How Indoor Environments Affect Health and Productivity

Presentation At Joint Meeting of the ASHRAE Golden Gate Chapter and Redwood Empire Section

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William J. Fisk
Sr. Scientist, Group Leader
Indoor Environment Group
Lawrence Berkeley National Laboratory

*Underlying analyses and reviews supported by the U.S. EPA Indoor Environments Division and the California Energy Commission
How Better Buildings Can Improve Health and Productivity

- Improve Building and HVAC Design and Operation
- Improved Indoor Environmental Quality (IEQ)
- Improved Comfort, Health & Work Performance, Reduced Absence
- Reduced Health Care Costs, Greater Value from Work
- Many other Influential Factors
OUTDOOR AIR VENTILATION RATES
Increased Ventilation Rates in Offices Reduces Sick Building Syndrome Symptoms

Statistical Analyses of 8 Studies with 43 data Points

Office Work Performance Increases with Ventilation Rate

Regression Analyses 10 studies, 24 points, Seppanen et al. 2006

1% reduction in work performance valued at 1% of employer’s annual cost for salaries and benefits

Graph showing the relationship between relative work performance and ventilation rate (L/s per person), with a code minimum for U.S. offices with default occupant density.
Increased Ventilation (VRs) Rates in Schools Improves Performance of School Work

Experiments in 4 Danish Classrooms*

*accuracy not affected

Two Primary Grade U.K. Classrooms
ventilation rate increased from 0.4 to 14 L/s per student

Sources:
Increased Ventilation (VRs) Rates in Schools Improves Pass Rates in Academic Achievement Tests

54 U.S. 5th Grade Classrooms

Pass Rates in Academic Achievement Tests Increase with Outdoor Air Ventilation Rate

% Increase per L/s per Student

* for < 8.7 L/s per student

Math

Reading

Source:
Haverinen-Shaughnessy et al. *Indoor Air*, 2011. 21(2): 121-131
Effect of VRs on Decision Making

Two Controlled Exposure Studies

- S1: Vary VR per person in low-pollution space
- S2: Vary VR per floor area, with constant high VR per person

Results:
- Lower VR per person, lower VR per floor area independently and statistically-significantly decreased most metrics of decision making performance

Overlaps in error bars reflect variability among subjects, within-person changes are highly significant.
Direct Effects of CO₂ on Decision Making

Controlled Exposure Studies
- Vary CO₂, other factors constant

Higher CO₂, with all other factors constant, was associated with statistically significant degradation in decision making
- Moderate effects at 1000 ppm vs. 600 ppm, Large at 2500 ppm vs. 600 ppm
- So far, only assessed effects with 3.5 h exposure periods
- Needs replication
Ventilation and Short Term Sick Leave in Offices

% Change = \[1 - 0.66^{(\Delta VR/12)}\] \times 100%

Source: 40 building study of Milton et al. (2000) Indoor Air Journal
Increased Ventilation Rate In Two Classroom Studies Reduced Student Absence

406 Classroom in US Northwest*

Study of 160 CA Classrooms for Two School Years

% Decrease in Absence

16
14
12
10
8
6
4
2
0

1000 ppm less CO₂

~10 – 20 more L/s-p

If Average VR in CA is Increased to Current Standard
- $6.2 million annual energy cost increase (rough est.)
- $33 million increased revenue to school districts
- $80 million reduced care giver costs
Cost vs. Benefits of Ventilation: CA K-12 Classrooms (Mendell et al. 2013 Indoor Air)

<table>
<thead>
<tr>
<th>Costs</th>
<th>Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity Costs ($)</td>
<td>Total Increase in Energy Costs ($)</td>
</tr>
<tr>
<td>Gas Costs ($)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>VR Increase</th>
<th>Costs</th>
<th>Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing VR of 4.0 L/s per person</td>
<td>2.8 M</td>
<td>4.8 M</td>
</tr>
<tr>
<td>Increasing VR from 4.0 to 7.1 L/s (15 cfm) per person</td>
<td>2.3 M</td>
<td>3.9 M</td>
</tr>
<tr>
<td>Increasing VR from 7.1 to 9.4 L/s (20 cfm) per person</td>
<td>1.8 M</td>
<td>3.1 M</td>
</tr>
</tbody>
</table>
Estimated Annual Economic Impacts of Increasing Ventilation Rates in U.S. Offices ($ US Billions)

