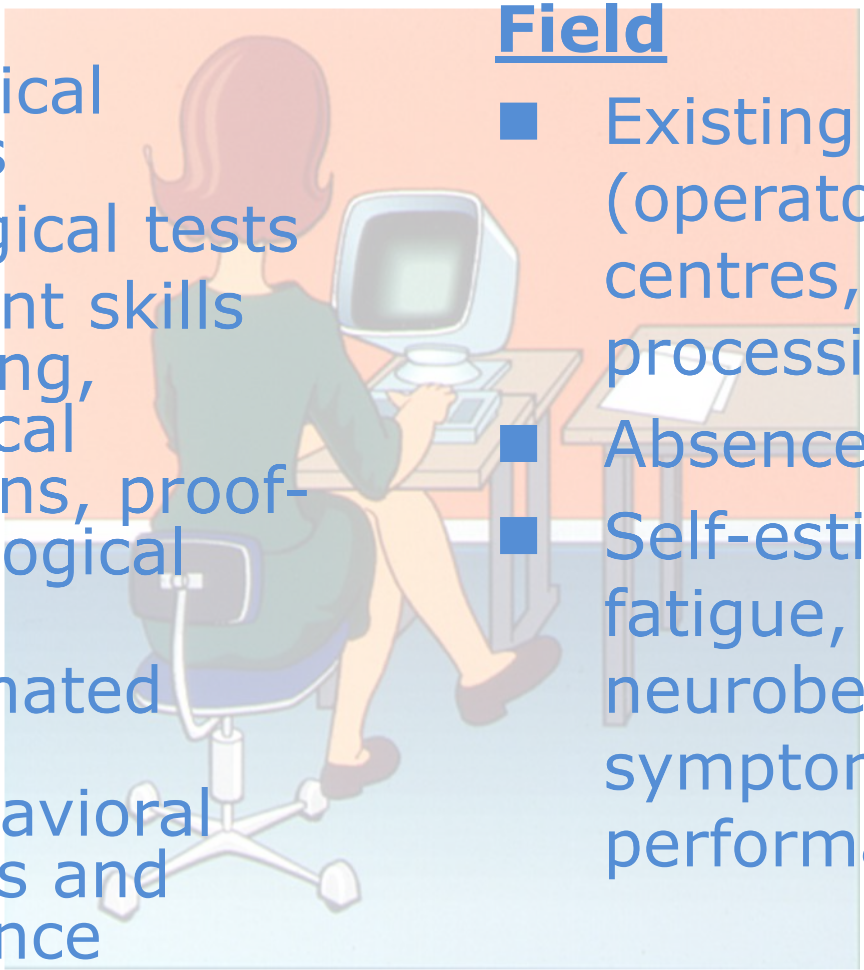


Indoor air quality and performance of office work



Source: Wargocki and Seppanen (2006)

Measurements of performance



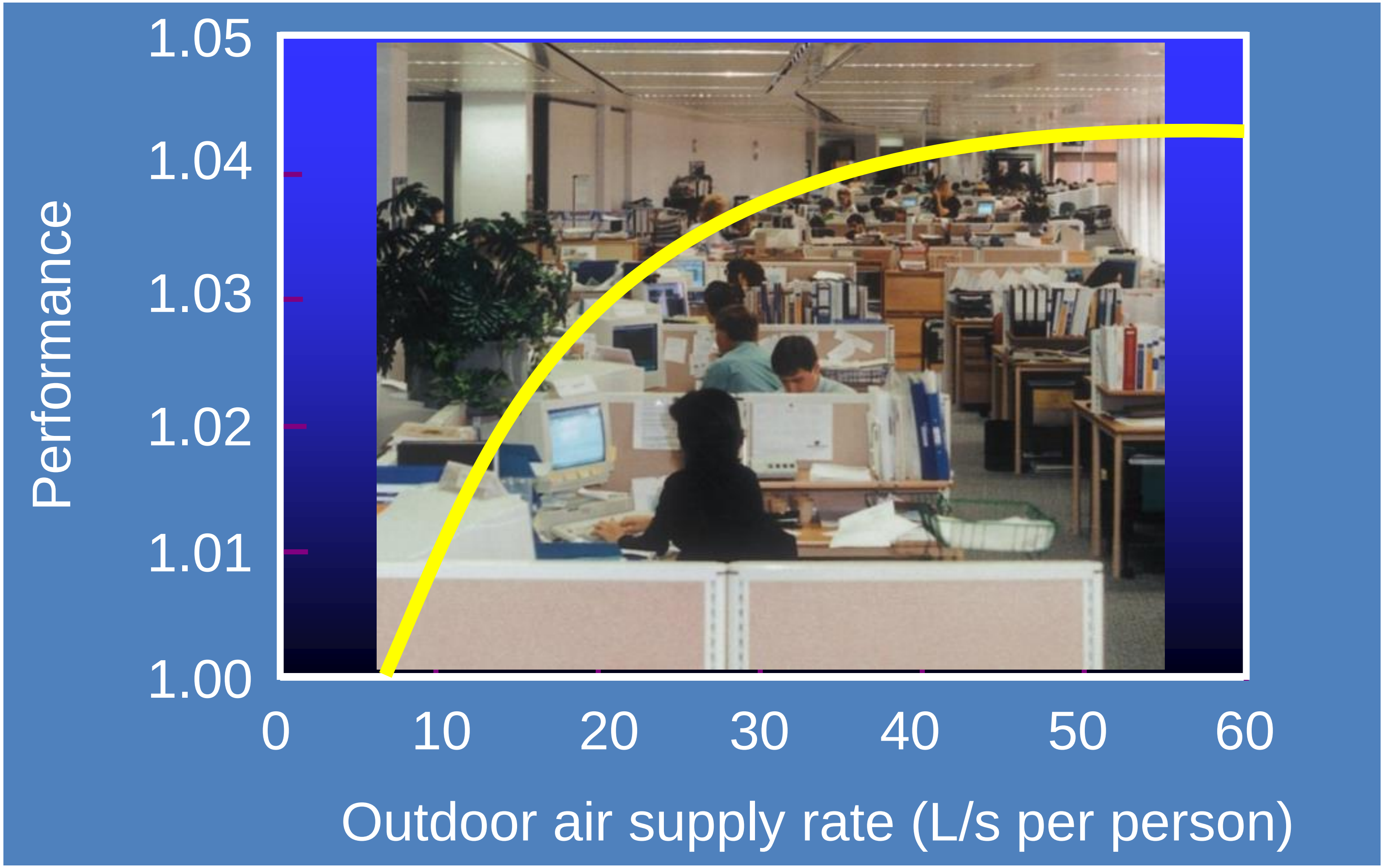
Laboratory

- Physiological indicators
- Psychological tests
- Component skills (text typing, arithemtical calculations, proof-reading, logical thinking)
- Self-estimated fatigue, neurobehavioral symptoms and performance

Field

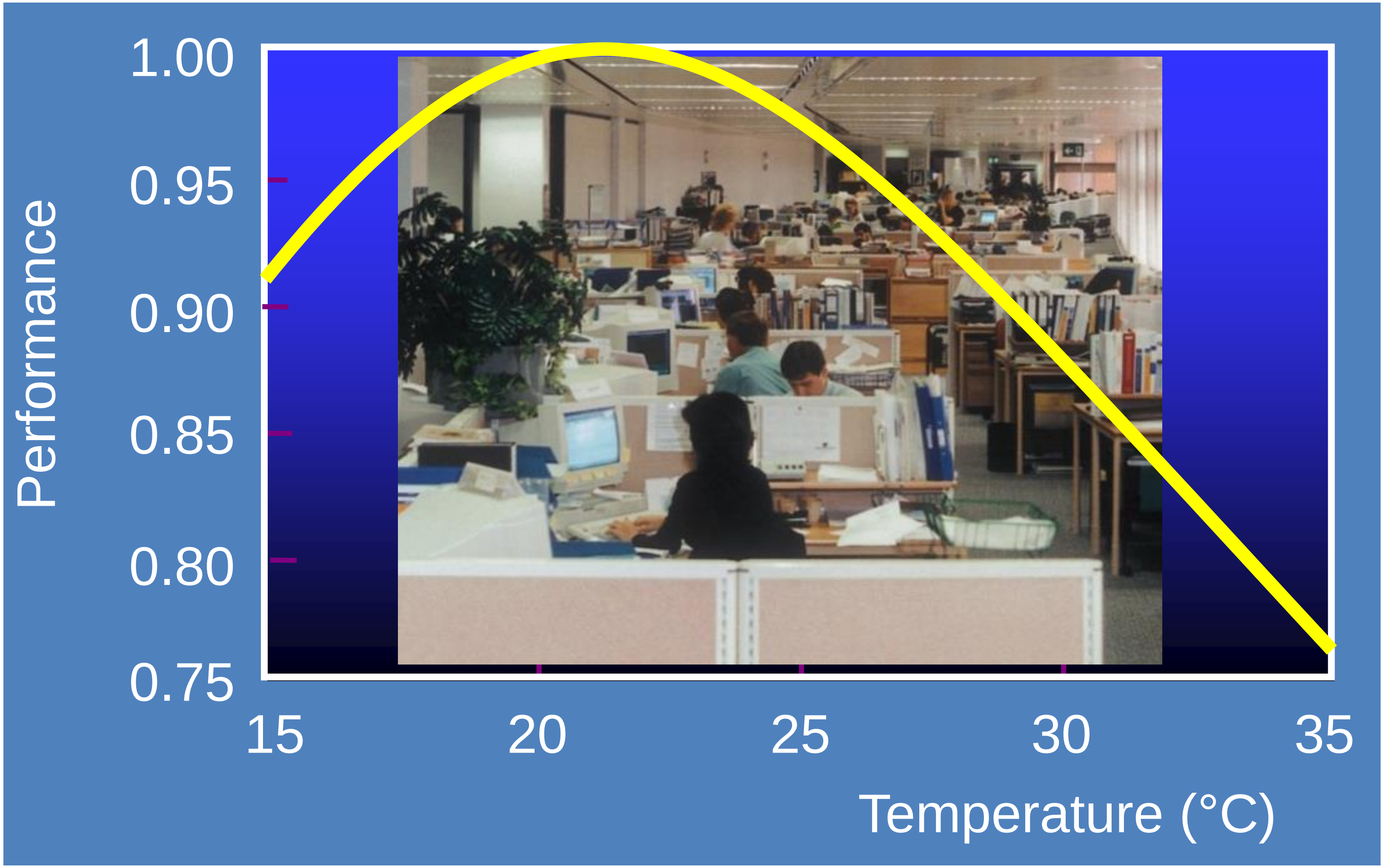
- Existing measures (operator time in call centres, claim processing time)
- Absence rates
- Self-estimated fatigue, neurobehavioural symptoms and performance

Ventilation and performance of office work



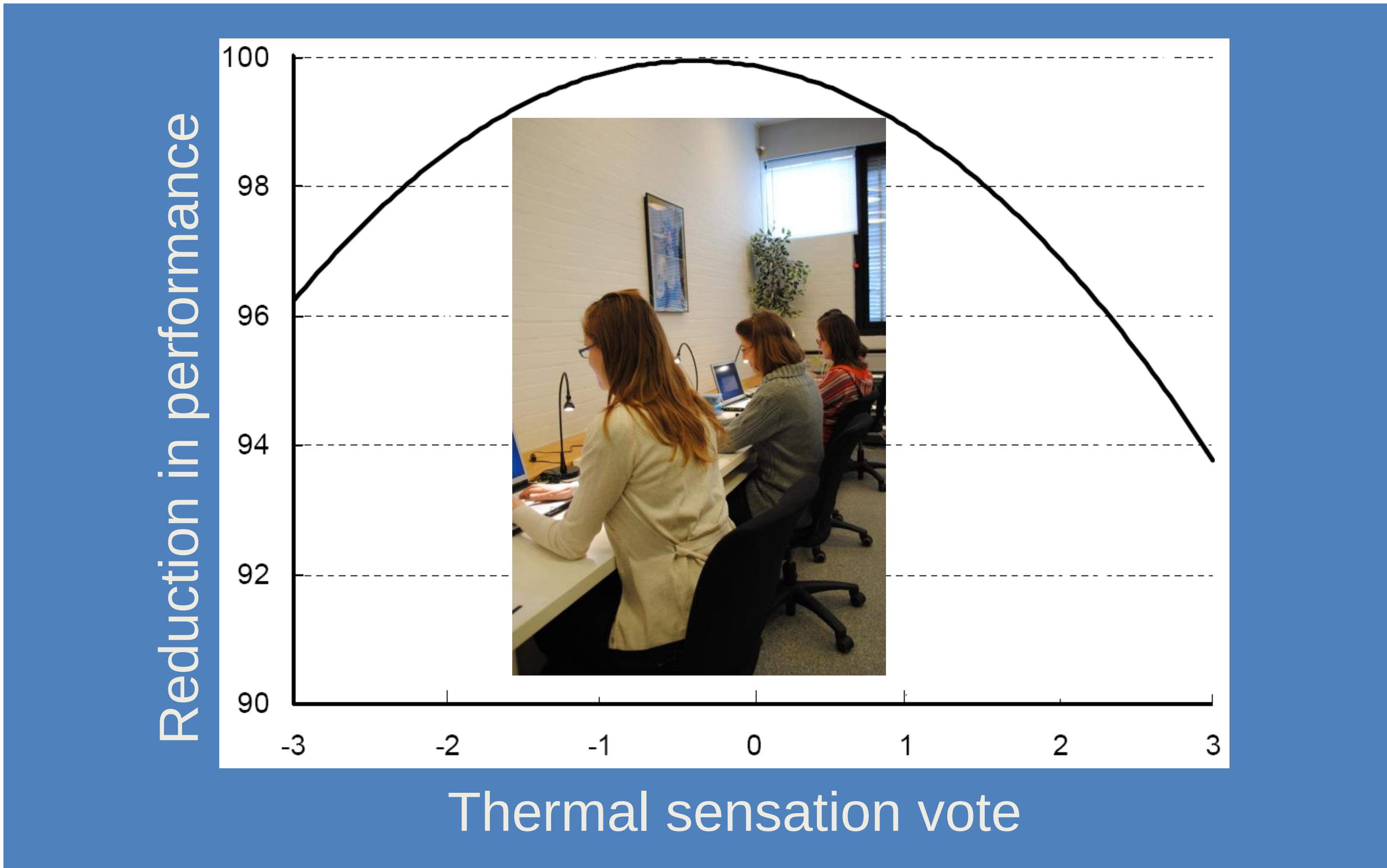
Source: Wargocki and Seppanen (2006)

