UNIVERSITY OF Southampton

Indoor Air Quality

Opportunities for behaviour change towards healthier offices, a two-part report

Executive Summary:

Part A: Known health effects and behaviour-based recommendations

Part B: A systematic review of behaviour change interventions aimed at improving air quality awareness and occupant actions

Dr Stephen Snow

Executive Summary

Brief

The Department for Environment, Food & Rural Affairs (Defra) commissioned the University of Southampton to conduct a systematic review of interventions aimed at improving awareness or changing behaviours in respect to indoor air quality (IAQ). The brief included an overview of behaviour change theories, the systematic review itself, and based on the results of the systematic review, suggestions for the design of IAQ interventions.

Research aim

The purpose of this research is to provide a focus on the sphere of influence available to building occupants themselves with respect to IAQ, rather than on engineered solutions which are a focus for existing research. Specifically, this research aims to understand the options, actions and behaviour change possibilities available to building occupants to affect and improve their IAQ on a day to day basis.

Report structure

To achieve this aim, the research is presented in a two part report consisting of Part A and Part B:

- **Part A:** Provides an overview of factors affecting IAQ in offices, applicable guidelines, effects on health, and behavioural options available to users to improve their IAQ, based on findings from literature.
- **Part B:** Based on the behavioural possibilities identified in Part A, Part B provides a systematic review of interventions seeking to improve awareness and change behaviour with respect to actions around IAQ.

Part A

Overview

Part A provides an overview of three key factors affecting IAQ in offices: (1) ventilation, (2) office fixtures and finishes, and (3) outdoor pollutants. For each factor, applicable guidelines, effects on health and options available to users to improve IAQ are discussed. Findings from this overview inform a series of recommendations for designers and policymakers with respect to maximising the efficacy of office occupants to improve their own IAQ prior to, or instead of, engineered solutions.

Part A: Recommendations

Provide feedback on indoor air quality in order to motivate users to ventilate

- Inadequate ventilation negatively affects productivity, cognitive performance and gives rise to minor health symptoms.
- CO_2 concentration indoors is a useful approximation of ventilation rate and thus the likely presence of other indoor pollutants including volatile organic compounds (VOCs) and indoor-sourced particulate matter.
- Install office-based feedback on real-time CO_2 concentration as well as other IAQ factors such as VOCs and particulate matter with alerts for when pollutant concentration exceeds guideline values (specified in report).
  - Operate windows/doors/vents to maintain CO_2 below 1,500 ppm at all times.
  - Provide complementary information on the need for regular airing of offices, including in winter.
- Reduce sources of noise in adjacent areas to enable doors to be kept open more often.

Regular active breaks

- Motivate occupants to take regular active breaks from work (at least once per hour) to areas with fresh air. Time active breaks outdoors to avoid peak hours where possible.
- Use office-based information campaigns or set reminders through technology such as pedometers/movement sensors and smart phones to remind users to take active breaks.
- Wearable particulate matter monitors can provide an approximation of the pollution levels outside and inform the route and timing of active breaks.

Reducing exposure to volatile organic compounds and indoor-sourced particulate matter

A number of human actions that can limit exposure to sources of VOCs and indoor-source particulate matter include:

- Motivate healthy ventilation behaviours through situated IAQ feedback.
- Move printers/copiers to a separate well ventilated room where possible, otherwise maximise distance from units to office workers as far as practicable.
- Limit large copying/printing jobs until after hours where possible.
- Use liquid cleaners instead of sprays.
- Time cleaning activities outside of peak office occupation.
- Request low-emissions paints, finishes and building materials to be prioritised in purchases or refurbishments.
- Where VOCs cannot be adequately controlled using human actions only- Request the installation of mechanical air filtration system(s).

Reducing infiltration of outdoor pollution indoors

- Limit window opening during known outdoor pollution events (e.g. peak hour, school drop-off time).
- Where it is possible to quantify the presence of common outdoor pollutants indoors (e.g. particulate matter, NO_2, SO_2, O_3, CO), and common indoor-sourced pollutants (e.g. CO_2, VOCs) simultaneously, instruct occupants to use ventilation to manage concentrations of pollutants such that all remain within guideline values specified in the report. This might involve ventilating less during peak hours, or basing ventilation decisions on wind direction, where known.
- In locations where outdoor air quality is known to be consistently poor- request mechanical air filtration system(s).

Part B

Overview

The main contribution of Part B is a systematic review searching three leading databases of scientific literature to find papers which assess interventions aimed at raising awareness or affecting behaviour of occupants with respect to indoor air quality (IAQ). A total of 15 empirical studies fitting the specified criteria were found and included in the review.

Part B: Recommendations

The report suggests that using situated technology to provide real-time quantifications of IAQ to office occupants holds promise for increasing awareness and promoting healthier behaviour change with respect to IAQ. Suggestions for the design of these systems include:

- **Actionable information (Self-efficacy):** Care should be taken to ensure self-efficacy, i.e. all information provided is actionable and users can influence the parameters measured.
- **Human analogies for IAQ effects:** Correlating IAQ information to work performance using human analogies, rather than numeric quantification only, may be an effective means of engaging users with IAQ and providing a visual correlation between cause and effect.
- **Situated:** IAQ information provided on a situated display may facilitate better shared sense-making, compared to personal exposure monitoring or providing information only on discrete personal devices such as smart phones or web browsers.
- **Minimal cues and unobtrusive:** IAQ feedback interventions should be unobtrusive, glance-able and seek to affect behaviour through minimal cues, rather than attempt to maintain constant engagement with the device.
- **Supporting information:** Simply making air quality information available does not guarantee it will be understood. Interventions should provide supporting information detailing the causes, effects and means of affecting any IAQ parameters which are visualised.
- **Theory-based:** Behaviour change interventions should be based upon behavioural theory. Behaviour change models such as the Behaviour Change Wheel and Habit Alteration Model hold promise for the design of IAQ-related behaviour change interventions.

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Part A: Indoor air quality in offices

Known health effects and behaviour-based recommendations

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Contents

Overview

Brief

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Research aim

The purpose of this research is to provide a focus on the sphere of influence available to building occupants themselves with respect to IAQ, rather than on engineered solutions which are a focus for existing research. Specifically, the research aims to understand the options, actions and behaviour change possibilities available to building occupants to affect and improve their IAQ on a day to day basis.

Report structure

To achieve this aim, the research is presented in a two part report consisting of Part A (additional to the initial brief) and Part B:

- **Part A (this document):** Provides an overview of factors affecting IAQ in offices, applicable guidelines, effects on health, and behavioural options available to users to improve their IAQ, based on findings from literature.

- **Part B:** Based on the behavioural possibilities identified in Part A, Part B provides a systematic review of interventions seeking to improve awareness and change behaviour with respect to actions around IAQ.

1: Introduction

The service economy makes up over 80% of the UK's GDP,[1] thus understanding and managing environmental factors which can affect the productivity and performance of office workers is a vital consideration. Poor indoor air quality (IAQ) can negatively affect health and productivity.[2–5] Yet in naturally ventilated buildings, where human actions such as opening doors/windows can directly influence IAQ, occupants typically lack information on their IAQ or how to improve it.[6,7] This paper provides a short desktop review of three key factors affecting IAQ in naturally ventilated offices, specifically: (1) ventilation, (2) office fixtures and finishes, and (3) outdoor pollutants.

Scope and Limitations

This overview concentrates on the effects of air quality and does not extend to other indoor environmental factors which may affect human performance, e.g. noise, lighting, temperature. The overview is human-centred in that it concentrates on the actions immediately available to occupants themselves to improve air quality, rather than discussing engineering solutions or factors outside of the immediate sphere of influence of the building occupants.

2: Indoor pollutants

Of the common environmental stressors in offices, e.g. noise, thermal comfort or lighting, IAQ is somewhat unique in that cognitive performance can be negatively affected without any effect on personal comfort. Due to sensory fatigue (acclimatisation to a room), cognitive performance can be negatively affected prior to the IAQ deteriorating to the point of occupant awareness of the poor IAQ or physical discomfort.[8,9]

Sources of indoor air pollution vary by ventilation type, e.g. dirty air supply filters are a problem specific to mechanically ventilated, buildings; whereas under-ventilation is typically more of an issue in naturally ventilated buildings where humans themselves achieve ventilation through opening windows, doors or vents. This review concentrates on pollutants in naturally ventilated buildings, because occupants of naturally ventilated offices have a greater number of behavioural affordances available to them to improve IAQ compared to occupants in mechanically ventilated offices.

The following paragraphs provide an overview of three sources of indoor air pollution:

- Ventilation/CO_2
- Office fixtures and finishes
- Outdoor pollutants indoors

These pollution sources are reviewed according to:

- Applicable guidelines/exposure limits
- Effects on health/productivity
- Behavioural possibilities to mitigate or improve conditions

2.1 Ventilation and carbon dioxide (CO_2)

Ventilation plays a critical role in controlling the air quality of indoor spaces in terms of replacing the air and flushing indoor-sourced pollutants including CO_2, Volatile Organic Compounds (VOCs) and human bio-effluents.[10,11] In naturally ventilated buildings, ventilation is achieved through occupant operation of windows, doors or vents, with additional extraction fans typically installed in bathrooms, kitchens or other specific-purpose rooms. 75% of the UK's building stock was built prior to 1980,[12] and natural ventilation is currently increasing in popularity as a building typology owing to the reduced operating costs and ease of meeting energy efficiency targets.[13]

In naturally ventilated buildings, reduced ventilation leads to a build-up of indoor-sourced pollutants, and thus ventilation rate can be directly proportional to IAQ. Windows are opened and closed primarily for comfort in naturally ventilated buildings,[14,15] which can lead to inadequate ventilation, particularly in winter when windows are closed for warmth.[16] Carbon dioxide (CO_2) is a product of human respiration, and rises in occupied spaces when the ventilation is reduced or restricted. CO_2 is far easier to measure compared to actual ventilation rate, and is often used as a real-time indicator of ventilation.[17]

2.1.1 Guidelines / Exposure limits

Ventilation: European building guidelines for non-residential buildings state that buildings must be capable of achieving a minimum ventilation rate of 8 litres/second/person (l/s/p) for acceptable air quality.[18] British guidelines for schools also state ventilation systems should be capable of achieving 8 l/s/p.[10] While building regulations set minimum required ventilation rates, literature suggests ventilation rates should be maintained as high as possible within the realistic constraints of energy efficiency,[19–22] and that occupants should be capable of lowering the CO_2 concentrations below 1,000 ppm at any occupied time.[10]

CO_2: Due to the greater ease and lower cost of measuring CO_2 compared to actual ventilation rate, CO_2 concentrations are increasingly becoming specified in operational building regulations and guidelines[23-25] Current guideline values for maximum average concentrations of CO_2 in indoor spaces vary between country and room type: 1,500 ppm for school classrooms in the UK[26], 1,200 ppm for offices in Finland,[27] between 860, and 1,590 ppm for different types of "comfort spaces" in Hungary[28]. The 8-hour workday health and safety limit for average CO_2 concentration in the UK and US is 5,000 ppm,[29] however this figure relates to the known toxicity of CO_2 gas rather than the cognitive performance effects of under-ventilation.