<table>
<thead>
<tr>
<th></th>
<th>Scenario 1 8 to 10 L/s-p</th>
<th>Scenario 2 8 to 15 L/s-p</th>
<th>Scenario 3 Economizers</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Performance</strong></td>
<td>$10.1 B</td>
<td>$28 B</td>
<td>$24.2 B</td>
</tr>
<tr>
<td><strong>SBS</strong></td>
<td>$0.09 B</td>
<td>$0.26 B</td>
<td>$0.2 B</td>
</tr>
<tr>
<td><strong>Absence</strong></td>
<td>$2.9 B</td>
<td>$9.4 B</td>
<td>$8.6 B</td>
</tr>
<tr>
<td><strong>Energy</strong></td>
<td>-$0.04 B</td>
<td>-$0.13 B</td>
<td>$0.22 B</td>
</tr>
<tr>
<td><strong>Equipment</strong></td>
<td>--</td>
<td>--</td>
<td>-$0.28 B*</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$13 B</td>
<td>$37.5 B</td>
<td>$33 B</td>
</tr>
</tbody>
</table>

*annual maintenance costs similar in magnitude to annualized capital cost
Ventilation Rates (VR) and Health in Homes: Few Studies

Green indicates benefits of increased ventilation

• Oie et al. (Norway) Epidemiology 1999
  – Low VR not directly associated with bronchial obstruction, but bronchial obstruction more strongly associated with dampness in homes with low VR

• Bornehag et al. Indoor Air 2005
  – In homes with low VR (0.05 to 0.24 ach), children had ~ twice as many allergic symptoms, OR = 1.95 (0.94 – 4.04)

• Emenius et al. Indoor Air 2004
  – Risk of recurrent wheeze not associated with VR

• Norback et al. Occup and Envir Med 1995
  – Risk of asthma symptoms increased in homes with high CO₂ (P < 0.05), but relied on only 1 hr CO₂ measurement [OR = 20 (2.7 – 146) for 1000 ppm increase]

• Wright et al Allergy 2009
  – Adding mechanical ventilation (0.5 ach to living room and bedroom) significantly improved peak expiratory flow in evening, but not at morning

• Lajoie et al. Indoor Air 2014
  – Adding mechanical ventilation (0.17 to 0.34 ach), did not significantly reduce days of asthma symptoms but significantly (by ~ 20%) reduced proportion of children with wheezing
Decreased Frequent Common Colds with Increased Winter – Time Ventilation Rates in Dorms Rooms in China*

*not statistically significant

Source: Sun et al. (2011) PlosOne
Particle Filtration
Known Health Effects of Outdoor Air Particles

- Premature death in people with heart or lung disease
- Nonfatal heart attacks
- Irregular heartbeat
- Aggravated asthma
- Decreased lung function
- Increased respiratory symptoms, such as irritation of the airways, coughing or difficulty breathing

- Globally 3.2 million deaths per year (~ 4 x the population of San Francisco) and 76 million disability-adjusted life years (Lim et al 2010, Lancet, WHO Study)

- Much our exposure occurs indoors, because, on average, we are indoors 90% of the time.
Findings from Intervention Studies of Filtration in Homes

Many Studies, Variable Study Quality

• Allergy and asthma outcomes → Modest improvements, when sources of allergens present

• Predictors of future adverse coronary events → Improvement in two of three studies

• Inflammation → No improvement 2 of 2 studies

• Lung function, blood pressure → Improved in study of First Nation homes with tobacco smoking