Temperature and performance of office work



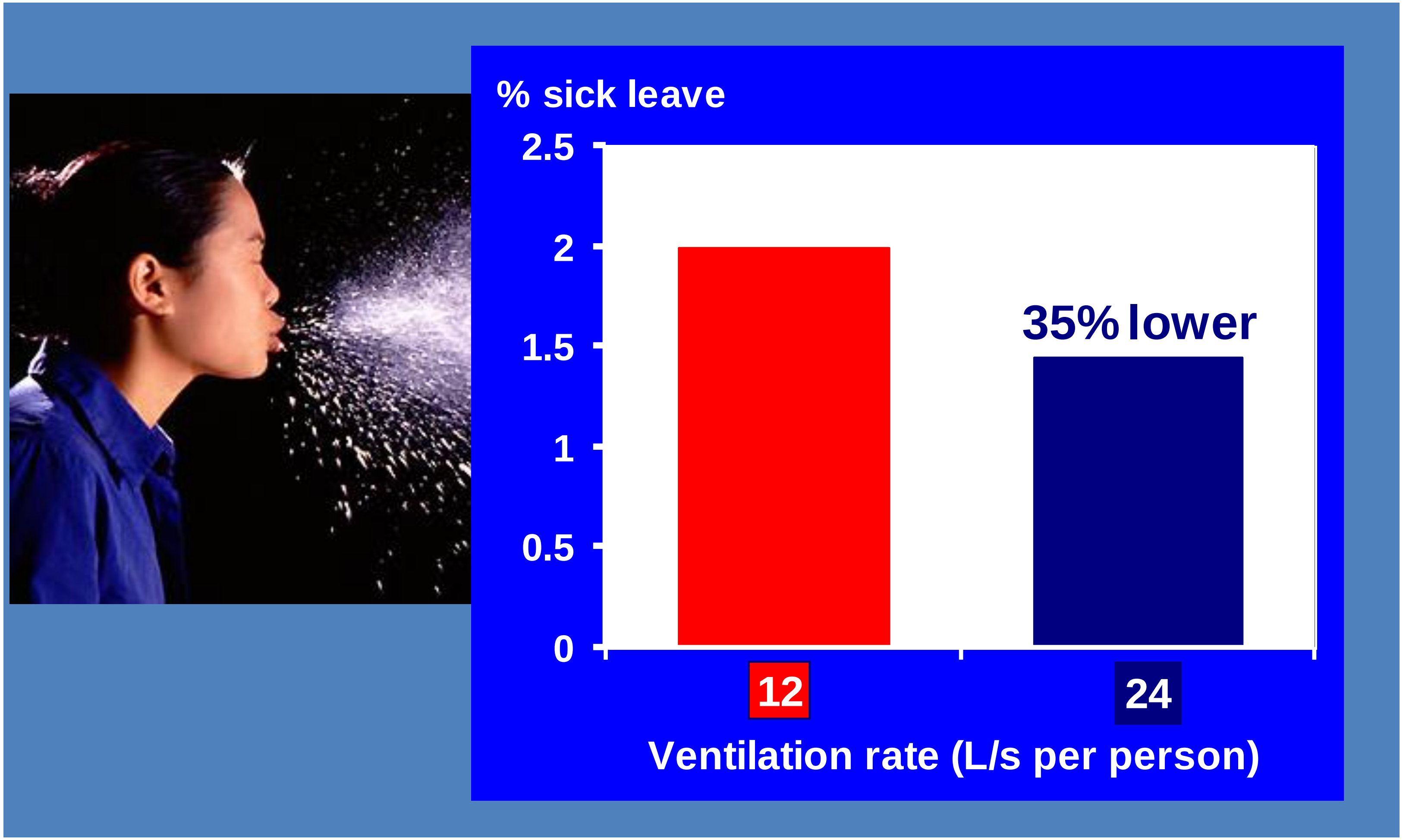
Source: Seppanen et al. (2005)

Thermal discomfort and performance of office work



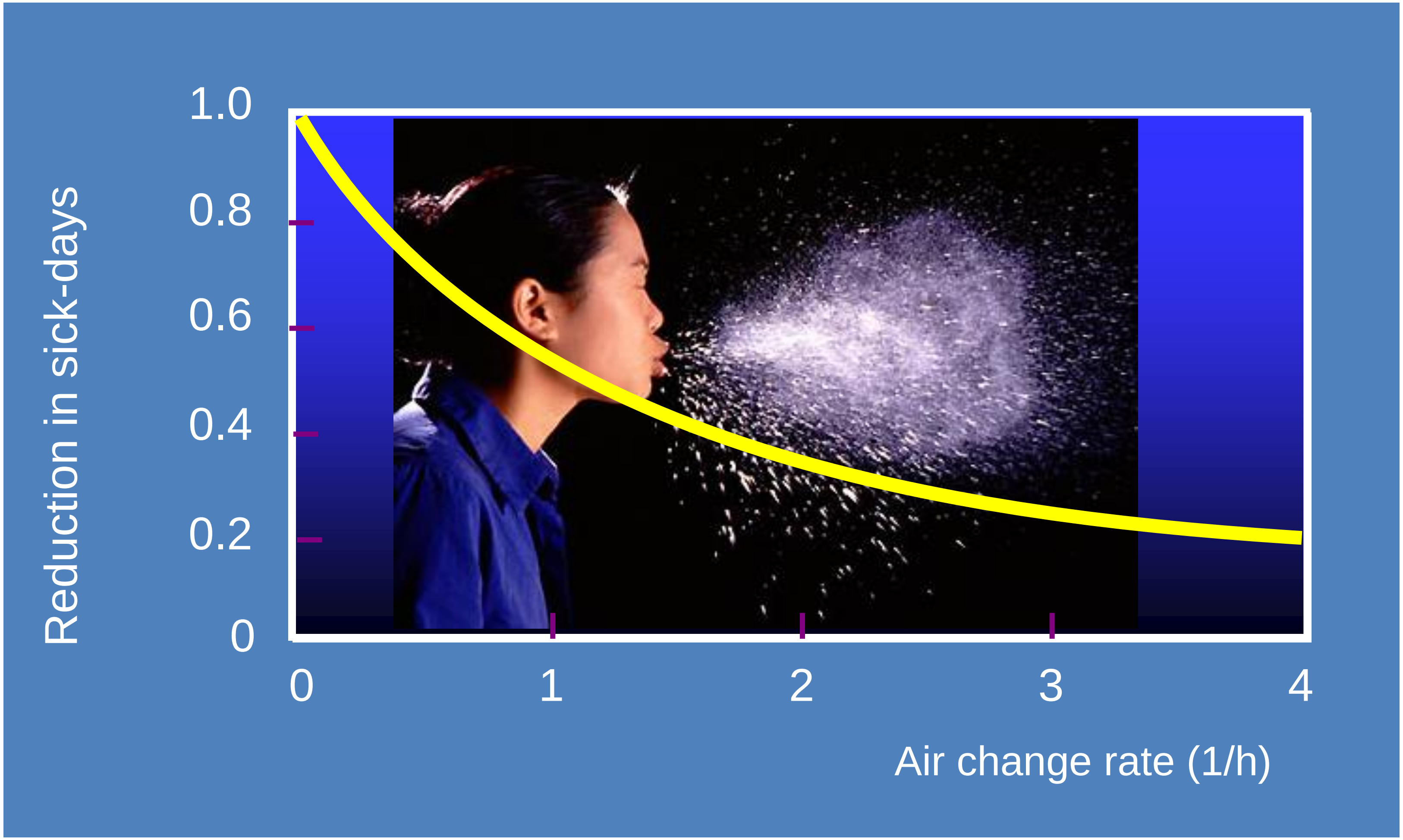
Source: Lan et al. (2011)

Absence rates



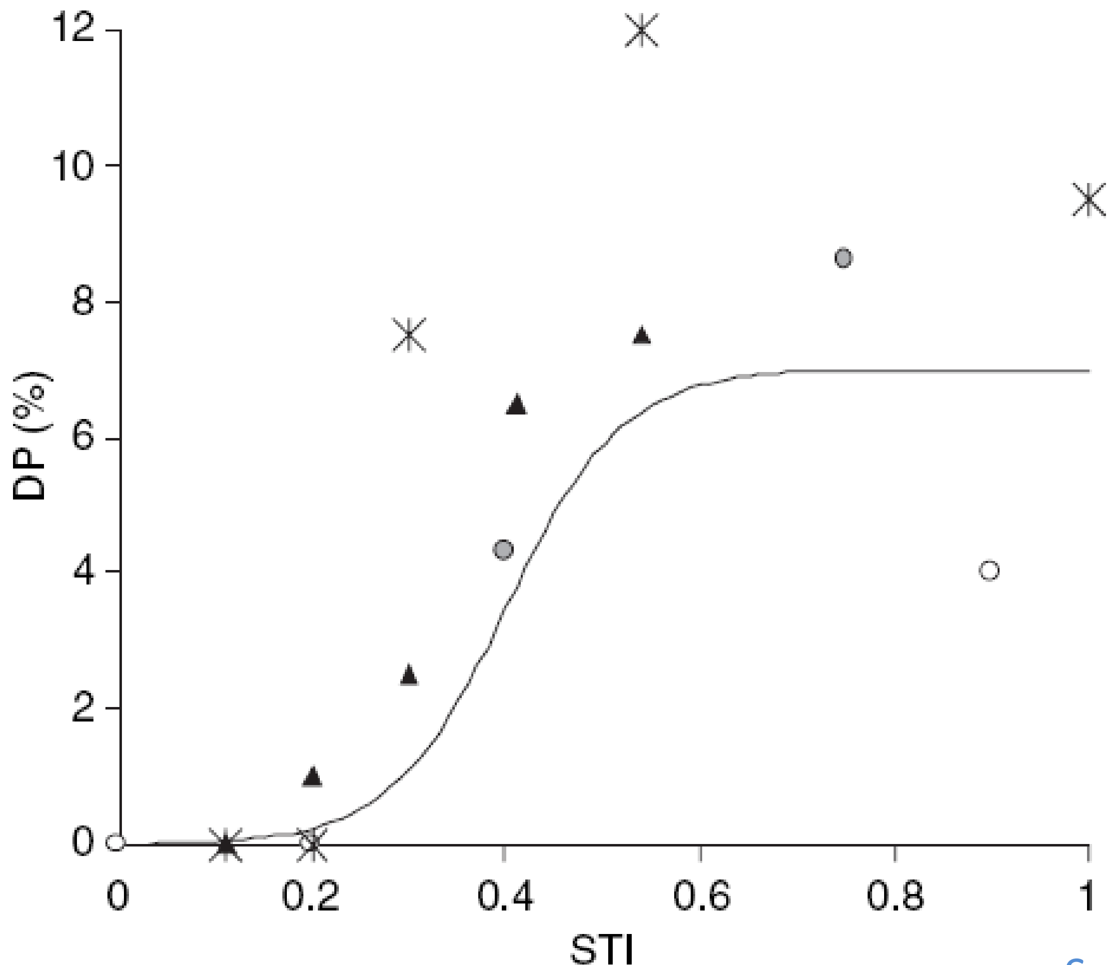
Source: Milton et al. (2000)

Short-term sick-leave (due to infections) and ventilation



Source: Wargocki and Seppanen (2006)

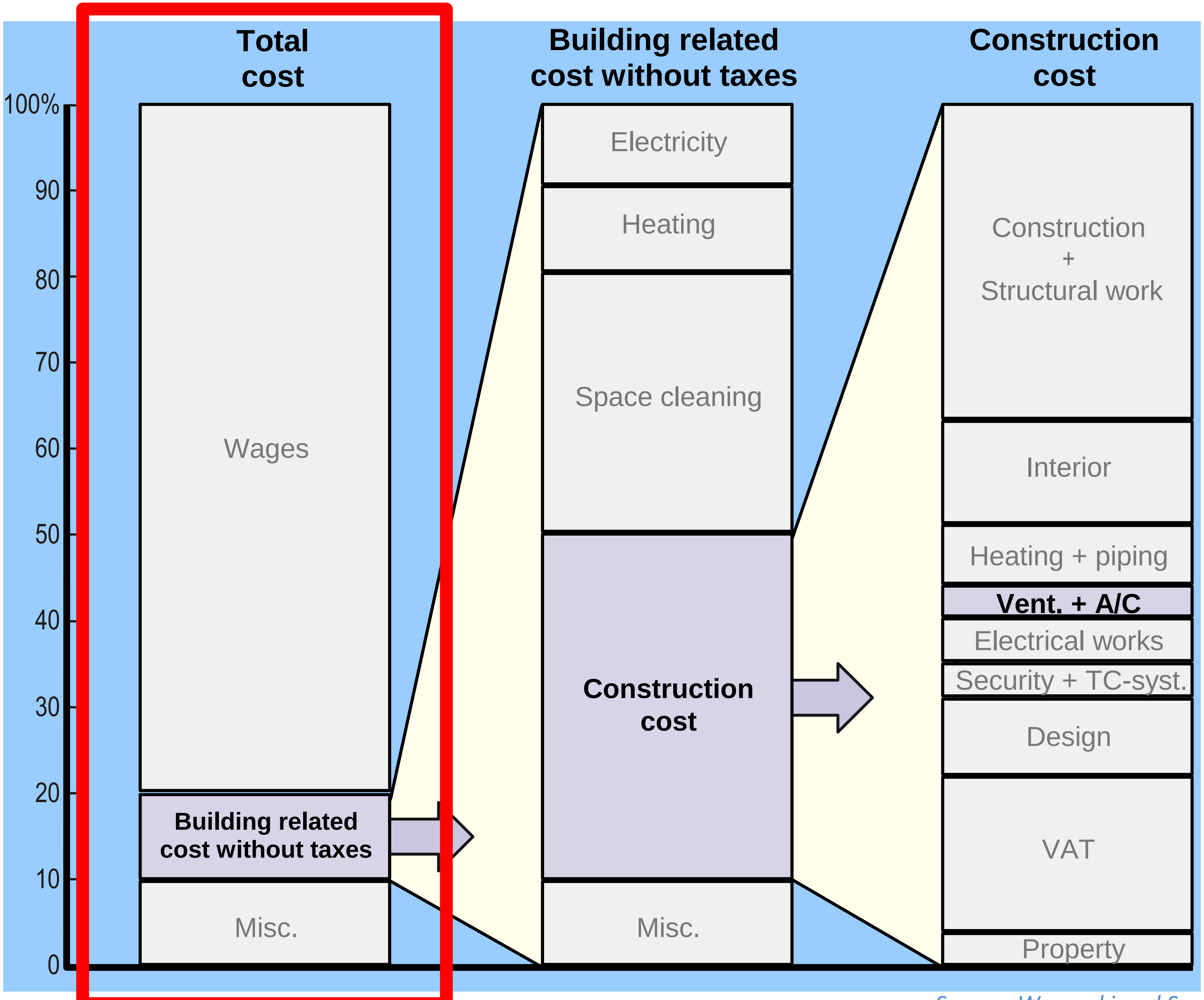
Loss of productivity (DP) and noise distraction (STI: Speech Transmission Index)