2.1.2 Effects on health/performance

A large body of literature associates continuous exposure to low ventilation rates (< 3 l/s/p) with health-related symptoms such as nausea, fatigue, headache, asthma, eye and throat irritation, poor concentration,[2,30-35] sick leave,[36] allergies in certain climates,[33] as well as impaired learning performance at school[37,38] (see Fisk[11] for a meta-review) and 6-9% lower productivity in the office[2]. Conversely, increasing ventilation rates from 5 to 10 l/s/p,[39] are found to improve cognitive performance. A meta-review of multiple studies finds that benefits such as improving cognitive performance and reducing sick building syndrome (SBS) symptoms can be achieved by increasing the ventilation rate up to 25 l/s/p.[33]

Indoor CO_2 concentrations of 2,000 - 5,000 ppm achieved due to human occupation in under-ventiled rooms (as opposed to introduced CO_2 gas[28,40]), are correlated with decrements in cognitive performance,[4,9,17] lower vigilance and increased sleepiness.[41] In multi-classroom studies, high mean CO_2 concentrations (> 1,800 ppm) achieved due to poor ventilation are linked to worse performance on academic test results and increased absenteeism.[42-44] Table 1 and Figure 1 summarise the cognitive performance and self-reported effects of indoor CO_2 concentrations caused by reduced ventilation found in recent studies.

Table 1- Overview of studies testing the effect of CO_2 on cognitive performance. Only studies that measure office-realistic concentrations of CO_2 and those which report on concentrations of CO_2 (as opposed to ventilation rates in litres per person per second) are included.

No.	Paper	Exposure level Average CO_2 in parts per million	Exposure duration	Sample size	Performance effects
*1	Zhang et al. 2017 [4]	3,192 ± 343	255 minutes[1]	25	**Cognitive:** ↓ speed of addition ↓ attention tasks **Subjective:** ↑ sleepiness ↑ fatigue ↑headache intensity
*2	Maddalena et al. 2015 [9]	1,800 (no ± given)	4 hours[1]	16	**Cognitive:** ↓ Decision making **Subjective:** No significant effects
*3	Vehvilainen et al. 2016 [41]	2,756 ± 1100, maximum 4,900	3x4hr meetings[2]	4	**Cognitive:** ↓ Vigilance **Subjective:** ↑ sleepiness ↑ headache
*4	Bako-Biro et al. 2012 [42]	1,000 – 5,000 (pre-ventilation improvement)	School hours for 3 consecutive weeks[3]	332	**Cognitive:** ↑ Cognitive performance improved following ventilation improvement which lowered mean classroom CO_2 to < 1,500 ppm
*5	Maula et al. 2017 [8]	2,260 ± 141 ppm	4 hours[1]	36	**Cognitive:** ↓ Weak negative effect on 1 of the 5 cognitive performance tasks **Subjective:** ↑ fatigue ↑ perceived workload
*6	Twardella et al. 2012 [45]	2,115 (no ± given)	2 school days[3]	417	**Cognitive**: ↑Errors on sustained attention task only

* Human-generated CO_2 concentrations, e.g. caused by reduced/inadequate ventilation.
[1] Climate controlled laboratories
[2] Office meeting room (variable CO_2 concentrations)
[3] Classrooms- effect on children (variable CO_2 concentrations)

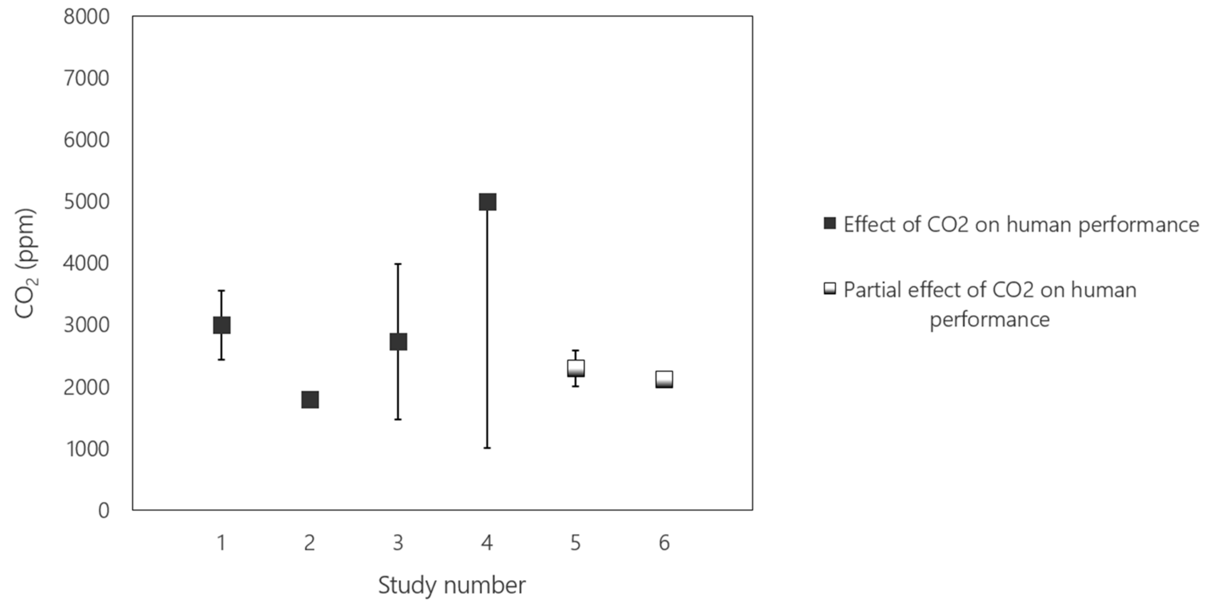

Figure 1: Effect of CO_2 concentration on human performance where CO_2 is a product of human respiration and inadequate ventilation

Table 1 and Figure 1 show that when CO_2 is a product of human-respiration and poor ventilation, cognitive performance decline can begin to occur as low as 1,800 ppm. Yet median CO_2 concentration in occupied rooms such as classrooms can remain consistently over 2,000 ppm throughout a school day.[11] Negative cognitive performance effects have also been found to precede awareness of poor IAQ, due to acclimatisation to a room.[8,9] Together, these findings suggest high CO_2 warning notifications might be beneficial in classrooms or offices.

How quickly cognitive performance is affected by poor ventilation, and how quickly it is restored when conditions improve, are imperfectly understood in the literature to date.[4,41] There is some indication that the onset of cognitive performance reductions may be gradual over this time. One study[41] found that arterial CO_2 measurements remained constant for the first two hours of exposure to elevated CO_2 concentrations (mean: 2,756 ppm), owing to physiological compensatory mechanisms, but rose in the second two hours of the experiment.[41] Arterial CO_2 was positively correlated to sleepiness.[41] **This finding suggests humans may be capable of physiologically self-regulating against the effects of poor ventilation for up to two hours, and that performance decrements may only present after this time.** Accordingly, it seems reasonable that breaking up exposure to indoor air, e.g. regular work-breaks involving fresh air, may be a means of limiting the cognitive performance effects of poor ventilation.

2.1.3 Behavioural possibilities to limit exposure to under-ventilation

(1) Because windows are opened/closed primarily for comfort,[14,15] yet cognitive performance decline can precede awareness of poor indoor air quality,[8,9] the following may be useful:

- Alerts based on CO_2 concentrations to open windows or ventilate the room may lead to healthier ventilation behaviours.
- Real time feedback on CO_2 concentration in offices. Situated CO_2 feedback has shown potential for improving ventilation practices in schools, however has not yet been tested in terms of behaviour change in office environments.[7,46]
    - A wide range of IAQ monitors which measure and visualise CO_2 concentration are available commercially for the office and home.
- Reducing sources of noise in adjacent areas enables doors to be kept open more often to maintain air flow and ventilation.

(2) Because the effects of poor ventilation/high CO_2 may only be felt after prolonged exposure to poor air quality, motivating regular fresh air breaks for office workers may additionally act to limit the cognitive performance effects, even if the air quality remains poor. Walking is found to increase creativity both during and after exercise due to IAQ,[47] and thus may offer additional cognitive performance benefits beyond simply limiting exposure to poor IAQ. A small but growing number of commercially available wearable air quality monitors exist which monitor personal exposure to particulate matter, e.g. AtmoTube (https://atmotube.com) and AirBeam (http://aircasting.org) . Wearable air quality monitors may help users understand their exposure to pollutants when outside the office on breaks or during commutes. However the accuracy of these monitors and of low cost gas and particulate matter sensors more generally is less than that of industrial monitors and can be up to ± 10% of the actual value.

2.2 Office fixtures, finishes and cleaning activities

Office fixtures, finishes and cleaning activities contribute to two key groups of indoor pollutants, Volatile Organic Compounds (VOCs) and Particulate Matter (PM). Modern detection methods identify thousands of individual VOCs,[48,49] with current workplace exposure limits available for 500 individual compounds.[50] Due to the large number and variety of point-sources, and difficulty in accurate measurement of individual VOCs, guidelines and literature often generalise VOCs as a group of chemicals, or Total VOCs (TVOCs),[24] rather than as individual chemicals. The oxidation of VOCs contributes to ultra-fine particulate matter.[51] Common point sources for VOCs include paints, sealants, adhesives, carpets, floor finishes, powdered floor polishes, timbers, lacquers, certain plastics and office equipment including personal computers, copiers and printers.[52,53] VOC concentrations vary with building age, and in new or recently renovated buildings can be an order of magnitude higher than established buildings.[54] TVOC concentration has been found to drop by 67-69% in the first week following a renovation, with the remainder taking up to two years to completely "off-gas".[54] Indoor VOC concentrations in a room can also vary according to ventilation rate.

Multi-function devices such as printers and copiers emit low concentrations of ultrafine particulate matter and a range VOCs including those known to be toxic and/or carcinogenic e.g. benzene and trichloroethylene.[50,53] While the emitted concentrations are low, pollution from office equipment can still be dangerous due to long-term or continuous exposure.[55,56]

Cleaning solutions including detergents, bleach, window, bathroom and toilet cleaners are additional sources of VOCs. The risks and effects of exposure to VOCs through cleaning products are heightened for occupational cleaners.[57] Cleaning activities including spraying, sweeping and dusting additionally contribute to short term elevations in indoor particulate matter, as does the use of chalk on blackboards and dusting of blackboards- where these are present.[58] In homes, cooking and smoking and spraying aerosols represent additional sources of indoor VOCs and PM.[59]

2.2.1 Guidelines / Exposure limits

UK Building regulations do not cover source control emissions, e.g. PM and VOC emissions from office activities or building products. Non-binding best practice standards stipulate total VOC concentration should be maintained below 300 μg/m³ [60] or 500 μg/m³. [61] Workplace exposure limits exist for over 500 individual VOCs,[50] however in practice, estimating personal exposure to any specific pollutants is difficult, given the various point sources of VOCs indoors, and accurately measuring dispersion.[53] Table 2 lists maximum recommended indoor concentrations of PM and VOC with the corresponding International Standards Organisation (ISO) method.