• Sick building syndrome symptoms → No improvement

*Fisk et al. (2014) Indoor Air Journal.*
How Models Are use to Estimate Health Benefits

From Use of Using Filters to Reduce Indoor Exposures to Outdoor Air Particles

Scenario

Mass Balance Modeling of Filtration or Empirical Data

Reduction in Particle Exposures

Reduction in Adverse Health Effects

Outdoor Air Particle Data & Time in Building

Concentration Response Functions

Epidemiologic Studies
Using Filtration to Reduce Exposures to Outdoor Air Particles: Example Scenario 1

Add Filtration to Office Building
OA Supply*
Beko et al. (2008) Building and Environment 43

• 30% to 90% reduction in PM10
• 7% to 21% reduction in PM-related health effects
• Annual mortality benefits of $37 to $144 per person
• Annual morbidity benefits of $8 to $30 per person
• Annual operating costs of $2.6 per person

*HVAC system does not recirculate air
Using Filtration to Reduce Exposures to Outdoor Air Particles

Example Scenario 2

Replace 14% efficient filtration with 90% efficient filtration (PM2.5) in home HVAC, run continuously


<table>
<thead>
<tr>
<th>Outcome</th>
<th># Prevented per year in 2.7 Million Residents</th>
<th>~ Annual Value $ (added by W. Fisk)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Death</td>
<td>700</td>
<td>$6000 x 10^6</td>
</tr>
<tr>
<td>Respiratory hospital admission</td>
<td>220</td>
<td>$3.6 x 10^6</td>
</tr>
<tr>
<td>Cardiovascular hospital admissions</td>
<td>160</td>
<td>4.4 x 10^6</td>
</tr>
<tr>
<td>Asthma ER visits</td>
<td>560</td>
<td>$0.21 x 10^6</td>
</tr>
<tr>
<td>Asthma exacerbations</td>
<td>130,000</td>
<td>6.9 x 10^6</td>
</tr>
<tr>
<td>Total savings</td>
<td></td>
<td>$6 billion (mortality)</td>
</tr>
<tr>
<td>Health-related savings per capita</td>
<td></td>
<td>$2200 (mortality)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$15 million (morbidity)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$6 (morbidity)</td>
</tr>
</tbody>
</table>

Study supported by air cleaner manufacturer
Using Filtration to Reduce Exposures to Outdoor Air Particles
Example Scenario 4

Increase filter $\epsilon$ from 40% to 85% for PM10 in Singapore offices

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Annual # (%) Prevented</th>
<th>Annual Benefit ($US)</th>
<th>Annual Filtration Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Death</td>
<td>780 (14%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chronic Bronchitis</td>
<td>82 (8%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asthma hospital</td>
<td>31 (11%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ER visit</td>
<td>6026 (14%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asthma exacerbation</td>
<td>628 (14%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Restricted activity day</td>
<td>1174 (14%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Work loss day</td>
<td>231 (14%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total economic benefit</td>
<td>$2.4 B (14%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$ Benefit (cost) per worker</td>
<td>$890</td>
<td></td>
<td>&lt; $22</td>
</tr>
</tbody>
</table>
Using Filtration to Reduce Exposures to Outdoor Air Particles

Example Scenario 5

Net annual benefit of supply air filtration versus filter efficiency rating for HVAC system with 100% OA  Montgomery et al. Building and Envir. 2015
Using Filtration to Reduce Exposures to Outdoor Air Particles
Example Scenario 5

Net annual benefit of supply air filtration versus filter efficiency rating for HVAC system with various amounts of recirculation
Montgomery et al. Building and Envir. 2015

Cost estimate includes recirculation air costs to overcome filter pressure drop plus an additional 375 Pa pressure drop of a duct system
PM2.5 from Outdoor Air in an Office versus MERV Rating (modeled)

