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

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

paw@byg.dtu.dk
www.ie.dtu.dk
www.dtu.dk
Indoor climate parameters (IEQ)

Indoor environment

Building
- Space
- Interior design
- Workstation design

Indoor air quality and climate
- Indoor air
- Thermal environment
- Cleanliness
  - Air temperature
  - Air movement
  - Surface temperature
  - Distribution
  - Ventilation
  - Air handling equipment
  - Space cleaning
  - Frequency distribution

Acoustics
- Sound level
- Speech intelligibility
  - STI-index
  - Sound insulation
  - Reverberation time

Lighting
- Quality
- Quantity
  - Luminance
  - Glare
  - Daylight
  - Reflections
  - Spectrum

* STI= speech transmission index
IEQ and human performance

Building design and operation

Indoor Climate (IEQ) → Human responses → Benefits → Value of the benefit

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)
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

Owner-occupied building

Investment

Better IEQ

Better productivity
  Improved performance
  Less sick leave
  Less complaints

Economic benefits
Driving force for the investment in high IEQ in office buildings

Higher market value of building

Building owner

Investment

Better IEQ

Better productivity
Less sick leave
Less complaints

Benefits to employer

Higher user satisfaction

Higher rent
Indoor air quality and performance of office work

Measurements of performance

**Laboratory**
- Physiological indicators
- Psychological tests
- Component skills (text typing, arithmetical 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

Temperature and performance of office work

Source: Seppanen et al. (2005)
Thermal discomfort and performance of office work

Reduction in performance

Thermal sensation vote

Source: Lan et al. (2011)
Absence rates

Source: Milton et al. (2000)

Ventilation rate (L/s per person)

% sick leave

12

24

35% lower
Short-term sick-leave (due to infections) and ventilation

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

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

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

Source: Fisk et al. (2011; 2012)

Total: ~$20 billion per year
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)
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 CO₂ 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% of 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 cannot 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

![Graph showing CO2 concentration (ppm) vs Ventilation rate (L/s/person) for Schools and Offices]
# Measurements of performance of schoolwork

<table>
<thead>
<tr>
<th>Laboratory</th>
<th>Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>N/A</td>
<td>Psychological tests</td>
</tr>
<tr>
<td></td>
<td>Typical school tasks (math and language based)</td>
</tr>
<tr>
<td></td>
<td>Standardized (national) tests</td>
</tr>
<tr>
<td></td>
<td>Absence rates</td>
</tr>
</tbody>
</table>
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)

Performance (speed)

Outdoor air supply rate

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

1-1.5% reduction in absence rate per 1 L/sp
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 noise from airplanes; the effect was linear.

There were no strong effects of traffic noise (cars) 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 daylight 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

AVERAGE EARNINGS, AGE 26-28 (includes those not working)

KINDERGARTEN CLASSMATES’ TEST SCORE PERCENTILE

Chetty et al., 2010
Socio-economic consequences

OECD 2010: countries with better test school results have higher growth rate
## Estimated socio-economic effects by adopting Swedish ventilation requirements in Danish schools*

<table>
<thead>
<tr>
<th>Public budget: TOTAL</th>
<th>Average annual effect</th>
<th>Trend of effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>• increased productivity (higher education level)</td>
<td>€16 million</td>
<td>Rising</td>
</tr>
<tr>
<td>• fewer pupils in Tenth Class</td>
<td>€15 million</td>
<td>Rising</td>
</tr>
<tr>
<td>• lower teacher sick leave</td>
<td>€6 million</td>
<td>Constant</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>GDP total</th>
<th>Average annual effect</th>
<th>Trend of effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>• increased productivity (higher education level)</td>
<td>€104 million.</td>
<td>Rising</td>
</tr>
<tr>
<td>• fewer pupils in Tenth Class</td>
<td>€67 million</td>
<td>Rising</td>
</tr>
<tr>
<td>• lower teacher sick leave</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

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

SDTSHOLM 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)

Adjusted national test result (%)

- Mechanical balanced (n=81)
- Exhaust (n=31)
- Natural (airing by windows) (n=140)

(P<0.008)

Uldahl Kjeldsen et al., 2013
OCCUPANTS or PARTICIPANTS

- “Passive recipients” (occupants) of predetermined 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
• Voluntary but prestigious framework to design and build green buildings as well as to assess sustainable building performance.
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

IAQ/temp/noise/light

Future socio-economic benefits
Teacher costs

? ?

Potentially very high
Technical Feature

How Indoor Environment Affects Performance

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

A s 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.

References

What would we be interested in thermal comfort and indoor air quality on performance?

There are four main reasons:

• In the added value of occupant performance that pays for indoor environmental quality.

• Performance is affected by thermal comfort and indoor air quality on performance.

• The combined effects of all indoor environmental factors, while subjective and physiological responses are usually selected because they are a function of the specific factors.

• It turns out that thermal and indoor air quality on performance can be observed even when there are no observable effects on comfort or on health-related symptoms.

• The primary purpose of factories, offices, and schools buildings is to provide an optimal indoor environment for work and for learning.

Effects of indoor environment on performance

We have found that people usually reduce the need for working, with both or no effect on accuracy.

About the Authors

David P. Wyon, Ph.D., is professor and founding chair of the International Centre for Indoor Environmental and Energy at the Technical University of Denmark, Kongens Lyngby, Denmark.
Selected references


Questions?
Thank you

paw@byg.dtu.dk