Source: Hongisto et al. (2005)

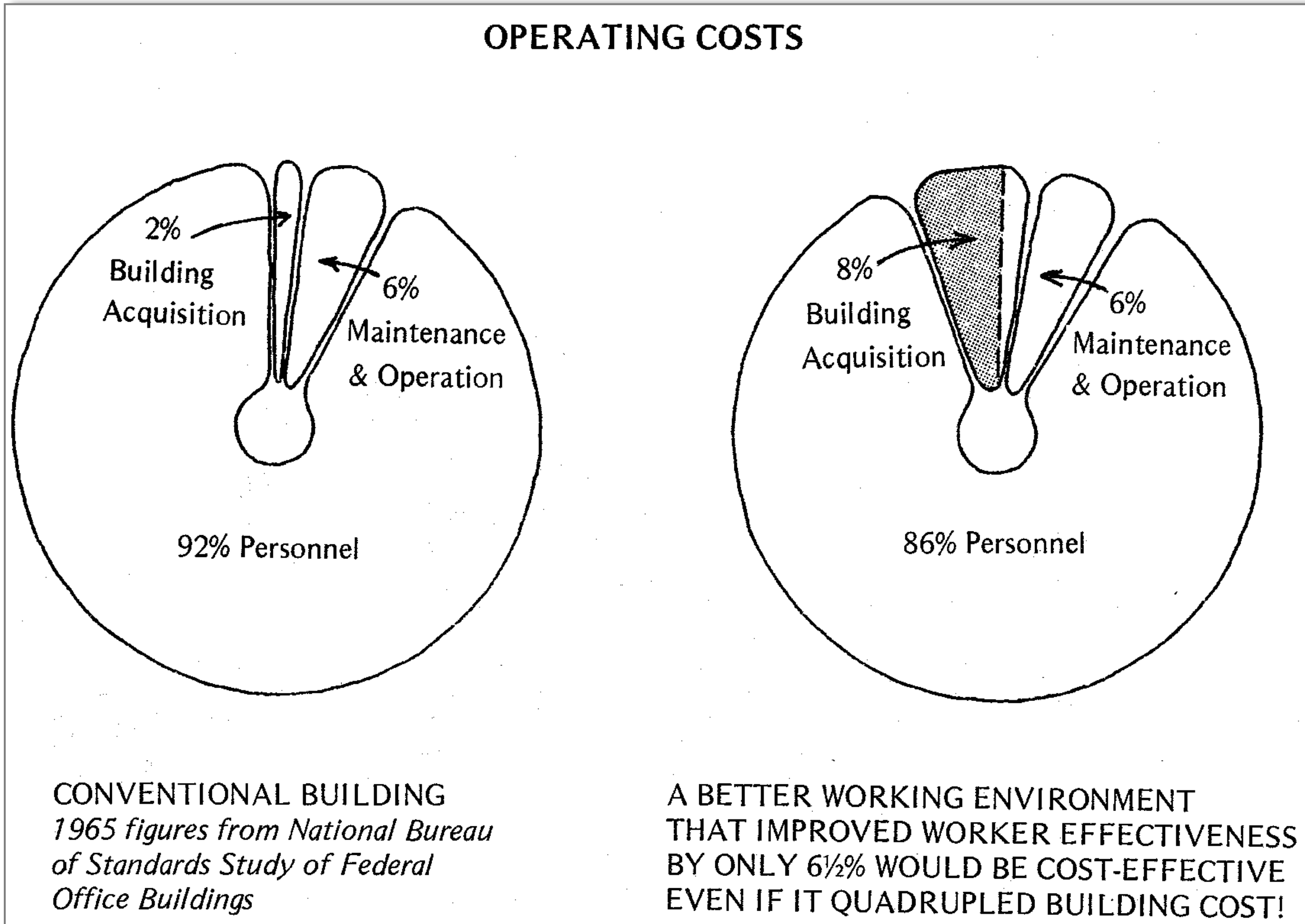
Elevated temperatures and poor air quality can affect performance of office work by 5% (laboratory) to 10% (field)

Relative significance of wage costs



Source: Wargocki and Seppanen (2006)

With some level of uncertainty it can be assumed that even improvements in productivity of ~1% are cost-effective



Source: Building Value, Energy Design Guidelines for State Buildings Office of the State Architect, California (1976)

Scenario	Annual Benefits and Costs*	Annual Economic Benefits ($ billion)*
1a) increase VRs to 10 L/s per person	avg. 0.7% (0.3%) increase in performance in 7.8 (4.2) million workers	$4.2 ($1.1)
	Average 13.2% (5.3%) decrease in weekly SBS symptoms in 7.8 (4.2) million workers	$0.06 ($0.01)
	4.5 (0.7) million days of short-term absence avoided	*$1.4 ($0.2)*
	Increased energy consumption	-$0.02 (-$0.003)
	Total economic benefit	**$5.6 ($1.3)**
1b) increase VRs to 15 L/s per person	avg. 1.1% (0.6%) increase in performance in 12.4 (16.1) million workers	$10.2 ($6.9)
	Average 18.8% (10.2%) decrease in weekly SBS symptoms in 12.4 (16.1) million workers	$0.11 ($0.06)
	10 (6.7) million days of short-term absence avoided	*$3.2 ($2.1)*
	Increased energy consumption	-$0.04 (-$0.02)
	Total economic benefit	**$13.5 ($9.0)**
2) add economizers when absent#	avg. 0.47% (1.0%) increase in performance for 20.7 million workers	$7.2 ($15.6)
	Average 26% (38%) decrease in weekly SBS symptoms in 20.7 million workers	$0.29 ($0.33)
	15.2 (21.2) million days of short-term absence avoided	*$4.7 ($6.6)*
	Energy savings	$0.12 ($0.17)
	Annualized economizer installation cost	-$0.22 (-$0.22)
	Total economic benefit	**$12.1 ($22.5)**
3) eliminate winter indoor T > 23 °C	avg. 0.23% increase in winter performance in 40.4 million workers	$2.3
	prevent 7.7 million weekly SBS symptoms in winter	*$1.1*
	reduce winter thermal comfort dissatisfaction by 12% in 40.4 million workers	----
	Total economic benefit	**$3.4**
4) reduce dampness and mold 30%	*1.5 million days of absence avoided*	*$0.5*
	Total economic benefit	**$0.5**

Total: ~$20 billion per year

Source: Fisk et al. (2011; 2012)

Estimated benefits of improving IAQ in U.S. buildings

- Total benefits - $62.7 billion/year
  - Productivity gains = $54.7 billion
  - Health-related savings = $8 billion: acute respiratory diseases = $1.2 billion; building-related illness (e.g. humidifier fever) = 0.8$ billion; IAQ illnesses including SBS = $6 billion)
- Total costs - $87.9 billion (initial) (in 40% of US buildings regarded unhealthy) + 4.8 billion/year (maintenance)

⇩

Pay-back time = 1.4 years

Source: Dorgan et al. (1998)

Estimated health costs in U.S.

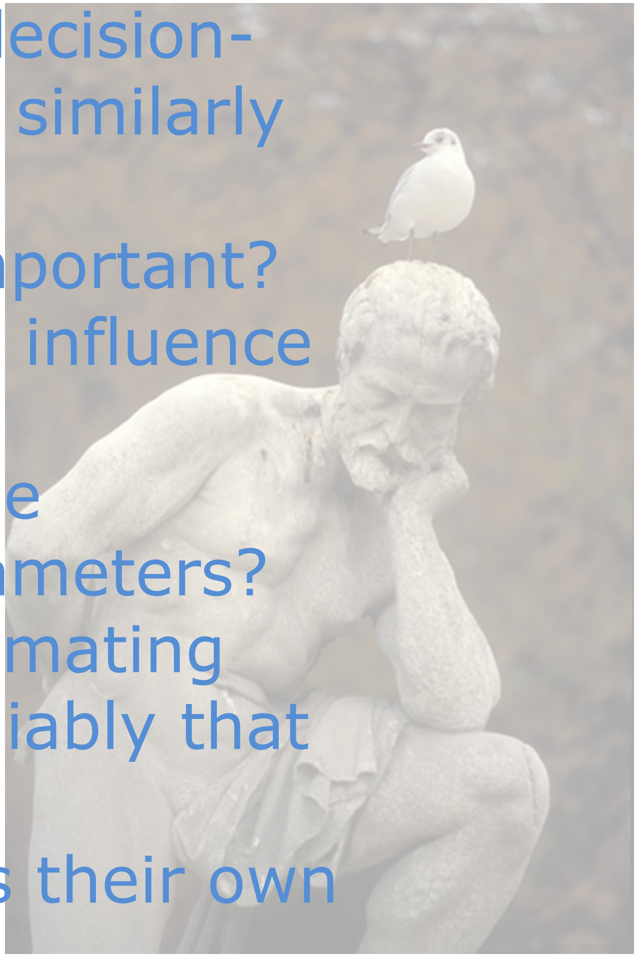
- Net savings (due to 35% decrease in short-term sick leave) following increase of ventilation from 12 to 24 L/s per person are estimated to be

⇩

$400/year/employee
$ 22.8 billion/year nationally

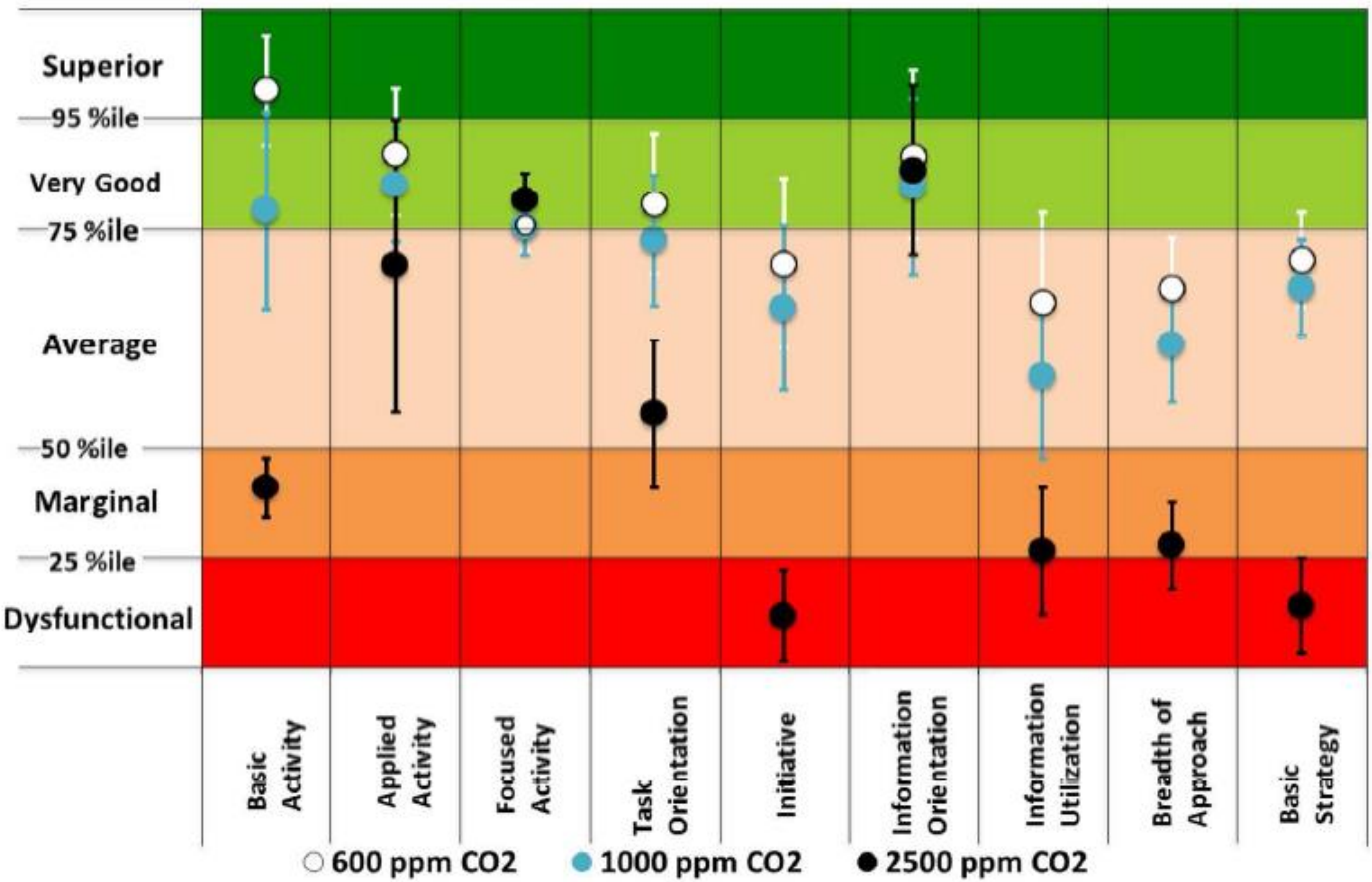
Source: Milton et al. (2000)

What else do we need to know?