1 ACH Ventilation, 0.25 ACH Infiltration, 4 ACH Recirculation

Dampness and Mold
Respiratory Symptoms are Increased in Damp or Moldy Homes

Implication: 4.6 (2.9 – 6.3) million cases of current asthma costing $3.5B/yr ($2.1 – $4.8B) attributed to dampness and mold
Increased Bronchitis and Respiratory Infections in Damp or Moldy Homes

Meta Analysis of results of 23 studies

Approx 40% increased risk

No increased risk

Source: Fisk et al. (2100) Environmental Health 9
Increased Risk of New Asthma in Damp or Moldy Homes

Meta Analysis of results of 16 studies

Risk Factor for New Asthma

- Any D&M Indication
- Mold Odor
- Visible Mold
- Dampness
- Water Damage

Odds Ratio if No Increased Risk

Source: Quansah et al. 2012 PlosOne
Increased Risk of Rhinitis in Damp or Moldy Homes

Meta Analysis of results of 31 studies

Risk Factor for Rhinitis

<table>
<thead>
<tr>
<th>Factor</th>
<th>Odds Ratio</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Any D&amp;M Indication</td>
<td>2.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Mold Odor</td>
<td>2.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Visible Mold</td>
<td>2.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Dampness</td>
<td>4.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Water Damage</td>
<td>4.5</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Source: Jaakkola et al. 2013 Allergy and Clinical Immunology
Economic Benefits: Dampness and Mold Scenario 1

Reduce Dampness and Mold in U.S. Homes by 30%

- 1.5 million Avoided Cases of Current Asthma ($1.3 billion)
- 20 million Avoided Respiratory Infections ($2.0 Billion)
- Unquantified Avoided Remediation and Repair Costs

$3.3 Billion Annual Total Savings

Source: Fisk et al. (2011) Indoor Air
COST EFFECTIVENESS OF DAMPNESS AND MOLD REMEDIATION: BACK OF THE ENVELOPE ANALYSIS

130 million US homes  
47% with some dampness  
30% remediated  
$3500* per remediation  
=  
$64 billion cost

$3.3 billion annual health savings for -30% in D&M  
~10 yr effectiveness of remediation  
=  
$33 billion health savings  
(excludes value of structural damage)

For Cost Effectiveness, Must Act Strategically:  
Prevent dampness and mold  
Target remediation where most helpful

*Kercsmar 2006 EHP
Indoor Temperature & Thermal Comfort
Temperature (or Thermal Comfort?) Affects Office Work Performance

Temperature and School Work Performance*

![Graph showing the relationship between temperature and normalized performance (speed). R² = 0.46; P < 0.001. *Accuracy not affected.]

Other Effects of Thermal Conditions

Thermal Comfort

Perceived Air Quality

Sick Building Syndrome Symptoms

Fang et al. Indoor Air 2004

Mendell et al. Epidemiology 2002
Economic Benefits: Temperature Control Scenario

Eliminate Winter Temperatures > 23 °C in U.S. Offices

Avg. 0.2 % Increase in Winter Performance in 40 million Workers ($2.3 billion)
Prevent Winter Weekly SBS Symptoms in 7.7 million Workers ($1.1 billion)
Reduce Winter Thermal Comfort Dissatisfaction by 18% in 40 million Workers
Unquantified Energy Savings

$3.4 Billion Annual Total Savings

Source: Fisk et al. (2011) Indoor Air
Air Conditioning
Air Conditioning

Risks
Fouled and Microbially Contaminated Surfaces

Benefits
Exposure Reduction: AC & Closed Windows & Filtration
Sheltering from Outdoor Pollutants
• Ozone
• Particles
• Allergens
Maintains Thermal Comfort and Reduces Performance Decrement From Poor Comfort
Estimated Annual $125 - $200 million Health Costs of Implementing Natural Ventilation in 10% of CA Offices

Source: Dutton et al. 2013 Building and Environment
Air Conditioning (AC) in Offices is Linked to Increased Sick Building Syndrome Symptoms