Table 2: Non-binding maximum recommended indoor concentrations of VOCs and particulate matter

Pollutant	Maximum recommended mean indoor concentration	ISO
PM10	50 μg/m³	ISO 7708
PM2.5	15 μg/m³	ISO 7708
Total VOCs (TVOC)	500 μg/m³	ISO 16000-6
Formaldehyde	27 parts per billion	ISO 16000-3

Note: Based on LEED v4 Building Design and Construction Addenda[60]. For details of individual exposure limits for over 500 individual VOCs refer.[50,60]

No formal limits exist for the operation or placement of electronic equipment, however best practice guidelines suggest printers/copiers be located in a separate, well ventilated room where possible, with the distance between units and office workers maximised as far as practicable.[53,62]

2.2.2 Effects on health and performance

Exposure to PM can irritate respiratory conditions in the short term and continuously elevated exposure (e.g. in polluted cities) is linked to lowered life expectancy.[51] Exposure to VOCs from floor polish, carpets and office equipment is associated with sick building syndrome (SBS) symptoms such as headache, dry throat, irritated eyes, dizziness.[52,56,63] In a controlled ventilation scenario, a 500 μg/m³ increase in total VOC's (achieved through introduced sources including: exposed packing tape, cleaning products, correction fluid and vinyl) was associated with a 13% decrease in cognitive performance scores.[64] Continuous exposure to elevated concentrations of chemical agents has been found to increase risk of asthma and respiratory irritation short term, and reduced lung function in the long term, in the case of occupational cleaners.[57]

2.2.3 Behavioural possibilities to limit VOCs, PM

Maintaining a sufficient ventilation rate is identified as key to controlling airborne pollutants including VOCs and PM.[52,53,65] Therefore promoting adequate ventilation in offices is vital, and the behavioural possibilities listed in Section 2.1.3 to maintain adequate ventilation and reduce CO_2 concentration are equally applicable to reducing the concentration of VOCs and PM.

Providing occupants with a visual quantification of CO_2 has shown potential for improving ventilation behaviour.[7,46,66] Thus providing visual information on VOC concentration specifically may increase awareness of VOCs and facilitate behaviour to reduce VOC concentration. A number of commercially available multi-parameter IAQ monitors measure total VOC concentration (FooBot[(1)], Air Mentor[(2)], Awair[(3)], Uhoo[(4)], Eve[(5)]) in addition to temperature, CO_2 and/or other pollutants.

Based on the information above, additional behavioural possibilities to limit the exposure to VOCs in offices include:

- Use liquid cleaners in preference to spray cleaners in order to limit spread of VOCs and PM.[57]
- Work with cleaning providers to favour liquid cleaning solutions rather than sprays where applicable.
- Time cleaning activities outside of peak occupation.
- Printers/copiers to be moved to a separate well ventilated room where possible, otherwise maximise distance from units to office workers as far as practicable.[53,62]
- Limiting continuous copying/printing operations until after hours.[61]
- Encourage participation of building occupants in building-related decisions, and where possible, advocate for:
  - Low-emission paints, finishes and building materials in refurbishments/renovations.[54]
  - Request a delay between renovation completion and building re-occupation, given TVOC concentration can drop by 67-69% in the first week following renovation.[54]
  - Phytoremediation using indoor plants has been found to be capable of removing VOCs, including formaldehyde from indoor air.[67]
  - Installing mechanical air filtration systems should be considered where acceptable IAQ cannot be achieved through natural ventilation alone, e.g. for offices adjoining a busy road.
- A range of domestic and commercial air purifiers which reduce VOCs are available, e.g. Camfil,[(6)] Dyson,[(7)] Phillips[(8)]

2.3 Outdoor pollutants indoors

In naturally ventilated offices, outdoor pollutants (e.g. PM, nitrogen dioxide, sulphur dioxide, ozone) can infiltrate indoors directly through open windows and vents, affecting indoor air quality.[68] One study found ultrafine PM in naturally ventilated classrooms closely correlated to levels measured outdoors, implying a predominantly outdoor origin of the particles measured.[69,70] Outdoor factors have also been correlated to indoor air quality in classrooms, including peak hour[70] and school drop-off times, when cars and buses can remain idling outside.[71] Overall, the influence of outdoor pollutants on IAQ is a knowledge gap which requires further investigation.[68–70]

2.3.1 Guidelines / Exposure limits

The World Health Organisation (WHO)[72] lists exposure limits for common outdoor-source pollutants:

Table 3- Non-binding exposure limits for common outdoor pollutants. Recommended indoor exposure limits are also listed where available.

Pollutant	Long term (Max recommended)	Short term (Max recommended)
Nitrogen dioxide (NO_2)	40 μg/m³ (annual mean)	200 μg/m³ (1-hr mean)
Sulphur dioxide (SO_2)	50 μg/m³ (annual mean)	125 μg/m³ (24-hour mean)
Ozone (O_3)	-	100 μg/m³ (outdoor) (8-hr mean) 0.075 ppm (indoor)
Carbon Monoxide (CO)	-	9 ppm; or no more than 2 ppm above outdoor levels (indoor)

Table 3 note: Outdoor exposure limits based on World Health Organisation[72]. Indoor exposure limits based on: LEED v4 Building Design and Construction Addenda[60]..

1 https://foobot.io/
2 http://air-mentor.eu/#page1
3 https://getawair.com/
4 https://uhooair.com/
5 https://www.elgato.com/en/eve/eve-room
6 http://www.camfil.co.uk/Products/Air-Purifiers--Air-Cleaners1/
7 https://www.dyson.co.uk/purifiers/indoor-air-pollution.html
8 https://www.philips.co.uk/c-m-ho/air-purifier-and-air-humidifier

2.3.2 Effects on health and performance

Long term exposure to elevated levels of outdoor pollution is positively correlated to asthma, respiratory disease and morbidity.[73] Elevated indoor concentrations of common traffic pollutants (specifically NO_2 and elemental carbon) concentrations indoors have been correlated to short term negative effects on attention amongst elementary schools students, suggesting an additional short-term effect of traffic pollution on mental concentration.[74] The amount of infiltration and the specific health effects of outdoor pollutants indoors is a knowledge gap which requires further research.

2.3.3 Behavioural possibilities

If measuring the concentration of outdoor pollutants (e.g. NO_2, SO_2, O_3, CO) indoors is not practicable, publicly available air pollution data, e.g. Met Office Air Quality Index information could be incorporated into office-situated displays of IAQ. Providing information on both indoor and outdoor air quality may allow occupants to maintain acceptable concentrations of outdoor and indoor sourced pollutants through ventilation actions. For example, timing the opening of windows has the potential to affect the amount/concentration of outdoor pollutants which infiltrate indoors through windows. This might involve closing windows during peak hours and ventilating at other times.[70] Mechanical air filtration may be a necessary solution where outdoor air quality is consistently poor, e.g. offices proximal to a busy road or industry.

3 Recommendations

This paper has provided a short desktop review of the health effects, human performance effects and behavioural possibilities to manage three key factors affecting IAQ in offices: (1) ventilation, (2) office fixtures and finishes, and (3) outdoor pollutants. Here we summarise the behavioural opportunities identified from this review for actions within the control of office occupants for improving IAQ. The opportunities listed are not categorical and none are recommended as a higher priority than others.

Opportunity A: Improving air quality awareness: The potential role of real-time IAQ monitoring to raise awareness and inform ventilation actions

"Indoor Air Quality" is a commonly used, yet poorly understood term. IAQ is affected by various individual pollutants which can originate from multiple sources and affect humans in different ways. Under-ventilation can lead to short term cognitive performance decrements, increased drowsiness and minor health symptoms (Section 2.1.2), while long-term exposure to elevated levels of outdoor pollutants including particulate matter, NO_2, SO_2, O_3 are linked to higher rates of respiratory issues and more serious health complications (Section 2.3.2).

A first step in improving general awareness of IAQ among office occupants might involve company-wide information campaigns aiming to highlight and differentiate the main pollutants that affect IAQ in offices and actions available to reduce exposure to each. Information campaigns might additionally involve the quantification of different aspects of air quality using commercially available monitors. Providing occupants with real-time IAQ information also offers an opportunity to better inform occupants' ventilation decisions in naturally ventilated buildings. Ventilation plays the biggest role in indoor air quality, reducing human bio-effluents, odours, CO_2, VOCs and indoor point sources of PM. Low ventilation rates / high CO_2 concentrations are correlated to lower cognitive performance, and cognitive performance reductions may precede awareness of poor IAQ. Thus a key priority is to motivate users to ventilate better. This might involve:

- Information on the need for regular airing of offices, even in winter.
- Install office-based feedback on real-time CO_2 concentration with alerts for when CO_2 concentration exceeds guideline values (e.g. IAQ feedback monitors.[7,46,66]
  - A number of commercially available multi-parameter monitors measure CO_2 and VOC concentration and other pollutants (see Section 2.2.3).
- If visual IAQ feedback is available:
  - Suggest occupants maintain CO_2 concentrations below 1,500 ppm (based on the WELL Building Standard[26]) and total VOC concentrations below 500 μg/m (based on[60]) at all times, through opening windows and doors.
- Reduce sources of noise in adjacent areas to encourage doors to be kept open more often in order to increase air flow and ventilation.
- Further academic work is warranted into determining whether quantification of multiple IAQ parameters, or presentation of a single metric (i.e. CO_2 only, or an overall "air quality index") is most effective in increasing awareness and/or improving ventilation behaviour.

Opportunity B: Encourage short but regular active breaks from work

Research suggests that it may take up to two hours for poor IAQ to affect cognitive performance. Active work breaks to areas of fresh air (e.g. outdoors away from busy roads, or to other areas of a building if outdoor air is known to be poor) act to break up exposure to poor IAQ and are linked to improved health outcomes and increased ability for creative thinking during exercise.[47] Therefore a second priority is to encourage active breaks during the work day irrespective of the air quality:

- Motivate occupants to take active breaks (at least once per hour) from work to areas with fresh air to limit continuous exposure to poor indoor air quality and achieve the health and productivity benefits of increased workday exercise.
- Use of office-based information campaigns or adaptation of technology such as pedometers/movement sensors to remind users to take active breaks.
- Wearable personal exposure monitors can provide an indication of the level of particulate matter exposure users are subjected to during outdoor exercise or commuting, which can inform route choice for active breaks (Section 2.1.3).

Opportunity C: Reduce VOC / Indoor-source particulate matter

Human actions which can limit exposure to sources of VOCs and indoor-source particulate matter include:

- Move printers/copiers to a separate well ventilated room where possible, otherwise maximise distance from units to office workers as far as practicable.
- Limit continuous copying/printing operations until after hours.
- Use liquid cleaners instead of sprays.
- Time cleaning activities outside of peak office occupation.
- Request low-emissions paints, finishes and building materials to be prioritised in any purchases or refurbishments.
- Request a delay of one week between renovation completion and building re-occupation .
- Commercially available situated air quality monitors can detect total VOC concentration (TVOCs), refer Section 2.2.3.
- Where VOCs cannot be adequately controlled using human actions only- Request the installation of mechanical air filtration system(s).
  - A range of domestic and commercial air purifiers which reduce VOCs are available (refer Section 2.2.3).

Opportunity D: Reduce infiltration of outdoor pollution indoors (only applicable where proximal to known sources of outdoor pollution)

- Limit window opening during known maximum outdoor pollution events (e.g. peak hour, school drop-off).
- Where it is possible to quantify the presence of common outdoor pollutants indoors (e.g. particulate matter, NO_2, SO_2, O_3, CO), and common indoor-sourced pollutants (e.g. CO_2, VOCs) simultaneously, instruct occupants to use ventilation to manage concentrations of pollutants such that all remain within guideline values (specified in Sections 2.1.1, 2.2.1 and 2.3.1). This might involve ventilating less during peak hours, or basing ventilation decisions on wind direction.
- Where outdoor air quality is known to be consistently poor, i.e. offices proximal to point-source pollutants such as industry, lower floor offices on main roads- request mechanical air filtration system(s) or commercial air purifiers.