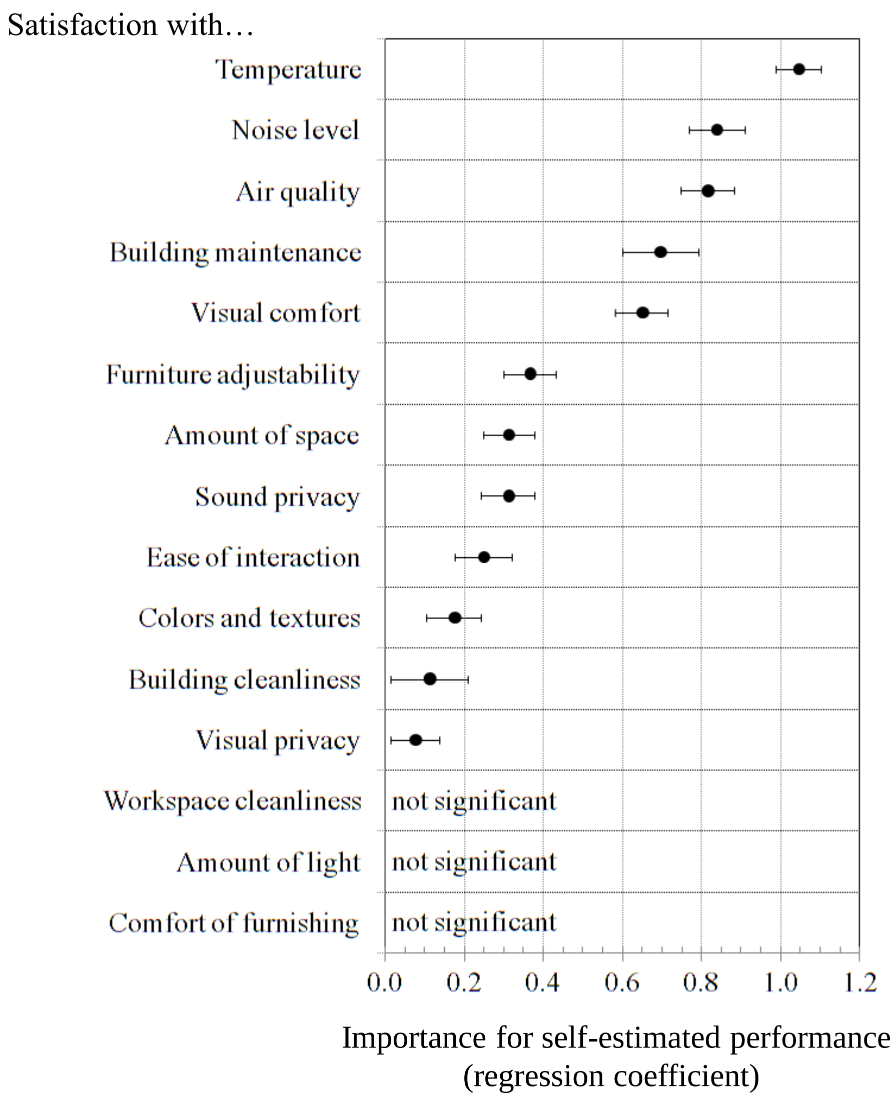
- Is high-level work involving decision-making and creative thinking similarly affected?
- Which conditions are most important?
- How energy saving measures influence performance?
- What is combined effect of the individual indoor climate parameters?
- Can we establish method estimating the effects on productivity reliably that can be widely used?
- Can occupants reliably assess their own productivity?

Effects on decision-making performance (Is CO_2 a pollutant?)



Source: Satish et al. (2012)

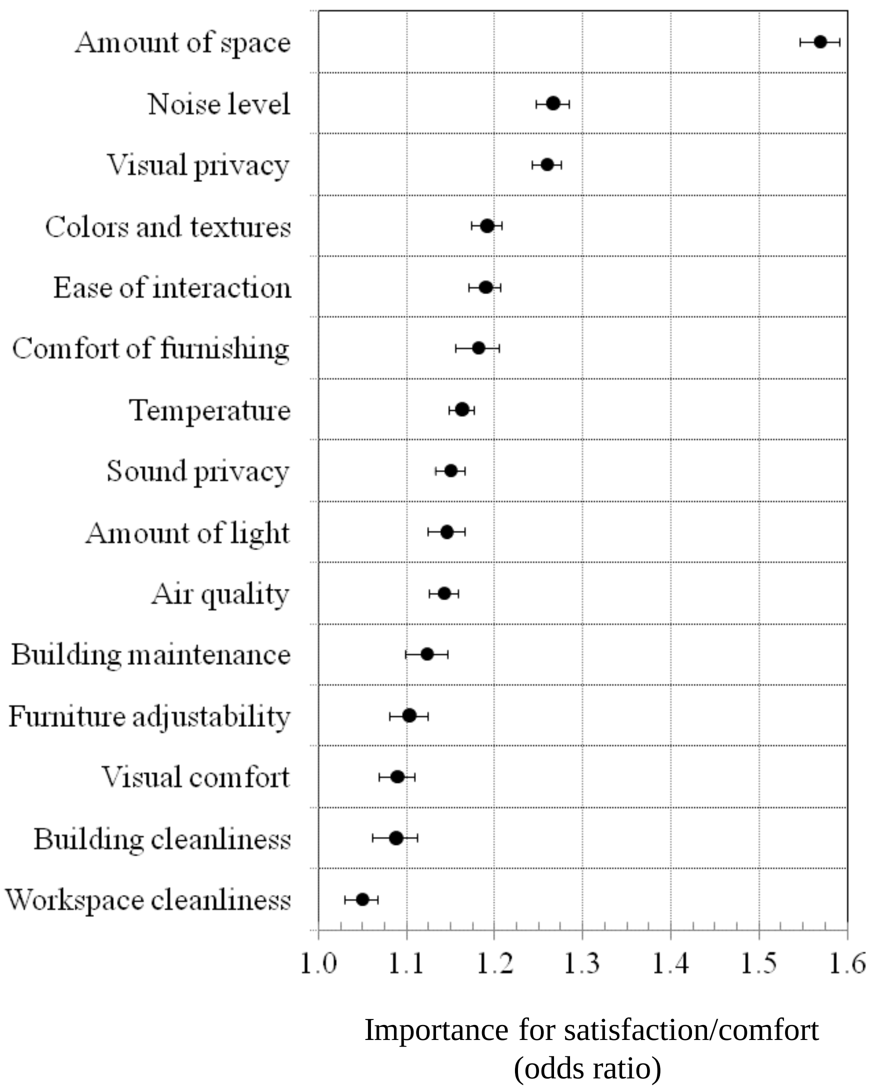
Parameters important for (self-estimated) performance



- **Satisfaction with temperature, noise level and air quality = satisfaction with IEQ**
- **For example, ~15% increase in satisfaction with temperature would increase self-estimated job performance by ~1%**

Source: Wargocki et al. (2012)

IEQ and building features important for satisfaction/comfort



- **All important ($p<0.05$)**
- **The most important is satisfaction with amount of space the most important regardless occupants' gender and age, type of office (single office, shared office, cubicles) and distance from a window**
- **Other important parameters include satisfaction with, noise level, visual privacy, colors and textures, etc.**
- **IEQ is not the most important**

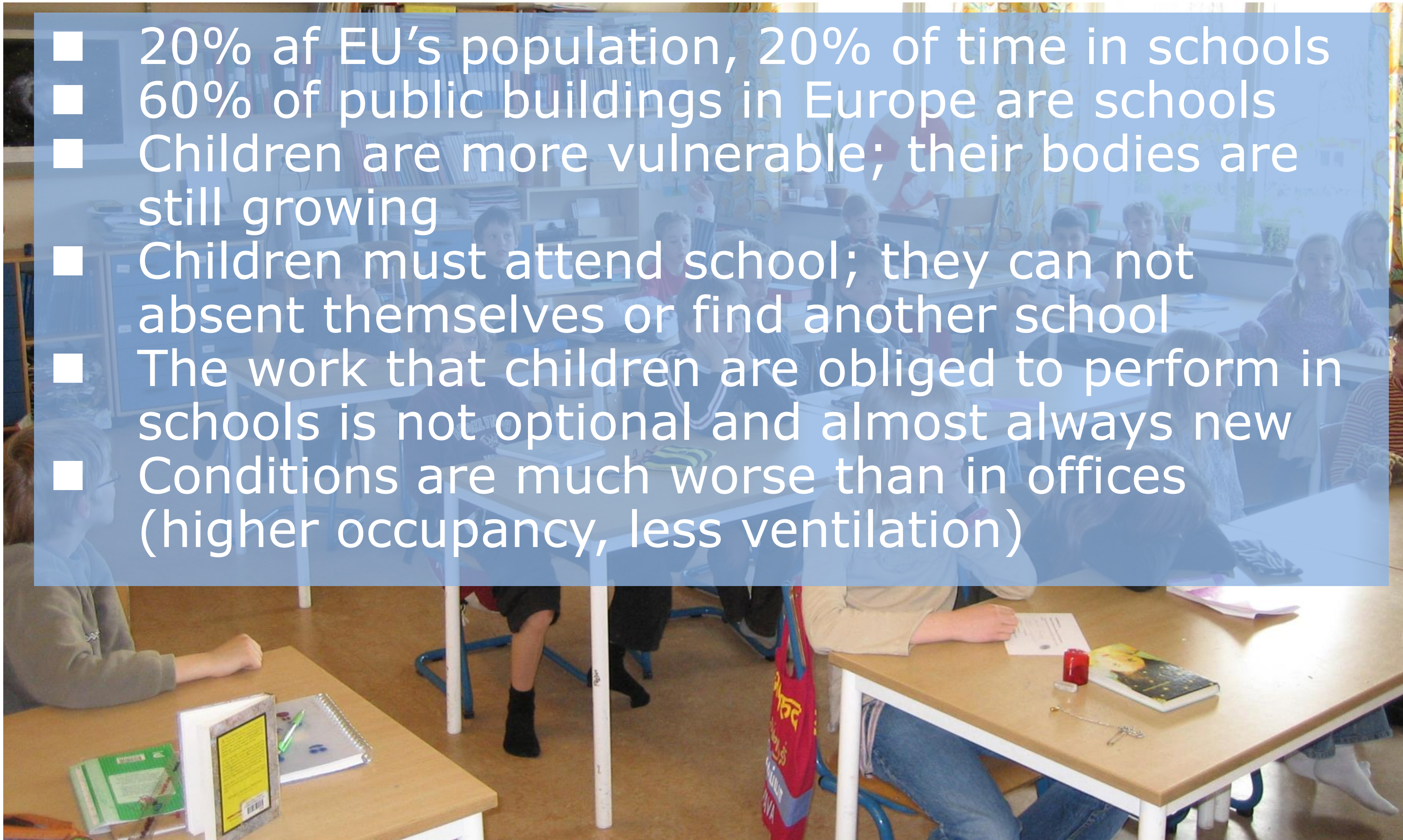
Source: Frontczak et al. (2011)

Energy saving measures and performance (can we use adaptive thermal comfort approach with no negative effects?)

- Elevated indoor temperatures should not be adopted to conserve energy in buildings because negative effects on performance will increase progressively even if some subjective habituation takes place and because people can often avoid discomfort by working less
- Acceptance (psychological) of undesirably warm thermal conditions should not be equated with achieving thermal comfort => physiological and mental changes occur in response to warmth: headache, fatigue, difficulty in thinking clearly, dry eyes, reduced oxygen saturation and increased CO_2 levels in blood, and decreased tear film quality all affecting performance
- Objective adaptation due to behavioral changes may not always occur: inconveniently high velocities, dress code, etc..
- One of the most reported behavioral adjustments is to ’take a break’ or to slow down work speed that definitely leads to decreased performance at high temperatures.