<table>
<thead>
<tr>
<th>Type of ventilation system</th>
<th>Natural Ventilation</th>
<th>AC + No Humid.</th>
<th>AC + Steam Humid.</th>
<th>AC + Evap. Humid.</th>
<th>AC + Spray Humid.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jaakkola</td>
<td>95</td>
<td>868</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mendell</td>
<td>96</td>
<td>710</td>
<td></td>
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<tr>
<td>Mendell, Burge</td>
<td>90, 87</td>
<td>1459</td>
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<td>Zweers</td>
<td>92</td>
<td>2806</td>
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<td></td>
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<tr>
<td>Jaakkola</td>
<td>95</td>
<td>335</td>
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<td>92</td>
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<td>Teeuw</td>
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<td>90, 87</td>
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<td>3846</td>
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<tr>
<td>Brasche</td>
<td>99</td>
<td></td>
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<tr>
<td>Hawkins</td>
<td>91</td>
<td>255</td>
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<td></td>
</tr>
</tbody>
</table>

○ = Reference Group       ○ = Significantly more symptoms       ⊙ = Same #

Air Conditioning (AC) Systems In Homes is Linked to Respiratory Symptoms

- European study of 19,000 homes: with AC → 30% more wheeze, 46% more current asthma

- US study of 13,000 homes: with AC → 14% more lower respiratory symptoms, 28% more bronchitis symptoms

- But not certain that dampness and mold causes the increased symptoms
Increase in Health Symptoms with Evidence of HVAC Contamination

80 Complaint Office Buildings

- Poor pan drainage: 260
- Debris in air intake: 180

Increases are statistically significant

100 Non-Complaint Office Buildings

Approx. 50% increase in eye symptoms and headache in buildings with less frequent cleaning of cooling coils and drain pans

Source: Mendell et al. 2003, 2008
UV Germicidal Irradiation of Coils: Health Benefits Study*

- Only one health study in literature
- UV alternately on and off, occupants blinded
- Dramatic (99%) reduction in viable microbial agents on irradiated surfaces
- Approx. 40% reduction in respiratory symptoms and 30% reduction in mucosal symptoms with UV lamps operating, reductions are statistically significant

*Menzies et al. (2003) Lancet
Indoor Environments, Health, and Productivity

Overall Findings

• Many well documented benefits of improved IEQ
  – Value of benefits often far exceeds implementation cost

• Many IEQ improvements measures do not increase energy consumption, some save energy
  – Economizers, avoid over cooling and over heating, prevent dampness and mold, etc.
Implications for Practice

• Minimize indoor pollutant sources
• Avoid low ventilation rates
  – Consider energy efficient systems for increasing rates above minimum requirements
• Use at least moderate efficiency filters
  – MERV 11 or higher
• Design, build, & maintain buildings to reduce dampness and mold
• Maintain thermal comfort
  – Stay well within ASHRAE comfort zone
• Minimize microbial contamination in air conditioning systems
Caution
Large Uncertainties Remain

- IEQ-health & IEQ-performance relations are uncertain
- Relationship will vary among buildings
More Information

www.iaqscience.lbl.gov
### Environmental Tobacco Smoke Health Impacts

**Analyses by California EPA**

<table>
<thead>
<tr>
<th>Health Effect</th>
<th>Estimated Annual ETS-Caused Cases in U.S.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asthma exacerbations in children</td>
<td>200,000</td>
</tr>
<tr>
<td>Otitis media (ear infection) in children</td>
<td>790,000</td>
</tr>
<tr>
<td>Cardiac deaths</td>
<td>46,000</td>
</tr>
<tr>
<td>Lung cancer deaths</td>
<td>3,400</td>
</tr>
<tr>
<td>Low birth weight</td>
<td>24,500</td>
</tr>
<tr>
<td>Pre-term delivery</td>
<td>71,900</td>
</tr>
</tbody>
</table>

California Tobacco Control Program $\rightarrow$ decreased smoking in CA $\rightarrow$ health care savings of $10$ Billion per year as of 2004 (Lightwood et al 2008). California has 12% of U.S. population.