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Part B: Indoor air quality in offices

A Systematic review of behaviour change interventions aimed at improving air quality awareness and occupant action

Dr Stephen Snow

Contents

Overview

Brief

The Department for Environment, Food & Rural Affairs (Defra) commissioned the University of Southampton to conduct a systematic review of interventions aimed at improving awareness or changing behaviours in respect to indoor air quality (IAQ). The brief included an overview of behaviour change theories, the systematic review itself, and based on the results of the systematic review, suggestions for the design of IAQ interventions.

Research aim

The purpose of this research is to provide a focus on the sphere of influence available to building occupants themselves with respect to IAQ, rather than on engineered solutions which are a focus for existing research. Specifically, the research aims to understand the options, actions and behaviour change possibilities available to building occupants to affect and improve their IAQ on a day to day basis.

Report structure

To achieve this aim, the research is presented in a two part report consisting of Part A and Part B:

- **Part A:** Provides an overview of factors affecting IAQ in offices, applicable guidelines, effects on health, and behavioural options available to users to improve their IAQ, based on findings from literature.
- **Part B (this report):** Based on the behavioural possibilities identified in Part A, Part B provides a systematic review of interventions seeking to improve awareness and change behaviour with respect to actions around IAQ.

Part B

Overview

The main contribution of this document is a systematic review searching three leading databases of scientific literature to find papers which assess interventions aimed at raising awareness or affecting behaviour of occupants with respect to indoor air quality (IAQ). A total of 15 empirical studies fitting the specified criteria were found and included in the review.

1 Introduction

Rationale: Humans spend more than 90% of their time indoors, yet typically lack access to information on the quality of the air which they breathe.[1] Despite the potential consequences of poor indoor air quality (IAQ) including headache, sore throat,[2–4] difficulty concentrating[5] and lower cognitive performance,[6–8] occupants themselves do not feature prominently in building guidelines.[9,10] Users are more often considered as passive recipients- rather than co-creators- of acceptable IAQ,[11] and human behaviour (i.e. users' ability to affect their IAQ themselves) is underexplored in the literature as a solution to poor IAQ relative to engineered solutions.[11] Yet human actions fundamentally affect IAQ, for example, opening/closing windows and doors for ventilation, choice of cleaning products, timing of cleaning activities and placement of printers and copiers which can emit chemicals during use. Accordingly the purpose of this report is to provide a focus on the sphere of influence available to building occupants themselves to affect and improve their IAQ.

This present study presents a systematic review of empirical, peer-reviewed papers which use technical interventions to raise awareness and/or change behaviour of users with respect to IAQ. The focus is on naturally ventilated buildings, where users themselves can affect IAQ through opening windows and doors

Structure: Foregrounding the systematic review, this report draws from relevant literature to provide a background into: (a) knowledge on the existing drivers of building-operation behaviour in offices (**Section 2.1**), (b) results from a number of meta-reviews of behaviour change interventions related to health and pro-environmental behaviour (**Section 2.2**) and (c) an overview of four models or "recipes" for behaviour change applicable to complex problems (**Section 2.3**). Secondly, using a systematic review methodology which incorporates searches of three leading academic databases, the report analyses findings from 15 studies concerned with improving occupant awareness and behaviour with respect to IAQ (**Sections 3-4**). Based on findings from this systematic review and from the related literature, the report provides recommendations for the design of technical systems to improve awareness and foster behaviour changes towards better indoor air quality (**Section 5**).

2 Background

2.1 Drivers of IAQ-related behaviours

In the absence of visual feedback on indoor or outdoor air quality, windows in naturally ventilated offices are opened and closed: (1) out of habit (e.g. the start and end of a work day), (2) due to external influences such as noise outside or bad weather, (3) for security in ground-floor offices, and (4) for comfort.[12] Comfort is identified as the primary driver of interactions with building controls in naturally ventilated offices.[13] This situation can be problematic in cooler months when windows and doors tend to remain closed for warmth, and can lead to under-ventilation and poor IAQ, which negatively affects concentration and cognitive performance.[4,14] Socially, offices have a relatively flat social hierarchy,[15] and decisions affecting air quality such as window opening may be negotiable. Social factors have been found to meditate interactions with windows and thermostats in shared offices,[16] where office occupants have been found to delay or refrain from making a request to open a window or adjust a thermostat, due to not wanting to disturb a colleague or make a fuss.[16] Motivations for interactions with printers, cleaning products and other point sources of indoor pollutants in offices are not widely explored in academic literature, but it may be assumed that IAQ is not likely to be a consideration in their use. Combined, these factors provide a rationale for exploring behaviour change interventions which seek to persuade users towards healthier building operation habits.

2.2 Existing literature on behaviour change interventions

Meta-reviews provide a synthesis of the existing academic literature on a given topic. To the best of our knowledge, no meta-reviews exist on behaviour change interventions specific to improving IAQ. Yet many meta-reviews assess the effectiveness of behaviour change interventions applied in related areas including health/wellness, pro-environmental behaviour and persuasive technology. Table 1 provides an overview of eight recent meta-reviews of behaviour change interventions applied in these areas in terms of (1) the area of application reviewed, (2) the number of papers reviewed in each study and (3) key findings.

Table 1: Overview of meta-reviews published on behaviour change interventions related to health, pro-environmental behaviour and persuasive technology

Author	Publication field	Area of behaviour change applications reviewed	No. of papers reviewed	Key findings
Orji and Moffat 2018[17]	Health informatics	Technology-related behaviour change interventions aimed at improving personal health and wellness	85	90% of studies reported partially or fully positive results of intervention. 45% of studies cited a theoretical underpinning, All but one of the studies that were based on a known theory reported positive results. Retention of behaviour change over time is a knowledge gap
Talor et al. 2012[18]	Psychology	Worksite physical activity interventions	26	Physical activity interventions are effective in improving active behaviour, however effect sizes are small. 41% of studies cited a theoretical underpinning. Theory-based interventions were more effective than non-theory-based. Interventions using theory had a higher effect size (d = 0.34) compared to the average (d = 0.21).
Webb et al. 2010[19]	Medical Research/ Psychology	Internet-based interventions to promote healthy behaviours including: physical activity, dietary behaviour, smoking abstinence and alcohol consumption	85	On average the interventions reviewed were effective in promoting health-related behaviour, however effect sizes were small (average overall d = 0.16). 35% of studies mentioned or incorporated at least one theory. Interventions with a larger effect sizes were associated with: (1) more extensive use of theory, (2) incorporation of more behaviour change techniques, (3) the use of Descriptive Norms (i.e. providing models to aspire to) rather than Injunctive Norms (i.e. rules to abide to in order to achieve a behaviour).
Oldander et al. 2013[20]	Health / nutrition	Changing obese individuals' physical activity behaviours	58	Reported positive results of behaviour change interventions on physical activity with a medium effect size. 61% of studies mentioned a theoretical basis. Four behaviour change techniques were most significantly associated with positive changes in self-efficacy in the context of changing obese people's activity behaviours: (1) Action planning, (2) time management, (3) prompt self-monitoring of behavioural outcome and (4) plan social support/social change.
Rosen et al. 2015[21]	Psychology / Public Health	Interventions to reduce tobacco smoke in homes	7	All the seven behavioural interventions reviewed were successful in reducing the amount of smoking indoors, but not completely removing contamination from indoor smoking. Recommends further regulatory measures may be necessary to further reduce risk of children's exposure to indoor cigarette smoke.
Osbaldiston and Schott 2012[22]	Environment and behaviour	Interventions to promote pro-environmental behaviour (general)	87	Interventions were successful on average in promoting pro-environmental behaviour. Many studies used multiple treatments, precluding evaluation of individual treatment options. Pro-environmental behaviour interventions which used the behaviour change techniques of: goal setting, social modelling and prompts, produced the largest effect sizes.
Lo et al. 2012[23]	Psychology	Interventions seeking to influence pro-environmental behaviour in organisations	21	Overall, interventions were effective in producing behaviour change, but effect sizes were small (d = < 0.2). Recommends interventions for pro-environmental behaviour focus on tailored persuasive communication, involvement of middle-management and physical facilitation.
Hamari et al. 2014[24]	Human-Computer Interaction	Behaviour change interventions incorporating persuasive technology (multiple domains)	95	> 80% of all studies reviewed produced fully or partially positive results. Identifies knowledge gaps in literature including: (1) most studies employ short timescales; lack of longitudinal studies, (2) small sample sizes (median n=26), (3) persuasive technologies typically employed where users already want to change.

In summary, the meta-reviews point to a strong potential for behaviour change interventions to positively affect a targeted behaviour or set of behaviours. Each meta-review reports overall positive results in terms of behaviour change (Table 1). Three reviews find that 80% or more of the interventions studied report fully or partially positive results.[17,21,24] However, the effect sizes reported in the studies are typically modest[18,19,21,23] and the long-term effectiveness of behaviour change interventions are infrequently reported and are highlighted as a knowledge gap in the literature.[24]

Theoretical underpinning is linked to improved intervention effectiveness by four meta-reviews, where despite a relatively low percentage of studies explicitly mentioning or using theory 35%[19], 41%[18], 45%[17] and 61% of studies,[20] the majority of meta-reviews found that studies grounded in behaviour change theories[17–20] or those using specific behaviour change techniques[22] were more effective than those which did/were not (Table 1). The fact that no meta-reviews exist of behaviour change interventions related to indoor air quality or human-building interactions specifically, justifies the purpose of this present report in providing the systematic review detailed in Sections 3-4.

2.3 Application of behaviour change theories

A total of 82 unique theories of human behaviour (e.g. why humans behave in a certain way) have been identified across the social and behavioural sciences field.[25] Michie et al.[26] additionally lists 93 separate behaviour change techniques (i.e. specific techniques used in behaviour change interventions). For this reason, it is beyond the scope of this report to attempt to review all existing behaviour theories or techniques in terms of their applicability to IAQ. Rather than focusing on theories of behaviour, or behaviour change techniques, this report instead describes a number of behaviour change models or "recipes" for successfully changing behaviour, each of which draws on a number of separate theories.

An indicative relationship between theories, models and interventions is illustrated below (Figure 1). Behaviour change **models** are grounded in behavioural **theories** (e.g. theory of planned behaviour, social cognitive theory). When applied to a specific problem area, models act as "recipes" which inform the design of behaviour change **interventions.** Interventions themselves may incorporate one or more behaviour change **techniques** (e.g. goal setting, social comparison, prompts).