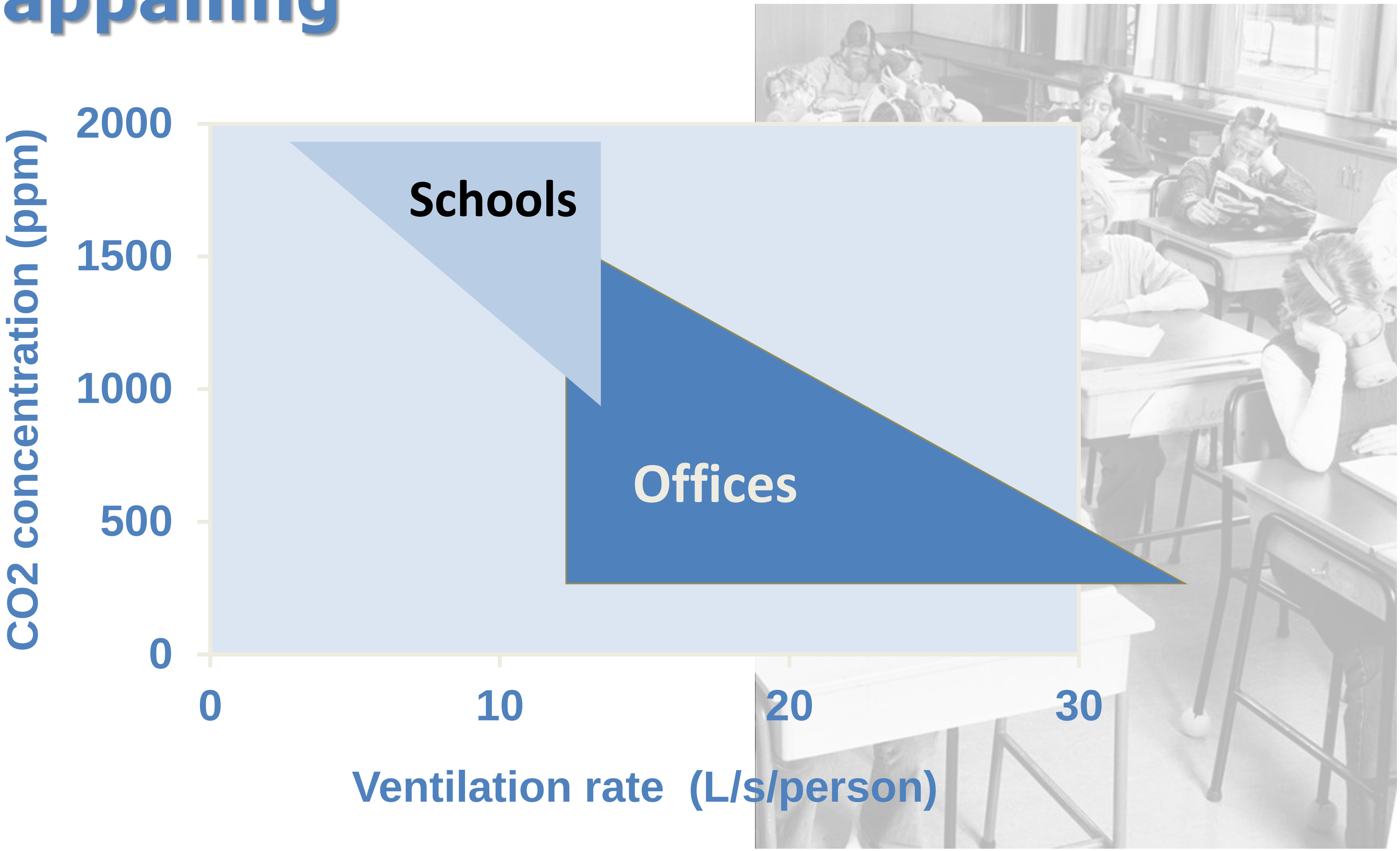
Source: Lan et al. (2013)

Schools

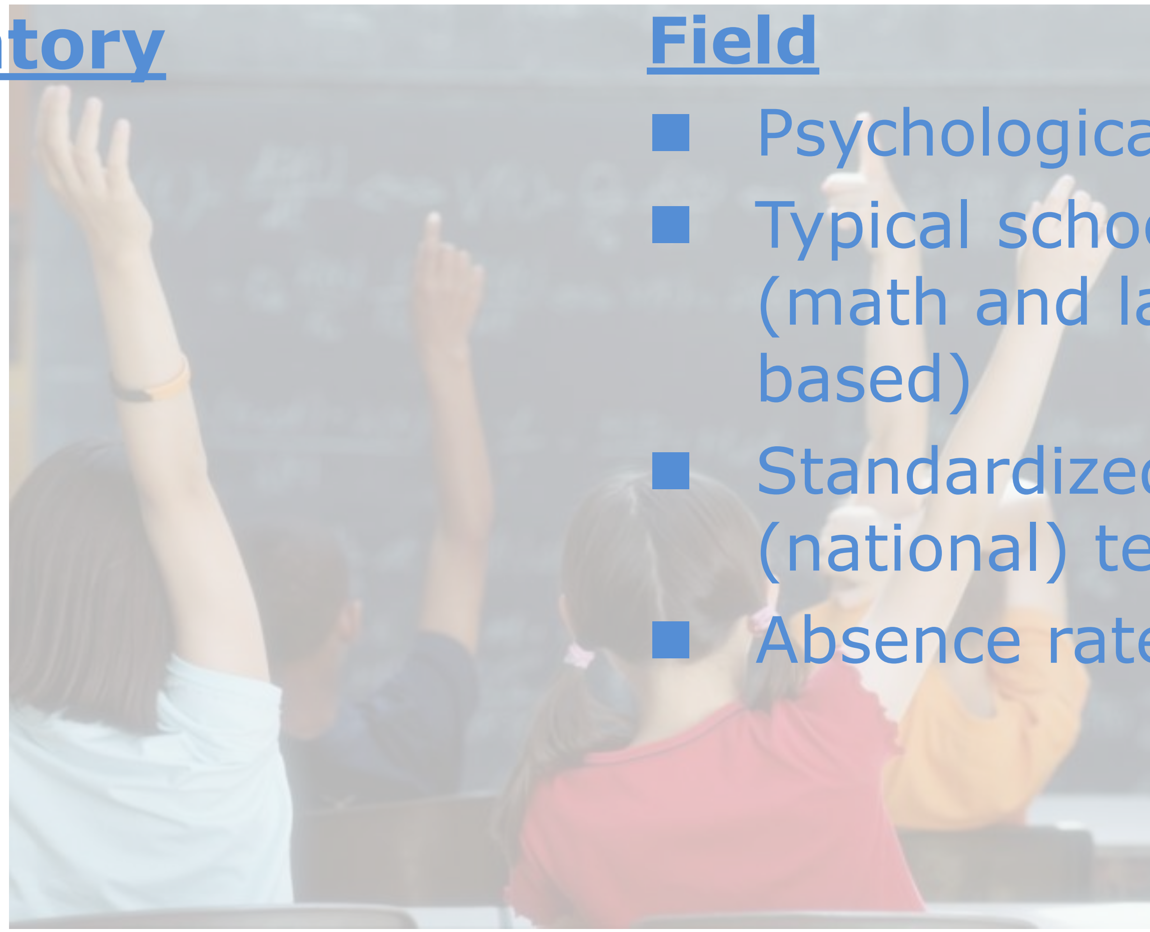


- 20% af EU's population, 20% of time in schools
- 60% of public buildings in Europe are schools
- Children are more vulnerable; their bodies are still growing
- Children must attend school; they can not absent themselves or find another school
- The work that children are obliged to perform in schools is not optional and almost always new
- Conditions are much worse than in offices (higher occupancy, less ventilation)

IEQ conditions in schools are appalling



Measurements of performance of schoolwork



Laboratory

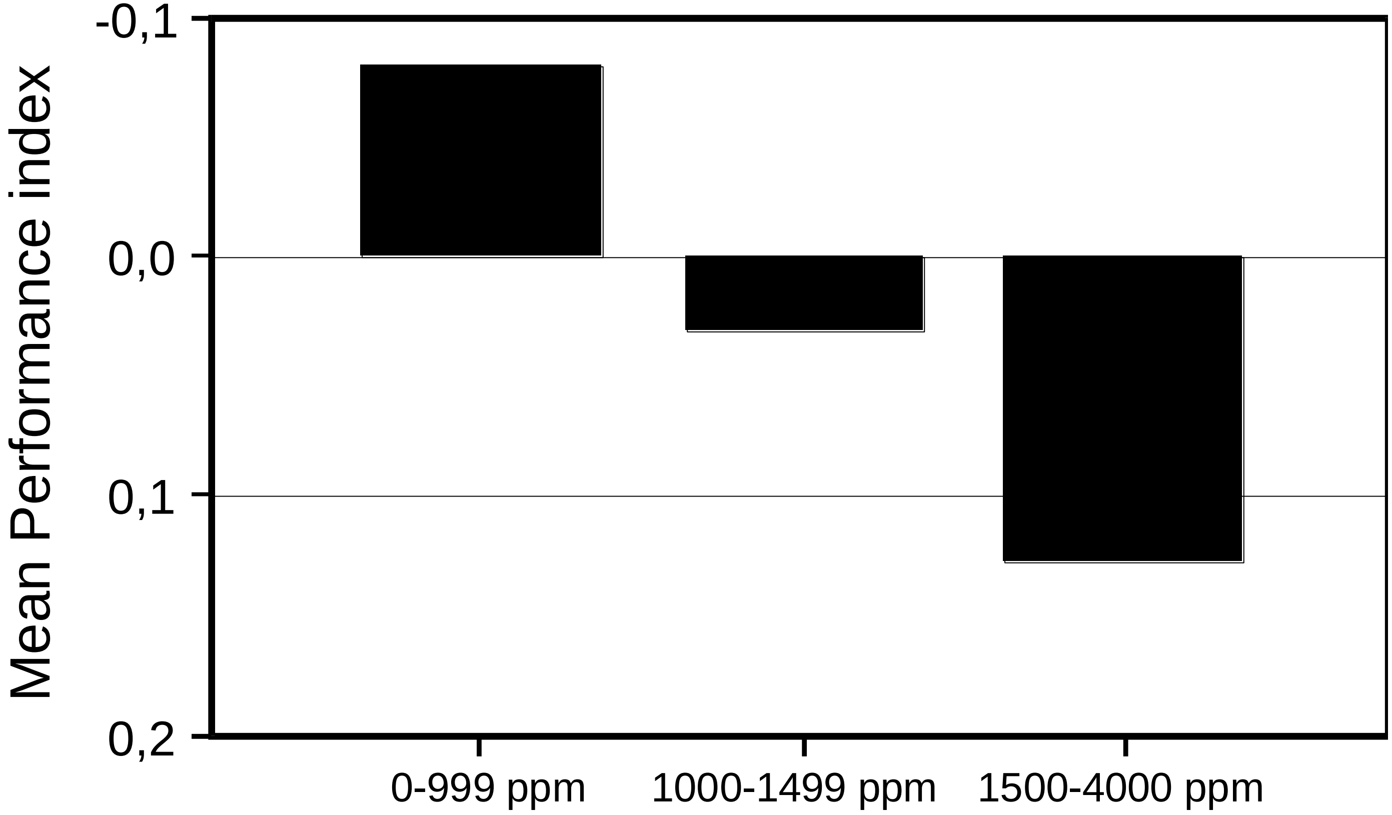
- N/A

Field

- Psychological tests
- Typical school tasks (math and language based)
- Standardized (national) tests
- Absence rates

Classroom ventilation and psychological tests

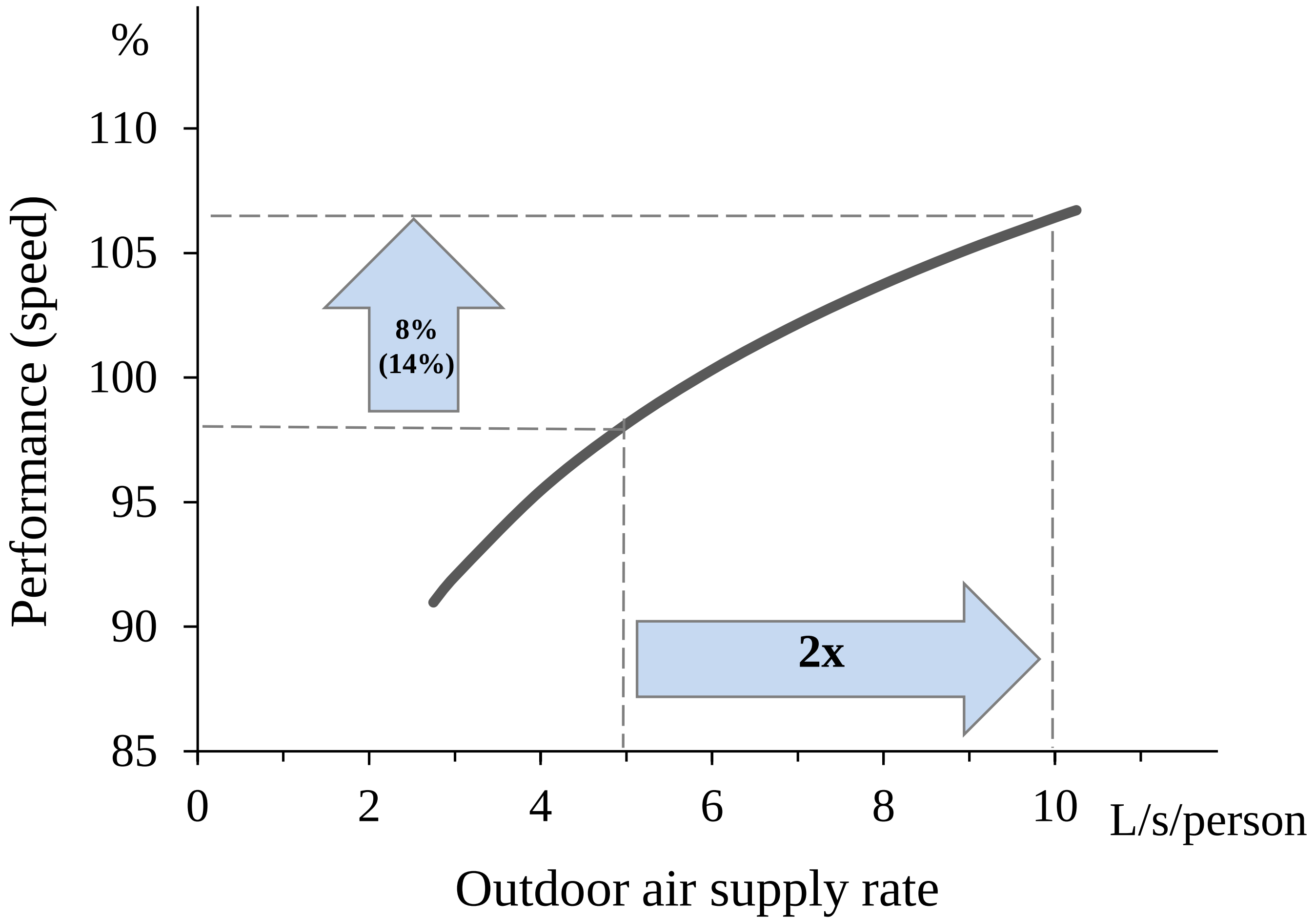
(simple/choice reaction time, colour-word vigilance)



Myhrvold et al., 1997

Classroom ventilation and typical school tasks

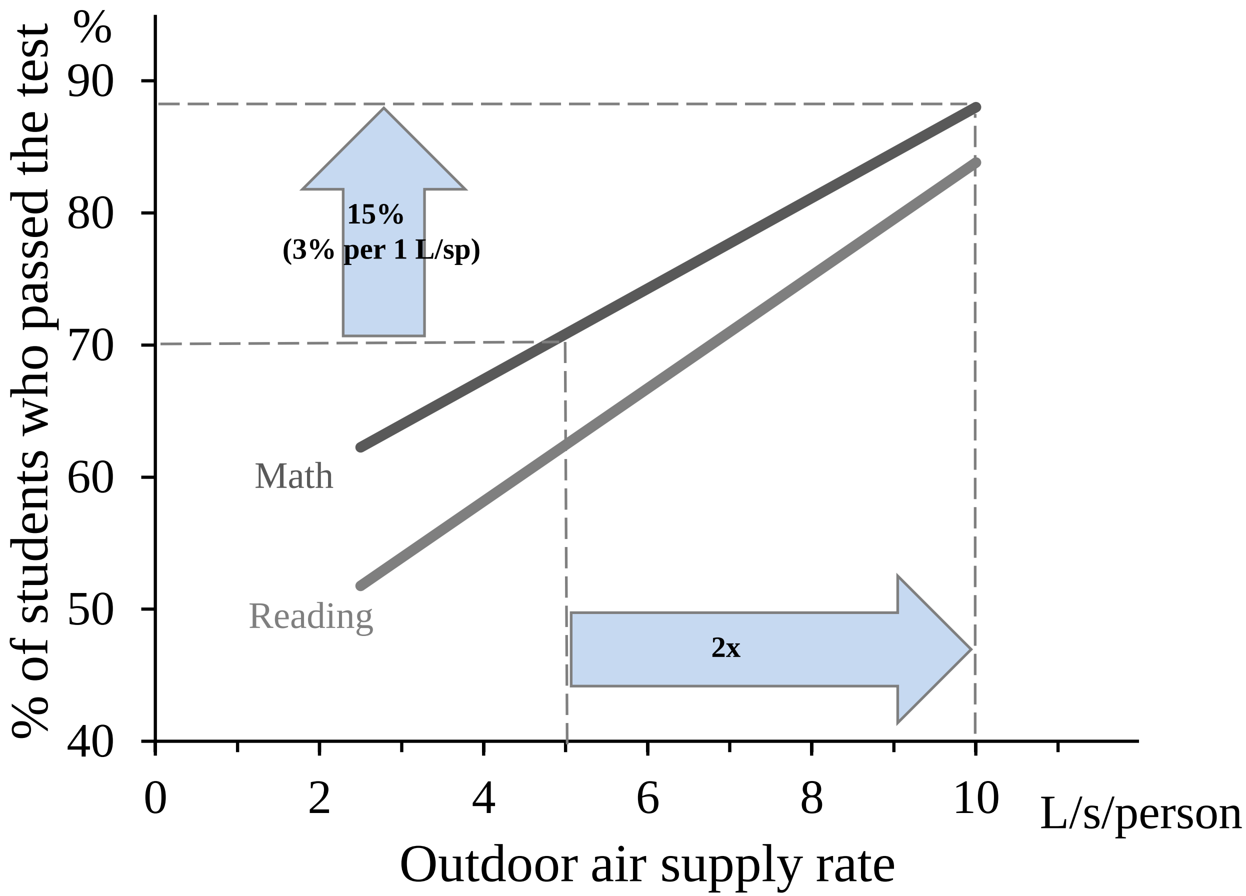
(math & language based)



Wargocki et al., 2012

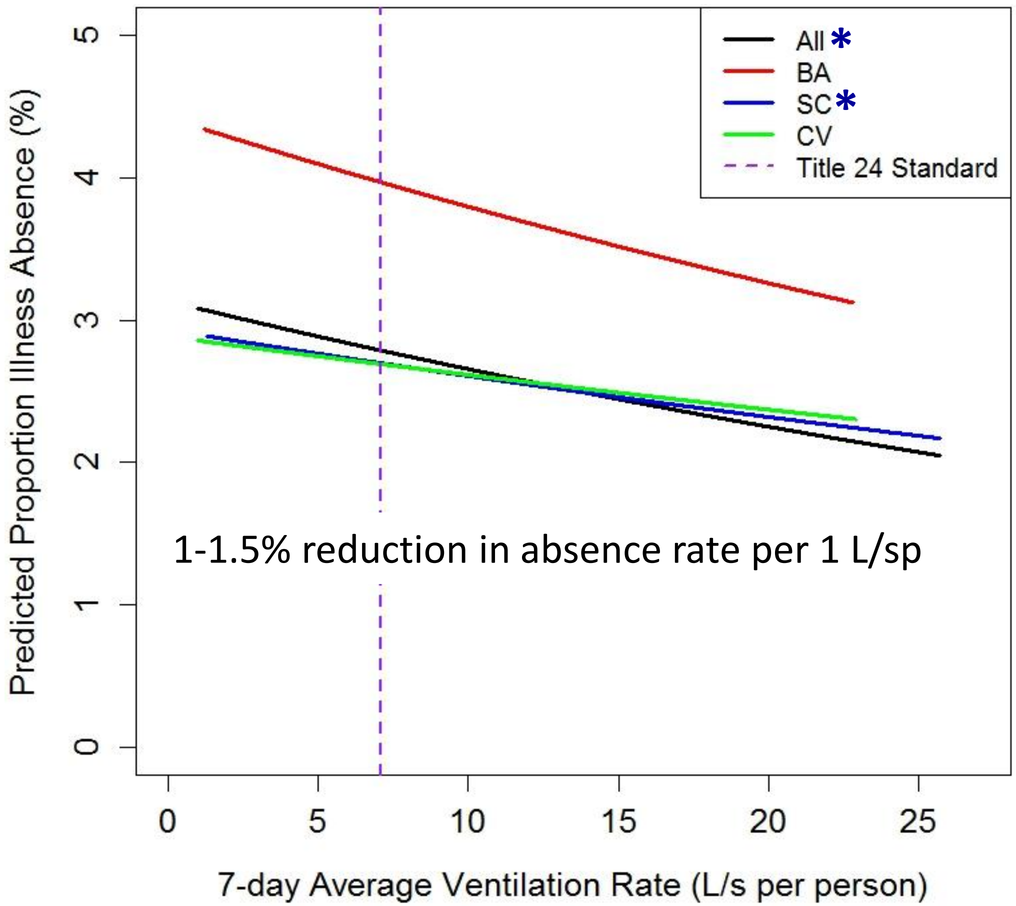
Classroom ventilation and standardized tests

(number of pupils who passed the test)



Haverinen-Shaughnessy et al., 2013

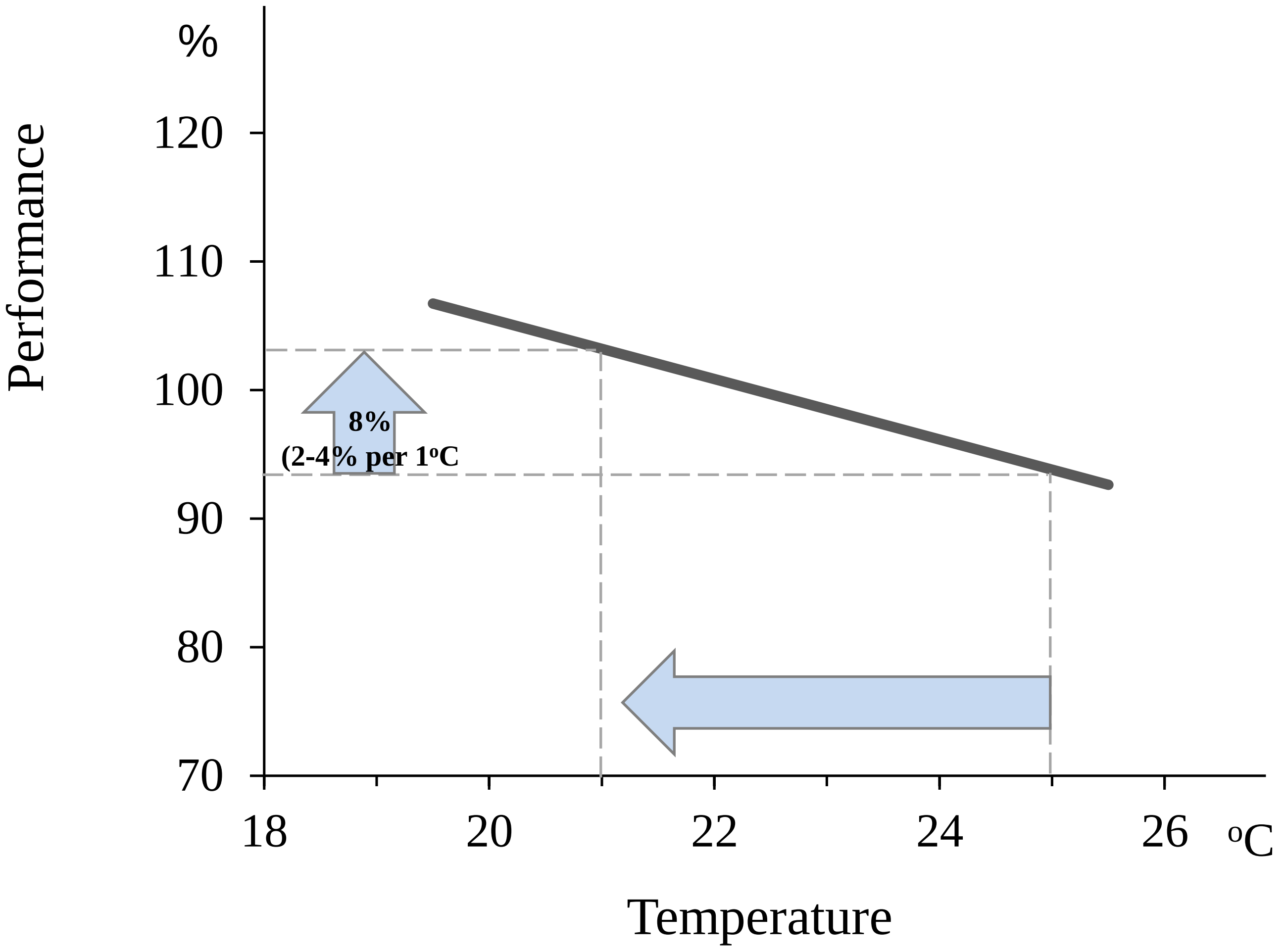
Classroom ventilation and absence rates



Mendell et al., 2013

Classroom temperature and typical school tasks

(math & language based)



Wargocki et al., 2012

Noise and daylight and the performance of schoolwork

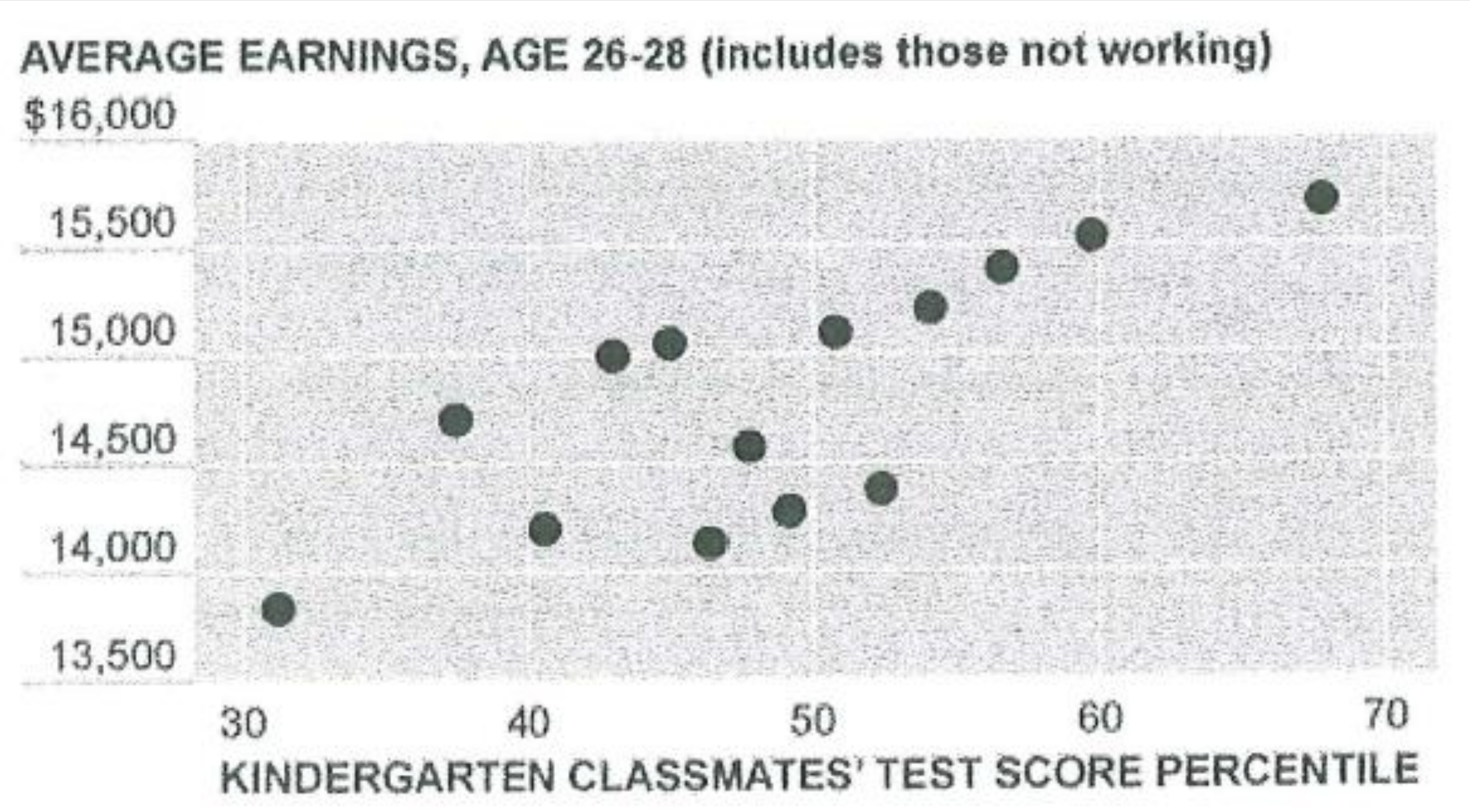
- Text comprehension and memory were negatively affected by increased <u>noise from airplanes</u>; the effect was linear
- There were no strong effects of <u>traffic noise (cars)</u> on the performance of schoolwork – cognitive tasks, only episodic memory was slightly affected
- School grades in elementary schools were improved by 21% for pupils in classes with much <u>daylight</u> compared with classes with least daylight