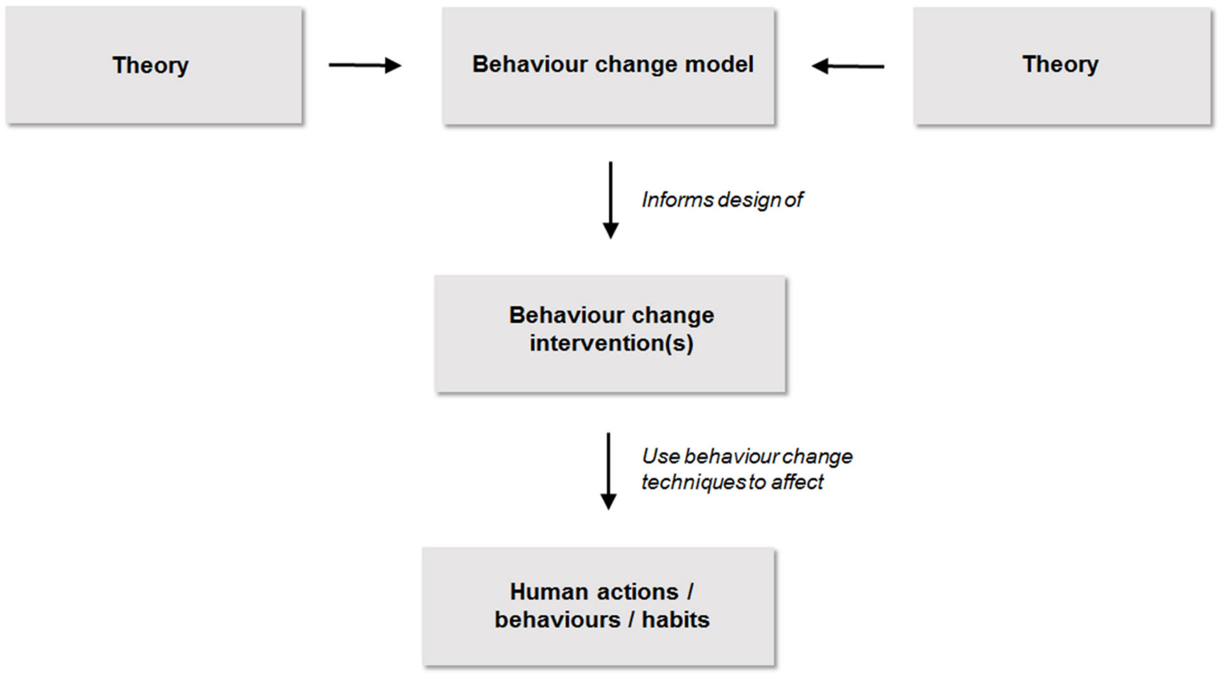

Figure 1: Indicative relationship between behaviour change theories, recipes and interventions

The behaviour change models reviewed in this section are based on those identified in a review by Pinder et al.27 as of relevance to designers of interventions targeting complex behaviours. The models reviewed are: (1) The Transtheoretical Model of Change, (2) Fogg's Behaviour Model, (3) Behaviour Change Wheel / COM-B and (4) the Habit Alteration Model. A determination of the potential applicability of each model to issues of IAQ is given.

2.3.1 Transtheoretical Model

Overview: The Transtheoretical Model of Change identifies six behavioural stages and a number of processes through which people can transition between stages.[28] The theory was developed out of findings from a large cohort study of adults attempting to give up smoking.[27] Table 2 lists each of the six stages in the model:

Table 2: Six stages of behaviour change according to the Transtheoretical Model [28]

Stage number	Name	Description
1	Pre-contemplation	No intention to take action in foreseeable future, may be unaware a behaviour is problematic
2	Contemplation	Beginning to understand a behaviour is problematic, weighing up positives and negatives of continuing the behaviour
3	Preparation	Intention to take action in the immediate future, potentially beginning minor steps toward change
4	Action	Specific modifications made to their problem behaviour or acquiring new healthier behaviours
5	Maintenance	Have been capable of sustaining the changed behaviour for > 6 months and working to prevent relapse
6	Termination	Certainty that old behaviours/habits will not be returned to, habits permanently changed

People's transitions between stages are facilitated by (1) Confidence or self-efficacy, i.e. perceived ability and confidence to achieve a certain goal, (2) Decisional Balance- weighing up positives and negatives of a change, determining that pros outweigh cons, (3) Strategies or Processes of Change, in which 21 separate processes are listed.[28]

Use and effectiveness: The Transtheoretical Model is widely applied in behaviour change research and is considered the dominant model of health-related behaviour change.[29] Two of the meta-reviews listed in Table 1[17,19] list the Transtheoretical Model as the most common theoretical basis of the interventions reviewed. Over 71 separate empirical applications of the model have been identified.[30] Yet results regarding its effectiveness are mixed. One meta-review found a higher average effect size of studies employing the Transtheoretical model compared to those which employ other theories,[19] while a separate meta-review focused on smoking cessation behaviour interventions found no significant effect of the model.[31] Further issues with the model highlighted in the literature include: (1) the stages imply behaviour is product of rational choice, which neglects environmental determinants and (2) the divisions between stages are argued to be arbitrary in nature.[27]

2.3.2 Fogg Behaviour Model

Overview: Developed by BJ Fogg, the Fogg model emphasises the role of technology in behaviour change, and technology's capability as a means of persuasion.[32] It proposes the key determinants of behaviour as motivation (M), ability (A) and a prompt/ trigger (T), when these elements occur at the same time.[33] If behaviour does not occur, one or more of these elements must be missing. Fogg has additionally created "Tiny Habits", an action plan for long-term behaviour change, achieved by changing ones' environment and breaking down desirable habits into smaller manageable actions.[34]

Use and effectiveness: Persuasive technology built referencing the Fogg Model has been successful in motivating behaviour changes, e.g. motivating active work-breaks,[35] health related behaviours[36] and changes in electricity use.[37] However these studies incorporated further theories, additional to the Fogg Model, meaning the specific contribution of the Fogg Model itself is difficult to identify.[27] In relation to motivating pro-environmental behaviour, persuasion is argued to be limiting, where a focus on "optimizing simple metrics" or changing individual behaviours fails to account for the cultural and social contexts in which actions take place.[38]

2.3.3 The Behaviour Change Wheel

Overview: The Behaviour Change Wheel[39,40] (Figure 2) is a comprehensive tool for designers to design and target behaviour change interventions. It is based on the COM-B model,[41] which states: *"for someone to engage in a particular behaviour (B) at a given moment they must be physically and psychologically capable (C) and have the social and physical opportunity (O) to do the behaviour and, in addition, want or need to do the behaviour more than any other competing behaviours [motivation (M)]"*[41, pp.91]

The Behaviour Change Wheel (BCW) involves a central hub describing sources of behaviour (the COM-B model) surrounded by nine intervention functions and seven policy categories to pick from, which may be chosen depending on the outcome of earlier investigations/analyses and the context of the intervention (Figure 2).

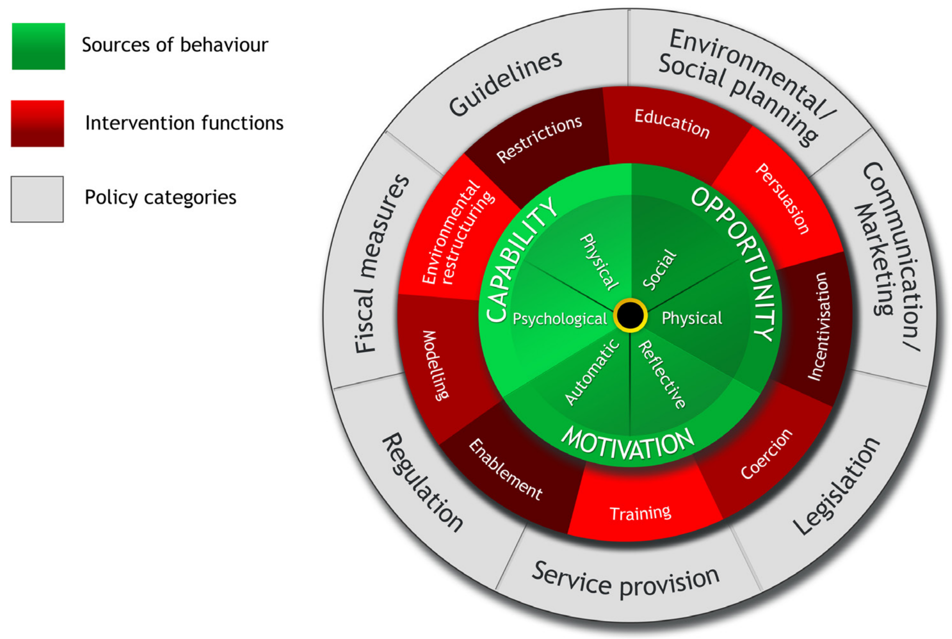

Figure 2: Behaviour change wheel (source: Michie et al.[39])

After selecting intervention functions and policy categories, a designer picks techniques and systems for delivery based on the 'Behaviour Change Wheel Guide'.[40] In this way the wheel links modes of delivery with theory.[41] The wheel represents a resource for designers and is recommended as a starting point to choosing which intervention(s) have the highest likelihood of efficacy in a given context.[27]

Use and effectiveness: An app designed using the BCW to motivate physical activity showed positive results relative to a control group.[42] The BCW has also been used as a framework to test existing interventions, and is highlighted as a useful tool for evidence synthesis in mobile phone-based health interventions.[43] However being relatively recently developed, the BCW is not yet as widely applied as the Transtheoretical Model or Fogg's Behavioural Model.

2.3.4 Habit Alteration Model

Overview: The Habit Alteration Model (HAM) proposed by Pinder et al.[27], focuses specifically on habits, contending that lasting behaviour change is dependent on changes to habits, not individual behaviours. HAM understands behaviour to be a function of (a) the environmental context, e.g. cues, (b) automatic Type 1 processes (unconscious/automatic/habitual processes), (c) Type 2 processes (deliberative/considered/rational processes) which produce intentions, and (d) individual differences which affect the relative contribution to behaviour of Type 1 and 2 processes.

The HAM identifies stages of action: (a) the Filter stage, where cues pass through Type 1 and Type 2 attention filters creating an input set, (b) the Prepare stage, where Type 1 and 2 memory processes match cues to different potential responses (c) the Act stage, where these processes compete to form one single response. Observed output and response is fed back into the model and iterations of the filter, prepare and act stages become progressively automatic with enough repetitions.[27]

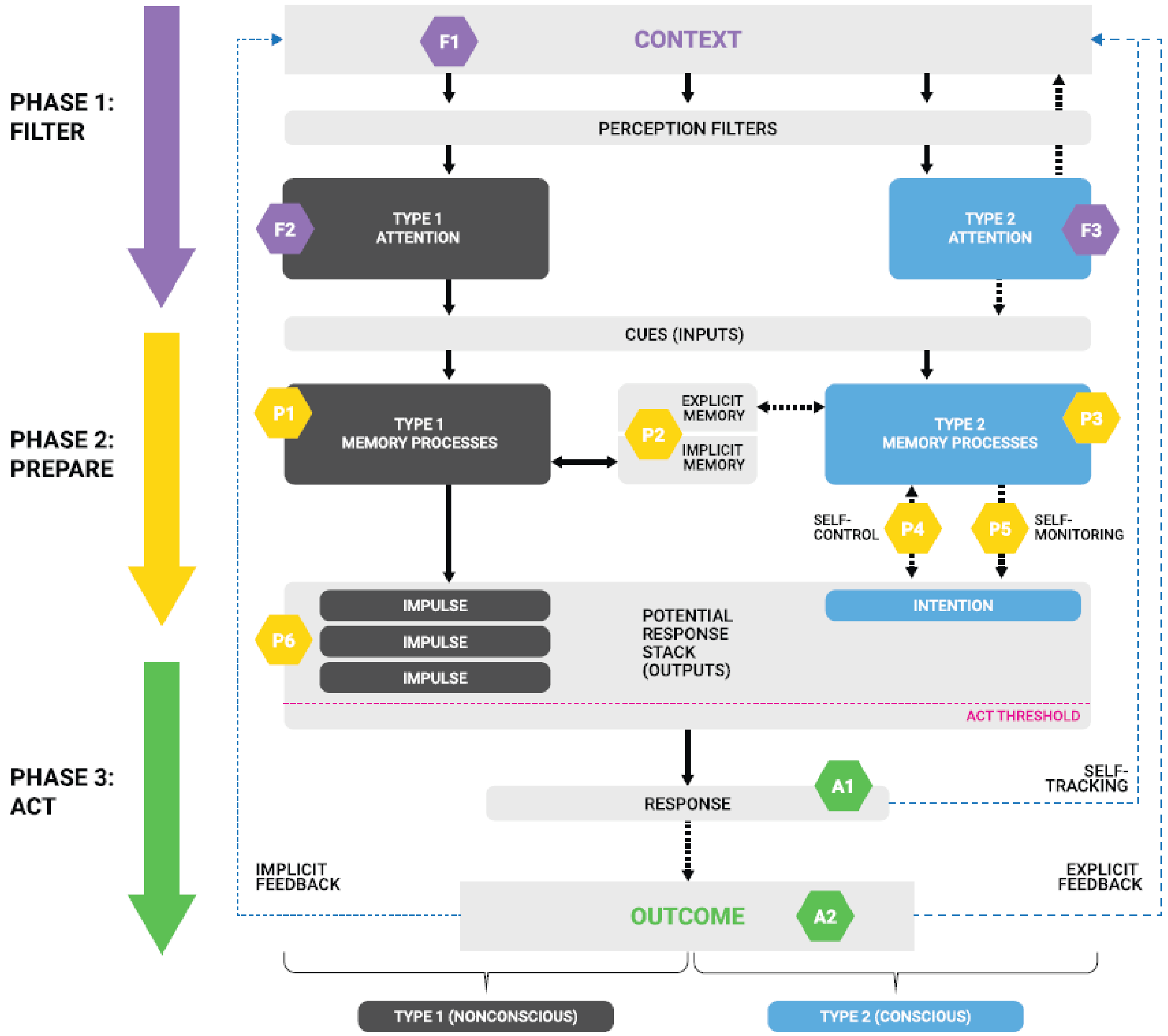

Figure 3: Habit Alteration Model. Reused from Pinder et al.[27] with permission (Copyright (c) 2018 Charlie Pinder, Jo Vermeulen, Benjamin R. Cowan, Russell Beale). The Figure is explained by Pinder et al. as follows: "context cues (F1) are filtered by both Type 1 (F2) and Type 2 (F3) attentional processes to form a set of inputs to subsequent memory processes of Type 1 (P1) and Type 2 (P3). These generate competing drivers to act (impulses and intentions) to populate the Potential Response stack (P6). These may be overridden by self-control (P4), and may face competition from intentions created by self monitoring (P5). The resulting behavioural response (A1) and (optional) outcome (A2) feed back into the model. Solid lines indicate processes that always run; dashed lines indicate optional processes" (Pinder et al.[27], pp.20).

Use and effectiveness: First published in 2018, the HAM has not yet been widely used in behaviour change interventions.

2.4 Summary and Recommendations

Table 3 below compares the behaviour change models reviewed above in terms of their applicability to problems or interventions associated with improving IAQ in offices. Based on existing understandings of behaviours that affect IAQ in offices (Section 2.1), we suggest the Behaviour Change Wheel and Habit Alteration Model may have the greatest potential applicability to issues around indoor air quality, but note that these two models have not yet been widely deployed.

Table 3: Comparison of applicability of behaviour change models to interventions around improving IAQ in offices

Model	Relevance to behaviour change interventions concerned with IAQ in offices	Justification
Transtheoretical Model	LOWER	The Transtheoretical Model is well placed to target unwanted individual behaviours, (e.g. quitting smoking or healthy eating), but the focus on individual behaviour/ reflection means it may be less applicable to situations where behaviours are often habitual and socially negotiated (e.g. interactions with building controls in shared offices[16]). In this respect we suggest it may be less applicable to problems associated with IAQ than the other models reviewed.
Fogg's Behaviour Model	MEDIUM	Fogg's focus on technology design is relevant to indoor air quality, owing to increases in the availability of affordable air quality sensors and use of technology in behaviour change interventions.[32–34] The model provides substantial guidance to designers wishing to design persuasive features into technical systems. However the focus is concerned primarily with individual behaviours rather than the context in which actions take place.[27] In this respect it may not be as applicable to habitual and socially negotiated behaviours compared to the Behaviour Change Wheel and Habit Alteration Model.
Behaviour Change Wheel	HIGHER	The Behaviour Change Wheel makes specific provision for (1) the context in which behaviours take place and (2) the outcome of previous interventions (if applicable). These factors make it potentially very applicable to issues around IAQ, e.g. motivating healthier ventilation, cleaning or printing practices. However the model has not yet been applied to technology design and further work is required to determine its applicability.
Habit Alteration Model (HAM)	HIGHER	The HAM synthesises proven attributes from existing theories,[27] and focuses on the broader context of habits rather than individual behaviours. Given many actions associated with IAQ such as opening windows, doors, adjusting radiators, cleaning etc are habitual, this model potentially has relevance for behaviour change in shared spaces. However similar to the Behaviour Change Wheel, the HAM is a very recent model and is also not yet validated or tested.

Incorporation of behaviour change models in the design of IAQ interventions offers potential to extend the influence of the interventions on behaviours beyond the office. This might involve designing interventions which seek to reduce one's exposure to pollution throughout the day, e.g. using wearable air quality monitors to inform commuting options which minimise exposure to polluted roads, adopting positive IAQ behaviours at work and home, and affecting purchasing behaviour of cleaning products, paints and plastics etc.

3 Systematic review: Methodology

The literature search methodology for this systematic review involved searching three major databases of scientific literature for empirical studies which describe technical or behavioural interventions aimed at raising awareness or affecting the behaviour of occupants with respect to IAQ. Searches for relevant articles were performed between June and August of 2018 using: (1) Scopus[(1)], (2) Association for Computing Machinery (ACM) Digital Library[(2)] and (3) Google Scholar[(3)]. The choice of databases was to ensure good coverage across various fields. Scopus, is the *"largest abstract and citation database of peer-reviewed literature"*[(1)] the ACM Digital Library archives conference proceedings from numerous technology-related conferences including the International Conference on Persuasive Computing, while Google Scholar is estimated to provide an 80-90% coverage of scholarly articles published in English.[44] The search was conducted sequentially (Scopus first, ACM second, Google Scholar third), and only unique inclusions from each database are listed. Additionally the reference lists of all papers were scoured for further relevant papers. The number of results per search term, per database used is available in Appendix A.

To provide adequate scoping, and a focus on human behaviour, the following studies were **excluded:**

- Studies of indoor air quality in the developing world (i.e. biomass burning or open fires indoors).
- Testing or deployment of interventions or retrofits for IAQ which are NOT in the control of occupants, e.g. air filtrations systems, mechanical ventilation retrofits, bio-remediation through plants etc.
- Where two or more papers report on the same intervention/technology, only the most recent is reviewed (e.g. inAir[49]).
- Studies which describe IAQ monitoring technology which have been evaluated with respect to technical function but not yet evaluated with humans (e.g.[45,46,47]).
- Studies of smoking reduction/cessation unless they are specifically concerned with improving indoor air quality through reducing indoor smoking.
- Studies not written in English.
- Studies more than 20 years old.
- Studies not published in peer-reviewed venues (e.g. websites, media articles etc).

1 https://elsevier.com/solutions/scopus
2 https://dl.acm.org/
3 https://scholar.google.com

4 Systematic review: Results

Compared to the numerous behaviour change interventions deployed with the purpose of encouraging health, diet, physical exercise, pro-environmental behaviours and ethical consumption (listed in Table 1, above), a remarkably small number of studies relate specifically to behaviours within users' sphere of influence for IAQ: Fifteen studies were found where an intervention was deployed with the intention of raising awareness and/or changing behaviour of users with respect to IAQ. Table 4 lists each of the papers found through the review process in terms of: a summary of the intervention design, the pollutants measured, type of feedback provided (to occupants), location, details of deployment, purpose of deployment, the behaviour change theories employed (if any) and an overview of the key findings.

Table 4 Papers captured through literature review search methodology: Behaviour change interventions within users' sphere of influence for indoor air quality