Elevated temperatures and poor air quality can affect performance of schoolwork by children by over 15-20% (field)

Consequences

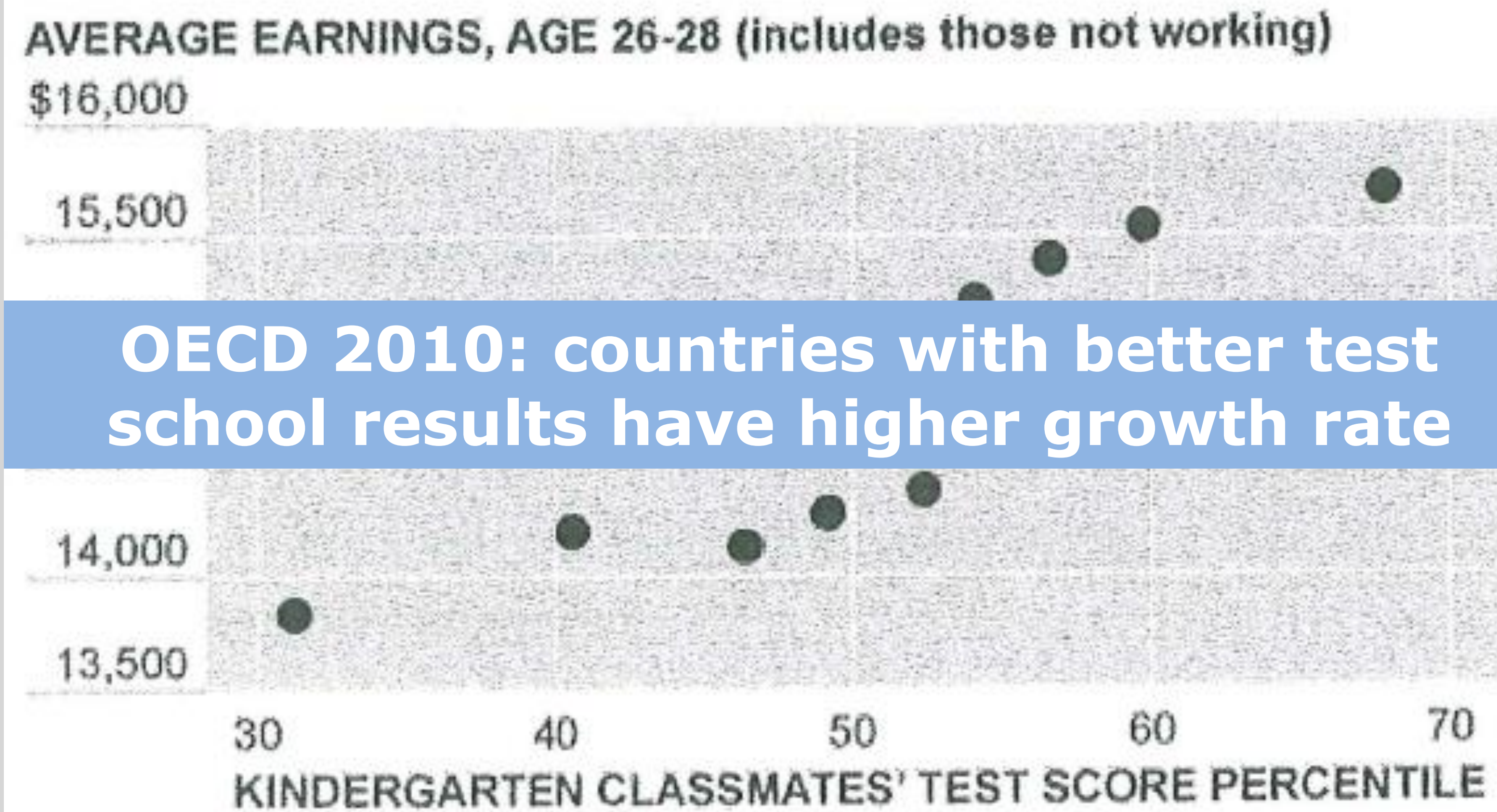
- 15% reduced performance (1/8) => 1 school year
- More time for teaching to reach the same educational targets
- Reduced teacher costs
- Absence rates of pupils (& care takers) and teachers => cost of absenteeism
- Loss of opportunity (salary) as regards future work => socio-economic impact
- Consequences for national economy => GDP and public expenses/incomes

Socio-economic consequences



Chetty et al., 2010

Socio-economic consequences



OECD 2010: countries with better test school results have higher growth rate

Chetty et al., 2010

Estimated socio-economic effects by adopting Swedish ventilation requirements in Danish schools*

	Average annual effect	Trend of effect
Public budget: TOTAL	**€37 million**	**Rising**
• increased productivity (higher education level)	€16 million	Rising
• fewer pupils in Tenth Class	€15 million	Rising
• lower teacher sick leave	€6 million	Constant
GDP total	**€170 million**	**Rising**
• increased productivity (higher education level)	€104million.	Rising
• fewer pupils in Tenth Class	€67 million	Rising
• lower teacher sick leave	N/A	N/A

*** 6 to 8.4 L/s; DANISH GDP (2011): €240,000 million**

SLOTSHOLM A/S, Wargocki et al., 2014

What else do we need to know?

- Technologies that need to be installed in classrooms to promote learning, and to reduce negative effects of IEQ parameters on health/behaviour
- Implementation of these technologies (renovations)

"It is certain that the additional expenses per pupil of the best ventilation needed not exceed the price of one or two cheap lunches."

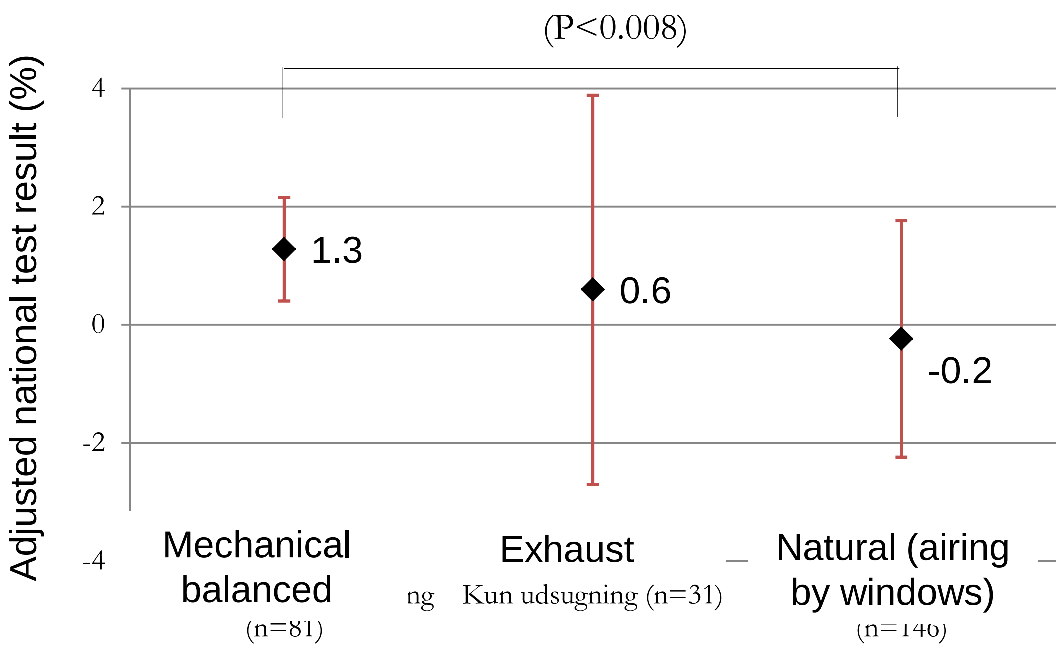
New Hampshire School District

Ventilation Code, 1893

Marxen et al. 2011

Classroom ventilation type and the national educational tests

(math, language-based, science (chemistry/physics, geography, biology), foreign language)



Uldahl Kjeldsen et al., 2013

OCCUPANTS or PARTICIPANTS

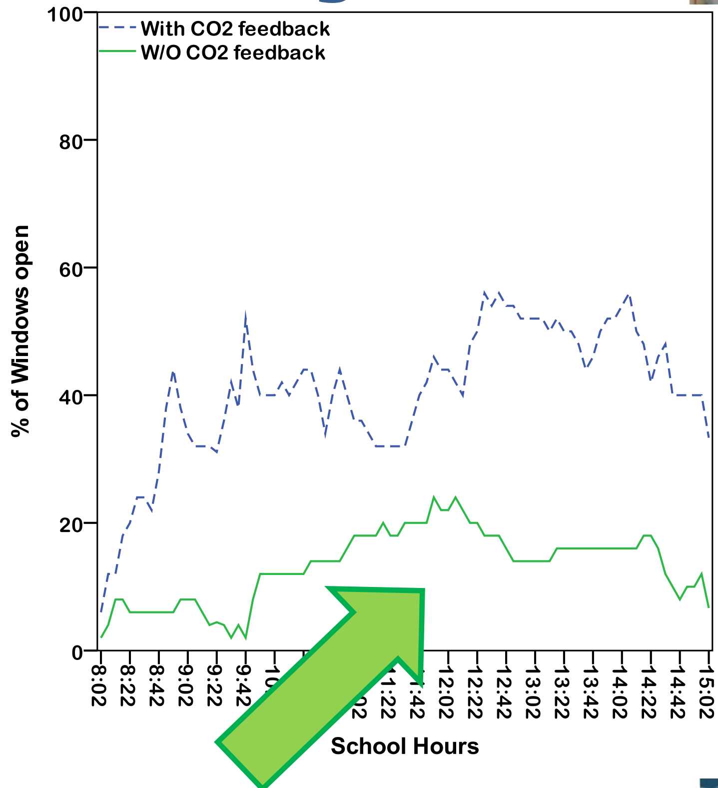
- "Passive recipients" (occupants) of pre-determined comfort conditions
  - outcomes predetermined by the building design parameters or performance metrics)

- "Inhabitants" (real users) playing an active role in the maintenance and performance of a building
  - an evolving practice considering dynamic (accept greater seasonal variety, new clothing, institutional flexibility – variable working hours, no dress code) and participatory (social and behavioral) aspects
  - Use of modern technologies

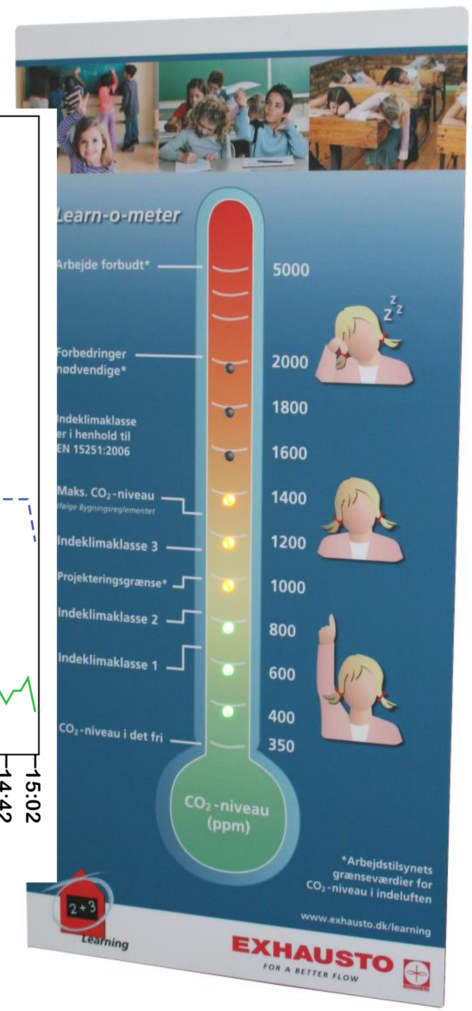
Cole et al. (2008); Brown et al. (2009)

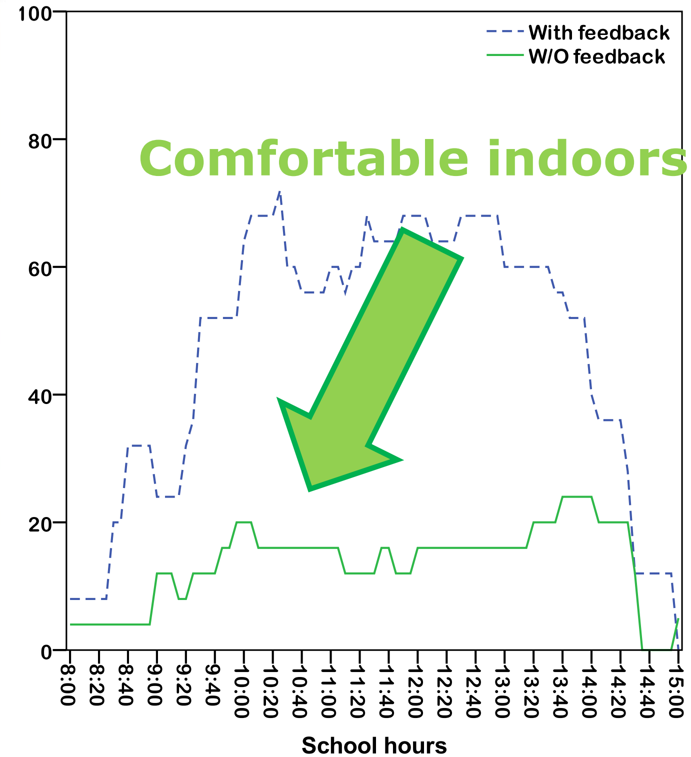
ALERT BUT NOT RESTRAIN

Heating season



Cold outdoors





Comfortable indoors

With cooling

Wargocki & da Silva (2012)