Paper	Intervention Design / Artefact deployed	Pollutants measured	Feedback	Place	Deployment	Purpose of deployment / Research question	Behaviour change theory	Key findings
Fang et al. 2016[1]	AirSense- detects pollution events, identifies pollution source, provides suggestions for remedial action. Information accessed via smartphone application. Post-deployment interviews regarding use of the app. No control condition.	PM, VOCs (non-specific), temperature, humidity.	Smartphone app: Graphical feedback on each parameter. Weekly IAQ report on both (a) individual parameters and (b) source of pollution events (smoking, spraying pesticides, cooking).	Home	3 families in which one member smokes. 10 weeks per deployment.	Testing for: (1) Accuracy of pollutant prediction (2) Whether increase in occupant IAQ awareness.	None specified	* Correlation of readings to subjective well-being state * Device acted as motivational trigger for better IAQ behaviours- ventilate, operate range hood etc. * Increased self-reported IAQ competence.
Kim 2018[48]	Analysis of users' reflections on using one of three indoor air quality monitoring devices: Neatmo, Awair and Foobot.	Multiple	Data available via smartphone app and web browser.	Home	729 product reviews of home indoor air quality monitors (Amazon reviews).	How is IAQ information constructed, performed and used by humans?	Sense making theory	* Evidence of behavioural changes to remove IAQ pollutants * Health concerns and allergies trigger IAQ information needs * Reliability and interpretability of IAQ info affects sense-making.
Kim et al. 2013[49]	InAir- a tool for visualising and sharing air quality information with ones' network of contacts. Post-deployment interviews on use of InAir, no control condition.	Particulate matter	Situated display in the home.	Home	4 month deployment, 6 households.	Does improved IAQ awareness leads to healthier IAQ behaviours?	None specified	* Awareness improved by intervention * Facilitated reflection upon air quality * Caused durable changes in behaviour
Wong-Parodi et al. 2018[50]	The Speck PM2.5 in-home display and supporting web-based platform offering information for how to reduce IAQ health risks. Sensor offered to public for free at local library.	Particulate matter	"Speck" sensor. In-home display of PM2.5 with LCD screen with web-based platform with supporting information	Homes	* 26 participants * 1 device per participant * 3 week deployment.	Does use of the Speck sensor empower people to reduce their risk of exposure to indoor pollutants?	None specified	* Increase in self-reported IAQ knowledge * Increase in self-reported confidence in mitigating IAQ risks * Self-reported use of behavioural adaptation to mitigate risks associated with indoor pollutants * Participants prompted their family/friends to consider IAQ.
Wilson et al. 2013[51]	Intervention to reduce smoking indoors. Informational packs, four home visits and motivational interview. 2x 24hour PM recordings taken and presented to participants during the second home visit.	Particulate matter	Historical readings of indoor PM shown to participants by the researcher including amount of time PM above health guidelines	Home	* 59 mothers who smoke participated * 1 month long intervention * PM data provided to participants during second home visit.	Does providing mothers who smoke with personalised IAQ information affect household IAQ?	None specified	* Self-described change in smoking behaviours * Quantitative reduction in PM2.5 during final recording indicative intervention reduced smoking indoors and improved IAQ.
Rosen et al. 2015[52]	Intervention to reduce smoking indoors. Real time PM feedback through commercially available air quality monitors	Particulate matter	Continuous display of PM2.5 concentration using Dylos or TSI Sidepak air quality monitors	Home	* 29 families who smoke participated * Dylos or Sidepak monitors deployed for 7 days.	Feasibility study into using continuous PM monitoring to persuade families not to smoke indoors.	None specified	* Difficult for participants (and researchers) to isolate tobacco smoke events from other indoor pollution events (e.g. cooking, cleaning) * Limited potential for continuous monitoring of PM to inform about tobacco smoke specifically.
Morgan et al. 2016[53]	Intervention to reduce smoking while pregnant. Participants were given a Dylos PM monitor to self-measure PM in the home (no immediate feedback available).	Particulate matter	IAQ results from Dylos sensor collated by research team and presented to participants in interviews	Home	* 39 women who smoke participated * Self-monitoring of indoor conditions using Dylos air quality monitor.	Does self-monitoring of IAQ parameters motivate pregnant smokers change smoking habits?	None specified	* Providing IAQ measurements can support changes to smoking behaviour in the home for some individuals * But did not measurably improve quit-rates.
Klepsis et al. 2013[54]	Intervention to reduce second-hand smoke indoors. Visual and auditory cues based on IAQ to prompt immediate action to change smoking habits.	Particulate matter	Dylos air quality monitor deployed in homes with laptop showing real-time IAQ display Pre and post-intervention interviews	Home	* 3 homes with occupants who smoke * 9-15 days- including baseline (monitoring but no feedback) and intervention (monitoring with visual and audio feedback) periods.	Can visual and auditory cues based on PM readings prompt users to change smoking behaviour?	None specified	* Two of the three families modified behaviour by ventilating when smoking, smoking outdoors or smoking less * One family expressed reluctance to change.
Jensen et al. 2016[55]	CO_2 meter deployed with households to determine whether CO_2 feedback causes householders to adopt "shock ventilation" (completely opening windows for 5 minutes, two to four times per day).	CO_2	Traffic light CO_2 meter. Few details given of the device	Home	* 12 households * Effect of CO_2 feedback on energy use tested after one month deployment.	Does providing information on CO_2 affect energy use through provoking "shock ventilation" behaviour?	None specified	* Adopters of CO_2 meter found to adopt shock ventilation behaviour. * Energy savings between 5-10%.

Paper	Intervention Design / Artefact deployed	Pollutants measured	Feedback	Place	Deployment	Purpose of deployment / Research question	Behaviour change theory	Key findings
Geelan et al. 2008[56]	(1) ventilation advice only (2) ventilation advice + CO_2 warning device (3) ventilation advice + a teaching package (4) no intervention (control). CO_2 concentration measured, follow-up questionnaires.	CO_2	Situated box with sensor, digital reading and red LED light which illuminates when CO_2 exceeds >1,200ppm	Middle school	* 20 classes per intervention type. * 1 week intervention, av. CO_2 levels and behaviour measured 2-3 before, and 0 and 6 weeks post intervention.	Does CO_2 feedback lead to improved ventilation behaviour?	None specified	* 95% of teachers considered CO_2 warning device useful. * Significant reduction in CO_2 concentration of classrooms with ventilation advice + CO_2 warning intervention at 0 and 6 weeks after intervention, compared to control classrooms.
Heebøl et al. 2018[57]	(1) Mechanical ventilation retrofit, (2) Automated window opening, (3) Automated window opening + heat recovery, (4) a visual display of CO_2 (5) no intervention (control).	CO_2	A visual CO_2 feedback display indicating when the CO_2 concentration was high	Elementary school	* 5 classrooms * 1 classroom per intervention type * Effect of CO_2 feedback monitored after 4 months.	Does CO_2 feedback lead to improved ventilation behaviour/reduce CO_2 level?	None specified	* Visual CO_2 feedback increased window opening behaviour relative to control condition in the short term * Yet a re-visit to the school 12 months later found the behaviour change had not lasted.
Rigger et al. 2015[58]	(1) Deployment of an art-based visualisation of indoor CO_2 concentration (2) No intervention (control) Post-deployment questionnaires	CO_2, temperature, humidity (only CO_2 visualised)	A black and white portrait of Albert Einstein which turns progressively green with increasing indoor CO_2.	Secondary school	* 8 week deployment * 10 classrooms. * 255 classes held during deployment. * A/B testing. A = treatment, B = Control.	Does art-based CO_2 feedback lead to improved ventilation behaviour?	Theory of self-efficacy	* Treatment group relative to control group recorded: higher subjective wellbeing, higher "perceived level of engagement in room climate" and lower average CO_2 concentration.
Wargocki et al. 2015[59]	(1) CO_2 feedback system deployed in a classroom (2) no intervention (control)	CO_2	Thermometer-style CO_2 indicator depicting a student (adjacent to the readings) who becomes increasingly sleepier as CO_2 increases.	Elementary school	* Four pairs of classrooms monitored * One week per intervention.	Does CO_2 feedback lead to improved ventilation behaviour?	None specified	Visual CO_2 display increased window opening frequency leading to reduced CO_2 levels.
Toftum et al. 2016[60]	(1) CO_2 feedback + pupils made to open windows when CO_2 >1000ppm (2) CO_2 feedback + pupils recommended to open windows when CO_2 >1000ppm (3) Pupils to open windows for 5 minutes during lecture (4) pupils to open all windows before leaving classroom for break.	CO_2	Visual CO_2 indicator (few details given)	Elementary school	* Eight classes * One scenario per class (see first column for scenarios) * Two week intervention period * One week baseline monitoring before intervention.	Does CO_2 feedback lead to improved ventilation behaviour?	None specified	* Visual CO_2 display unit led to modified behaviour and 40-60% reduction in the time that CO_2 concentrations were above 1000ppm.
Mathur et al. 2015[61]	IAQ visualised alongside multiple parameters on an office-situated TV display: "Quantified Office"	CO_2	"Air Quality" provided as a number (CO_2 in ppm) on a screen alongside multiple environmental parameters (temperature, noise) and self-input parameters (e.g. mood, activity).	Office	* Four month deployment * 70 employees surveyed, 20 semi-structured interviews	Which of the "Quantified office" parameters (temp, noise, IAQ, mood, activity) is of most relevance and interest to office occupants?	None specified	* Air quality was the most preferred of the environmental metrics displayed * Quantification of air quality had no effect on the behaviour of employees * Quantification can be considered disadvantageous if users lack the capacity to act on it.

4.1 Overview of studies

All of the 15 studies had an experimental design which involved the provision of sensor-based quantifications of IAQ as means of improving occupant awareness and/or motivating healthier IAQ behaviour. The majority of interventions relate to the home (nine studies) compared to the school (five studies) or the office (one study).

Home: The studies of IAQ interventions in the home can be divided into: (1) four studies analysing how occupants understand and use IAQ feedback to base decisions[1,48–50]; (2) one study determining the effect of CO_2 feedback on ventilation behaviour[55] and (3) four studies with the specific intention of improving IAQ through motivating users to reduce cigarette smoking indoors.[51–54] Findings suggest IAQ feedback can improve occupant awareness and inform healthier remedial actions in the home.[1,49] For example, "InAir" was found to improve awareness of IAQ.[49] Fang et al.[1] and Wong-Parodi et al.[50] both found their IAQ feedback interventions increased self-reported confidence in mitigating IAQ risks and encouraged behavioural adaptation to mitigate IAQ risks. On the other hand, although IAQ feedback can foster healthier IAQ behaviour,[1,49,50] simply making information available is not a sufficient pre-requisite for users to make sense of the information.[48] Rosen et al.[52] found participants had difficulty determining which spikes in their air quality data were related to cigarettes specifically, compared to other sources. These findings suggest IAQ information may be less useful if it is not clearly related to actions available to occupants to improve it.

Schools: Each of the five IAQ interventions in schools involved deployments of IAQ monitors (specifically CO_2 monitors) with the intention of determining the effect of CO_2 feedback on ventilation behaviour.[56–60]One study, Rigger et al.[58] employed an artistic representation of CO_2, with a portrait of Albert Einstein's face becoming progressively more sickly (green in colour) as CO_2 rose. The other four studies use visualisations of CO_2 concentration as a number, in parts per million. All five of the studies found CO_2 feedback lead to healthier ventilation behaviour in classrooms, particularly when deployed as part of a teaching package or with further information. However only Heebøl et al.[57] measured the persistence of behaviours over time and found that while CO_2 feedback caused behaviour change initially, the change did not persist and diminished after four months.

Offices: Only one of the 15 interventions was based in offices. Several proof-of-concepts exist for office-based IAQ awareness or behaviour change interventions,[45–47,62] however these have not yet been evaluated with users or with respect to behaviour change potential and thus were thus not included in the review. In their "Quantified Office" deployment, Mathur et al.[61] visualised IAQ on a screen in a break-out space of an office alongside multiple parameters including noise, temperature and self-input parameters such as mood and activity. The study found office occupants preferred the quantification of IAQ over that of temperature and noise, but that none of the environmental metrics visualised had any effect on user behaviour.[61] The quantifications were found to be disadvantageous if users lacked the capacity to act on them.[61]

4.2 Overall similarities between studies

Potential to influence behaviour: Almost all of the 15 studies found some suggestion that providing occupants with IAQ information leads to greater awareness and/or healthier IAQ behaviours (Table 4), however this is contingent upon users' being able to interpret and act on the information provided.[48,61] It is not possible to quantify the behaviour changes observed in the studies, as none of the 15 studies reported effect sizes, and the majority did not seek to *instigate* behaviour changes specifically, being more concerned with understanding how occupants used and appropriated IAQ feedback devices and whether behaviours changed organically (Table 4).

Short term: All but three of the 15 studies (Table 4) involved a relatively short deployment, with only Kim et al.[49] Mathur et al.[61] (four months) and Heebøl et al.[57] (follow up visits four months following cessation of the two week interventions) employing interventions longer than 10 weeks. The deployment period of the remaining 12 interventions vary in length from one week (with follow-ups)[56] to 10 weeks.[1] In their longitudinal study, Heebøl found CO_2 concentrations in the classroom which had received the CO_2 feedback device did not remain low after four months, indicating the window-opening behaviour change had not persisted. Kim et al.[49] on the other hand reports that the InAir feedback resulted in alterations to habits and does not report the behaviour changes decreased over the four months. Mathur et al.[61] found office occupants appreciated feedback on their IAQ, but that the feedback did not measurably affect behaviour.

Not a specific behaviour change intent: Only four of the 15 studies[51–54] report a specific intention to change behaviour. These four studies relate to improving IAQ through reducing smoking indoors. Three[51,53,54] of the four report their interventions reduced indoor smoking, while one found less of an effect due to users having difficulty isolating smoking events from other indoor pollution events.[52] The remaining 11 interventions were deployed with a wish to understand how IAQ quantifications were used and appropriated in users' everyday lives,[1,48–50,58,61] but lacked a specific intention to persuade them towards a given behaviour.[56,57,59,60]

Minimal use of theory: Only two of the 15 studies reviewed employed a theoretical foundation.[48,58] Kim[48] used sense-making theory to understand the ways in which people made sense of air quality monitors. Sense-making theory understands information seeking as a process which occurs in a given space, time and socio-cultural context and is understood through metaphors including gap, bridge and outcome[48,63] Rigger et al.[58] used the theory of self-efficacy in the design of their study. Self-efficacy theory suggests that people are likely to have little motivation to act or persevere with a behaviour or course of action unless they believe their actions are capable of producing a desirable outcome.[64] Rigger et al. assumed students would not be motivated to engage with a system which visualises IAQ parameters over which they do not have control, and thus chose not to include humidity in their visualisation.[58]

5 Recommendations for the design of IAQ-related behaviour change interventions

Based on attributes of the 15 studies included in our systematic review (Table 4) and on findings from meta-reviews of behaviour change interventions in related areas (Table 1), the following recommendations are made for the design of technical systems aimed at improving IAQ awareness and/or affecting IAQ behaviour. While the potential for each of the subsequent design suggestions to affect behaviour needs to be tested and validated, the following represents a starting point for distilling a list of attributes for the design of IAQ interventions.

Actionable Information (Self-efficacy): We recommend systems aimed at affecting IAQ behaviour should ensure information is actionable, i.e. occupants must feel capable of affecting the IAQ parameters visualised through their own actions. Self-efficacy theory epitomises the need for actionable information, suggesting people will not persevere with an action if they do not think it will lead to a desired outcome.[58] Almost all the interventions which emphasised a direct link between information (IAQ feedback) and remedial actions (i.e. open doors/windows) reported increased awareness/improved ventilation behaviour.[1,55–57,59,60] On the other hand, Kim[48] found many owners of IAQ monitors which visualised multiple parameters simultaneously had difficulty correlating the IAQ information provided, to the health concerns which had prompted the purchase in the first place; compromising the value of the monitors.[48] Rosen et al.[52] whose participants had difficulty isolating smoking episodes from other indoor pollution events shown in their IAQ feedback, did not report the same level of success as the other studies aimed at reduce indoor smoking through IAQ feedback.[51,53,54] Accordingly, we suggest that designers of IAQ interventions take care such that only "actionable information" is provided, in accordance with self-efficacy theory.[64]

Human analogies for IAQ effects: We suggest correlating IAQ information to work performance using human analogies may be a useful means of engaging users with IAQ. Two studies which report positive effects on ventilation behaviour employ a specific visual correlation between cause and effect: Rigger et al.[58] designed an art-based installation of Albert Einstein's face, which becomes green in colour with increasing CO_2 concentration. Wargocki et al.[59] designed a wall-based CO_2 feedback display incorporating pictures of a child who gradually slumps over as CO_2 concentrations rise.[59] Both studies report positive ventilation behaviour changes[58,59] and suggest human-based metaphors may serve to connect people with IAQ on a more emotional level and offer greater promise than numbers alone.[58] Lo et al.[23] (Table 1) additionally found behaviour change interventions utilising tailored persuasive communication were more effective than whose which did not. We suggest human analogies for IAQ information can provide a visual link between cause and effect.

Situated: Because actions affecting air quality in offices can be socially negotiated,[16] we recommend systems for IAQ feedback take the form of situated displays, rather than information made available only to individuals through an app. The "Quantified Office" display[61], which was located in a breakout space, acted as a talking point for colleagues who would interact with the system together and collaboratively make sense of the information.[61] Providing situated IAQ feedback in multiple locations facilitates social comparison where users can compare their air quality to their colleagues' in separate rooms or in different parts of an open plan office. Social comparison is found to facilitate behaviour change by two meta-reviews[20,22] (Table 1). Accordingly, we suggest that in multi-occupant spaces, IAQ feedback be provided in the form of situated displays at multiple locations, where this is practicable. Personal exposure monitors and wearable air quality sensors are well suited to individuals wishing to understand their exposure to pollutants outside the office, such as on breaks from work or during commutes. However the continuous wearing and need for regular recharging and downloading means wearable monitors may be less suitable for continuous IAQ monitoring in offices compared to office-situated monitors.

Minimal cues and unobtrusive: Because interactions with building controls are motivated primarily by comfort,[13] IAQ in shared spaces may not be an issue during warmer months when windows are left open for cooling.[58] Accordingly, we recommend systems should be unobtrusive and provide minimal cues, rather than regular notifications or requirements for consistent engagement. A number of studies reviewed (Table 4) found that even minimal visual cues from a system can be sufficient to motivate a behaviour such as opening a window[56,58,59] or to check suggestions of how to improve air quality on a smartphone app.[1] The "quantified office" display was situated in a breakout space and allowed occupants to interact with it on their own terms rather than requiring attention from users.[61] Minimal cues means providing prompts (e.g. open a window if CO_2 or VOCs exceeds a given value, or to take a break if seated continuously) to be activated only when required, rather than providing regular updates.

Supporting information: We recommend supporting information is provided with IAQ feedback. This might include information cards detailing the causes, effects and remedies for poor IAQ, and/or briefings from the installer of IAQ monitors with this type of information (e.g. Geelen et al.[56]). Findings from papers reviewed in this systematic review (Table 4) suggest that simply making information available does not guarantee it will be understood, making a case for the provision of further information to occupants.[48,61]

Based upon theory: Several meta-reviews of behaviour change interventions focusing on health and pro-environmental behaviour (Table 1) found that studies which were grounded in behaviour change theories[17–20] or which used specific behaviour change techniques[22] were more effective than those which did not. We suggest behaviour change interventions should be informed by behaviour change theories or models. While the choice of specific behaviour change theories should be dependent on context of any given intervention,[18] this research suggests that models such as the Behaviour Change Wheel and Habit Alteration Model hold promise for the design of IAQ-related behaviour change interventions.

6 Conclusions and limitations

Knowledge work (i.e. office work) accounts for over 80% of the UK's GDP.[65] Poor IAQ can impair cognitive performance,[2,4,14] natural ventilation remains a common building typology,[66] and yet the role of human efficacy as a solution to poor IAQ is underexplored relative to engineering solutions.[11] This report has sought to understand means of maximising user efficacy in realising better IAQ as far as practicable within existing building constraints.

Based on (1) an understanding of the existing drivers of human interactions with building controls in naturally ventilated buildings, (2) a review of four behaviour change models or "recipes" applicable to complex problems, and (3) the systematic review, this report makes the following recommendations for the design of IAQ interventions:

- *Actionable information (Self-efficacy)*: Care should be taken to ensure self-efficacy, i.e. users' actions are capable of influencing the parameters measured.
- *Human analogies for IAQ effects*: Human analogies (e.g. an office worker becoming progressively sleepier as air quality declines) may be used to allow occupants to better correlate poor IAQ to the corresponding cognitive performance effects and increase the relevance of IAQ interventions. Human analogies offer greater promise for engagement with IAQ than quantification of numbers alone.
- *Situated displays*: In shared spaces such as multi-occupant offices, homes and classrooms, IAQ information provided on a situated display allows for shared sense-making compared to personal exposure monitoring or providing information only on discrete devices such as smart phones or web browsers. The physical presence of monitors in the office may additionally serve to legitimise the information provided. Wearable air quality monitors may instead be used to inform commuting options and timing/route choice of active work breaks.
- *Minimal cues and unobtrusive*: IAQ feedback interventions should be unobtrusive, glance-able and seek to affect behaviour through minimal cues, rather than attempt to maintain a more involved engagement with the device.

– *Supporting information:* Simply making information available does not guarantee it will be understood, thus interventions should entail supporting information detailing the causes, effects and means of influencing any IAQ parameters which are visualised. Supporting information may be provided as a paper supplement to interventions deployed, or a briefing from installers of IAQ monitors.

– *Theory-based:* While further research is necessary, this report suggests behaviour change interventions should be based upon behavioural theory. Literature suggests behaviour change interventions based on theory are more effective than those which are not. Behaviour change models such as the Behaviour Change Wheel and Habit Alteration Model hold promise for the design of IAQ-related behaviour change interventions (Section 2.4).

6.1 Limitations and future work

While every effort has been made to capture all relevant papers, it is possible that some relevant articles have not been captured. Indirect IAQ benefits of other behaviour change interventions are also possible e.g. interventions aimed at encouraging ethical consumption may lead to indirect benefits to air quality through the use of eco-friendly detergents or deodorants, smoking cessation and this possibility has not been a focus of this research.

The scope of this present meta-review has been purposefully limited to only those IAQ behaviour change interventions which are in the immediate sphere of influence of building occupants. We suggest future research additionally explores interventions to affect IAQ by focusing on the persuasion of different groups of people associated with building design and operation, e.g. building managers, estates and facilities teams, company managers. These might include:

- Influencing decision makers to specify low VOC building materials and finishes in building renovations and retrofits
- Influencing procurement in purchasing low VOC furniture and office equipment
- Influencing commercial cleaning companies to purchase and use low-emission cleaning products
- Influencing planners and building designers to adopt certification and rating systems which consider operational IAQ issues e.g. WELL Certification,[67] and best practice certification schemes for refurbishments, retrofits and new builds, e.g. LEED,[68] BREEAM.[69]

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Appendix A on overleaf

8 Appendix A

8.1 Meta-review search terms used

	SCOPUS		ACM DIGITAL LIBRARY		GOOGLE SCHOLAR		
Search terms	**Total articles found**	**Unique inclusions in meta-review**	**Total articles found**	**Unique inclusions in meta-review**	**Total articles found**	**Unique inclusions in meta-review**	**Notes**
“behaviour change” + “indoor air quality	12	2	24	1	596	0	Perused all
“behaviour change” + office + health	235	0	2	0	17,900	1	Perused first 500
“sick building syndrome” + “behaviour change”	14	0	173	0	144	1	Perused all
Office + “behaviour change”- search in within results for “air quality”	7	0	N/A	0	N/A	0	Scholar does not “search within”
Office + “behaviour change”- search in within results for “pollution”	2	0	N/A		N/A	0	Scholar does not “search within”
“behaviour change” + co2	55	0	148	0	5,900	0	Perused first 500
Persuasive + “air quality”	9	0	190	1	290	0	Perused all
“indoor air quality” + feedback	71	2	2	0	17,800	3	Perused first 500
“persuasive design” + air quality	0	0	1	0	1,520	0	Perused first 500
“persuasive design” + workplace	47	0	12	0	465	0	Perused all
“behaviour change” + cleaning products	8	0	0	0	414	0	Perused all
“behaviour change” + VOC	6	0	1	0	75	0	Perused all
“behaviour change” + “persuasive” + “indoor air quality”	1	1	0	0	60	0	Perused all
“air quality monitor” persuasive	0	0	0	0	67	3	Perused all
“volatile organic compounds” + behaviour change	14	0	65	0	525	0	Perused all
TOTAL	**481**	**5**	**618**	**2**	**45,756**	**8**	**Total inclusions: 15**

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