Dwellings

- No data
- Home offices
- Sleep quality

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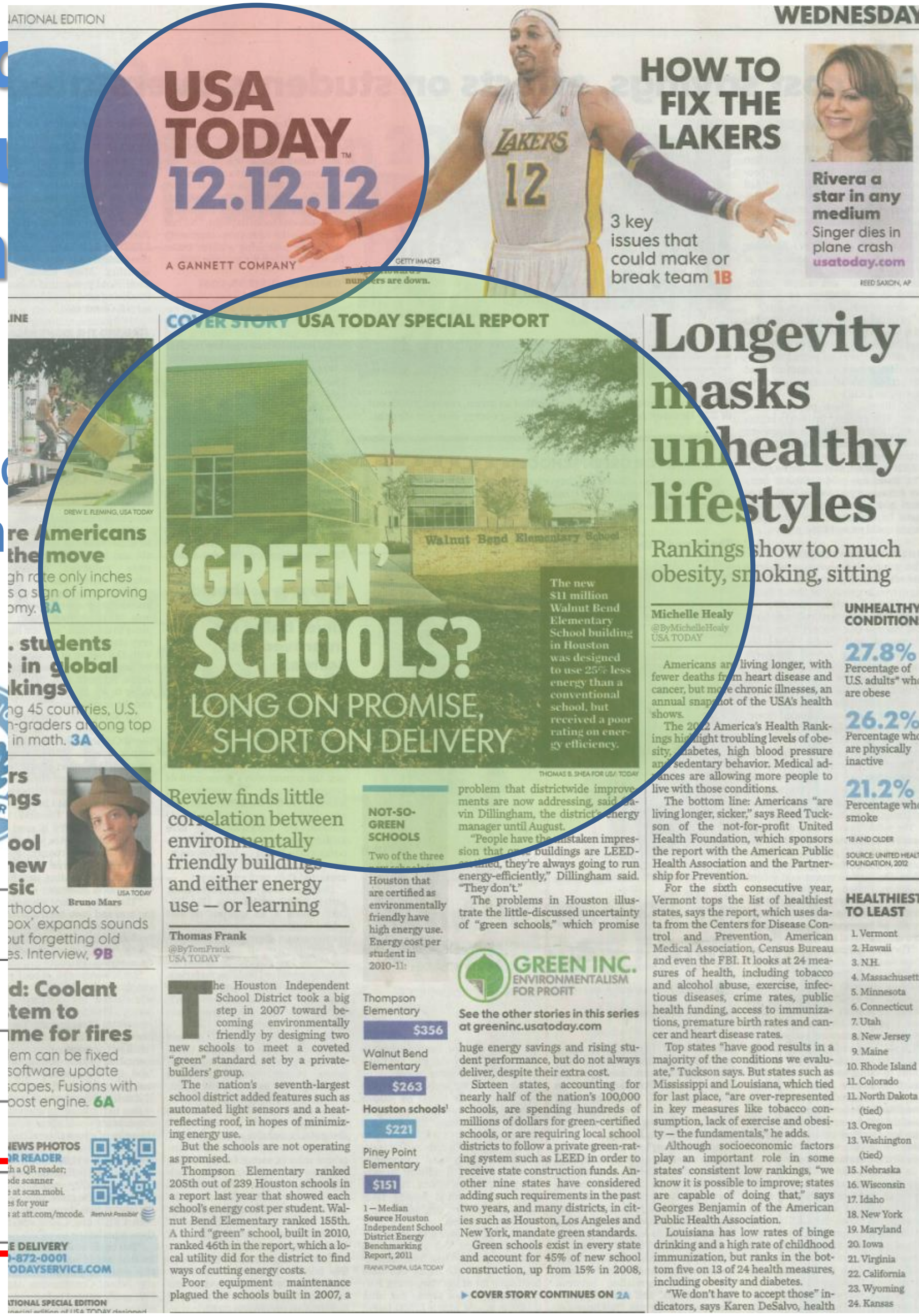
- Voluntary … …ign and build green buil… …able building performan…



NATIONAL EDITION WEDNESDAY

USA TODAY 12.12.12

A GANNETT COMPANY

HOW TO FIX THE LAKERS

3 key issues that could make or break team 1B

Rivera a star in any medium

Singer dies in plane crash usatoday.com

…re Americans …the move

…gh rate only inches …s a sign of improving …omy. 3A

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…ng 45 countries, U.S. …-graders among top …in math. 3A

Bruno Mars

…thodox …box' expands sounds …ut forgetting old …es. Interview, 9B

…d: Coolant …tem to …me for fires

…em can be fixed …software update …scapes, Fusions with …oost engine. 6A

COVER STORY USA TODAY SPECIAL REPORT

Walnut Bend Elementary School

'GREEN' SCHOOLS?

LONG ON PROMISE, SHORT ON DELIVERY

The new $11 million Walnut Bend Elementary School building in Houston was designed to use 25% less energy than a conventional school, but received a poor rating on energy efficiency.

Review finds little correlation between environmentally friendly buildings and either energy use — or learning

Thomas Frank @ByTomFrank USA TODAY

The Houston Independent School District took a big step in 2007 toward becoming environmentally friendly by designing two new schools to meet a coveted "green" standard set by a private-builders' group.

The nation's seventh-largest school district added features such as automated light sensors and a heat-reflecting roof, in hopes of minimizing energy use.

But the schools are not operating as promised.

Thompson Elementary ranked 205th out of 239 Houston schools in a report last year that showed each school's energy cost per student. Walnut Bend Elementary ranked 155th. A third "green" school, built in 2010, ranked 46th in the report, which a local utility did for the district to find ways of cutting energy costs.

Poor equipment maintenance plagued the schools built in 2007, a…

NOT-SO-GREEN SCHOOLS

Two of the three Houston that are certified as environmentally friendly have high energy use. Energy cost per student in 2010-11:

Thompson Elementary $356

Walnut Bend Elementary $263

Houston schools' $221

Piney Point Elementary $151

1 — Median

Source Houston Independent School District Energy Benchmarking Report, 2011

GREEN INC. ENVIRONMENTALISM FOR PROFIT

See the other stories in this series at greeninc.usatoday.com

COVER STORY CONTINUES ON 2A

Longevity masks unhealthy lifestyles

Rankings show too much obesity, smoking, sitting

Michelle Healy @ByMichelleHealy USA TODAY

UNHEALTHY CONDITIONS

27.8% Percentage of U.S. adults* who are obese

26.2% Percentage who are physically inactive

21.2% Percentage who smoke

*18 AND OLDER

SOURCE: UNITED HEALTH FOUNDATION, 2012

HEALTHIEST TO LEAST

1. Vermont
2. Hawaii
3. N.H.
4. Massachusetts
5. Minnesota
6. Connecticut
7. Utah
8. New Jersey
9. Maine
10. Rhode Island
11. Colorado
11. North Dakota (tied)
13. Oregon
13. Washington (tied)
15. Nebraska
16. Wisconsin
17. Idaho
18. New York
19. Maryland
20. Iowa
21. Virginia
22. California
23. Wyoming
24. Kansas

LEED rating
Certified
Silver
Gold
Platinum

	Possible Points
	26 Points
	10 Points
	35 Points
	14 Points
	15 Points
	100 Points
	6 Points
	4 Points

The primary purpose of a building should be ….

…..to provide **optimal conditions for work/learning** and not to **conserve energy**

Summary

IAQ/temp/noise /light

5-10%

Significant economical loss
Health costs
Short return on investment < 2 y

IAQ/temp/noise /light

>15%

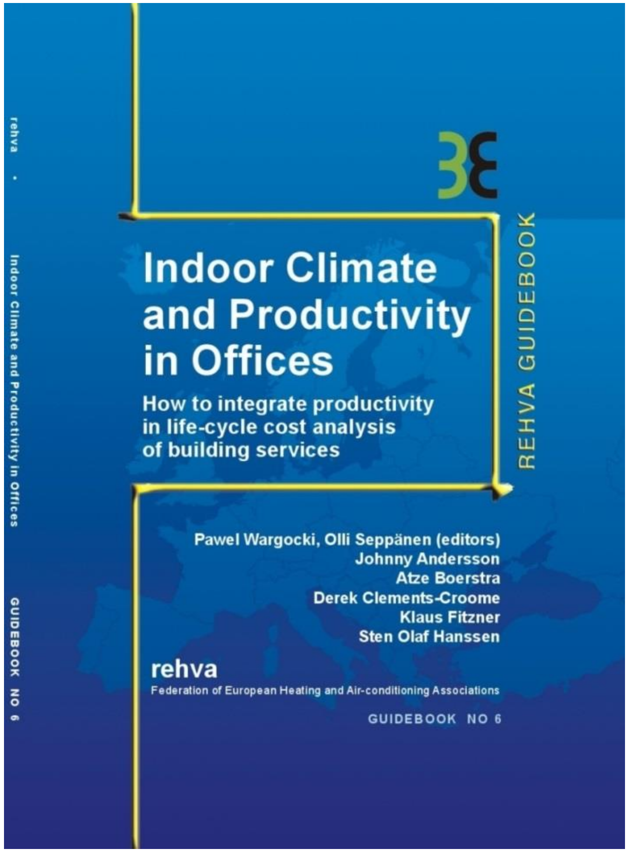
Future socio-economic benefits
Teacher costs

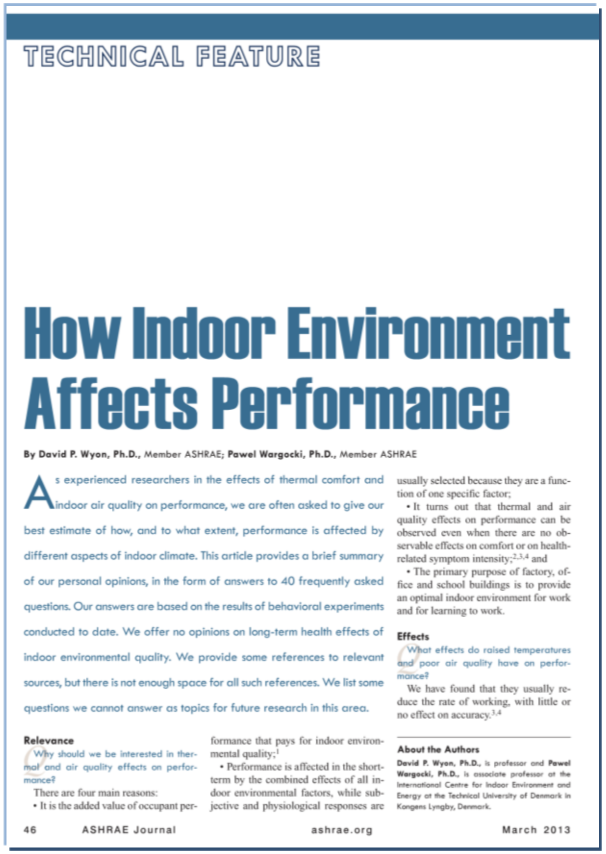
?

?

Potentially very high

Selected reading





TECHNICAL FEATURE

How Indoor Environment Affects Performance

By David P. Wyon, Ph.D., Member ASHRAE; Pawel Wargocki, Ph.D., Member ASHRAE

As experienced researchers in the effects of thermal comfort and indoor air quality on performance, we are often asked to give our best estimate of how, and to what extent, performance is affected by different aspects of indoor climate. This article provides a brief summary of our personal opinions, in the form of answers to 40 frequently asked questions. Our answers are based on the results of behavioral experiments conducted to date. We offer no opinions on long-term health effects of indoor environmental quality. We provide some references to relevant sources, but there is not enough space for all such references. We list some questions we cannot answer as topics for future research in this area.

Relevance

Q Why should we be interested in thermal and air quality effects on performance?

There are four main reasons:

• It is the added value of occupant performance that pays for indoor environmental quality;[1]

• Performance is affected in the short-term by the combined effects of all indoor environmental factors, while subjective and physiological responses are usually selected because they are a function of one specific factor;

• It turns out that thermal and air quality effects on performance can be observed even when there are no observable effects on comfort or on health-related symptom intensity;[2,3,4] and

• The primary purpose of factory, office and school buildings is to provide an optimal indoor environment for work and for learning to work.

Effects

Q What effects do raised temperatures and poor air quality have on performance?

We have found that they usually reduce the rate of working, with little or no effect on accuracy.[3,4]

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Articles

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Effects of indoor environment on performance

Thermal and air quality control account for a large proportion of any commercial building's first cost and subsequent operating costs, so HVAC engineers have learnt to argue that they are outweighed 100:1 by the economic value of their positive effects on occupant performance, any positive effects on health and comfort being cited as additional benefits.

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Engineers are used to having to act on incomplete evidence, but if they are wise they like to have this evidence reviewed for them by specialists in any field that is outside their own experience and training. As experienced researchers in this particular field, we are often asked to give our best estimate of how and to what extent performance is affected by different aspects of indoor climate, so we now offer this very brief summary of our personal opinions, in the form of answers to 40 frequently asked questions (FAQs). Our answers are based on the results of the behavioral experiments that have been conducted to date. We offer no opinions on the long-term health effects of indoor environmental quality. We provide some references to where the relevant findings and a discussion of them may be found, but there is not enough space for all such references. We also list some questions we cannot answer as topics for future research in this area.

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Questions?

Thank you

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