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Indoor living plants' effects on an office environment

Structured Abstract

Purpose
The use of indoor living plants for enhancement of indoor relative humidity and the general environment of a large, modern, open plan office building; are studied using a mixed-methods paradigm.

Design/methodology/approach
The quantitative element involved designated experimental and control zones within the building, selected using orientation, user density, and users' work roles criteria. For a period of six months, relative humidity was monitored using data loggers at 30-minute intervals and volatile organic compounds (VOCs) were measured using air sampling. Qualitative 'perception data' of the building's users, were collected via a structured questionnaire survey among both experimental and control zones.

Findings
Study findings include that living plants did not achieve the positive effect on relative humidity predicted by (a-priori) theoretical calculations; and that building users' perceived improvements to indoor relative humidity, temperature, and background noise levels, were minimal. The strongest perceived improvement was for work environment aesthetics. Findings demonstrate the potential of indoor plants to reduce carbon emissions of the [as] built environment, through elimination or reduction of energy use and capital-intensive humidification air-conditioning systems.

Originality/value
The study's practical value lies in its unique application of (mainly laboratory-derived) existing theory in a real-life work environment.

Keywords: Indoor air quality, Comfort, Temperature, Volatile organic compounds, Living plants, Relative humidity

Article classification: research paper

1. Introduction

Indoor air quality (IAQ) of commercial and domestic buildings has been widely researched over the past three decades. Studies have focussed on aspects such as respiratory irritants, for instance, nitrogen and sulphur dioxides (Taylor, 1996; Chao, 2001; Meininghaus *et al*, 2003; Baur *et al*, 2012); carcinogens such as asbestos (Reynolds *et al*, 1994; Latif *et al*, 2011; and other volatile organic compounds (VOCs) such as formaldehyde (Wolverton and McDonald, 1982; Ekberg, 1994; Meininghaus *et al*, 2003; Zuraimi *et al*, 2006; Rios *et al*, 2009; Salonen *et al*, 2009). Research has also investigated optimum percentage relative humidity (%*RH*) of indoor air (Wyon *et al.*, 2002; Wolkoff and Kjaergaard, 2007; Wan *et al.*, 2009); this being the ratio of percentage water vapour held within it to its equivalent 'saturation level' at a given

44   temperature. This study extends these concepts in terms of their being influenced by the

45   introduction of indoor living plants, in a large modern building. The building users' perceptions

46   of their internal environment in relation to these plants, are also considered.

47

48   Typically, humidity is not classified as an indoor air contaminant (Nagda and Hodgson, 2001).

49   Nonetheless, many studies (for example, Wyon *et al.*, 2002; Wolkoff and Kjaergaard, 2007;

50   Wan *et al.*, 2009) and building design guides (CIBSE, 2005; 2006), recommended that indoor

51   %*RH* should be in the range of 40-60%. Beyond these parameters there are negative health

52   implications for building inhabitants as described in the literature review later; and for levels

53   above the maximum recommended *RH* value especially, there are additional risks of building

54   (components') damage. Examples of this include material expansion, salt staining, corrosion,

55   pattern staining, interstitial condensation, and fungal growth (CIBSE 2005; Hetreed, 2008;

56   Oxley and Gobert, 2011).

57

58   Mechanical humidity control is available, but the use of living indoor plants for this purpose is

59   much less researched or understood (existing studies include Costa and James, 1995;

60   Wolverton and Wolverton, 1996). The primary aim of this study therefore, is to investigate the

61   potential of plants to supplement indoor air relative humidity (*RH*), during cold winter months.

62   This is important because decreasing air temperature reduces the ability of air to hold water

63   vapour. Hence, as cold air from ventilation is heated up to indoor temperature, its ability to

64   retain water vapour increases, resulting in a proportionate decrease in its relative humidity.

65   This could lead to prolonged periods of below recommended indoor %*RH* and the resultant

66   associated problems such as occupant discomfort (addressed in the literature review below).

67   The study was undertaken empirically, where indoor %*RH* was measured over a period of six

68   months in a large (approximately 10,300m^2 gross floor area), modern 'atrium design' office

69   building. The building was selected as a case study, because its facilities management were

70   investigating low carbon and sustainable methods of humidification, during the winter months.

71   An objective linked to this aim, was to compare these empirical data with those of theoretical

72   a-priori calculations. The latter 'predicted' the humidification effect of indoor plants as a

73   product of their plant transpiration rates and foliage area, to identify an 'ideal' indoor planting

74   density. The building users' perceptions of (the introduction of) indoor plants were sampled in

75   relation to humidity, temperature, noise, light, space, aesthetics, and working environment

76   privacy.

77

78 2. Literature review

79   Indoor relative humidity $<30\%RH$ is only acceptable for limited periods of time, otherwise,

80   building occupants can become prone to allergies and respiratory illnesses due to dust and other

81   airborne particles (CIBSE, 2006). At significantly low levels of humidity, Bron *et al.* (2004)

82   reported a change in the precorneal tear film in humans' eyes, that results in discomfort (dry

83   eyes), while Doty *et al.* (2004) reported sensory irritation of the upper airways. Wyon *et al.*

84   (2002) identified that human skin exposed to $15\%RH$ was significantly drier than the same skin

85   exposed to $35\%RH$ and associated this kind of health symptom, with the classic definition of

86   sick building syndrome.

87

88   More recently, Wolkoff and Kjaergarrd (2007) confirmed that the health implications of indoor

89   humidity are complex. Further, that these have not been widely investigated due to the

90   complicated influence of RH on the combined impact of VOCs and other indoor air

91   contaminants. Low humidity levels are also associated with susceptibility to electrostatic

92   shocks. Human body voltage is a function of indoor air such that a decline in $\%RH$ yields an

93   increase in body voltage (CIBSE, 2006) – a situation exacerbated in buildings with a

94   combination of underfloor heating and carpet flooring due to sustained dryness of carpets.

95

96   Higher *RH* levels are associated with poor ventilation and/or significant evaporation from

97   moisture sources (such as bathrooms, kitchens, and indoor plants). High humidity can also lead

98   to surface (or interstitial) condensation on (or within) external walls and other building fabric

99   whose temperature ≤ the prevailing dew point. Mould, microbial, and house dust mite growth

100   often result from this (CIBSE, 2005). In colder climates such as those typical in Northern

101   Europe, buildings where no humidification equipment is installed can experience prolonged

102   periods where indoor *RH* falls below the recommended lower value of 40% *RH*. This happens

103   because the ability of air to hold water vapour decreases commensurate with declining air

104   temperature. Resultantly, as cold ventilation air is heated to indoor temperature, its enhanced

105   ability to retain water vapour means that its *RH* decreases proportionately.

106

107   Mechanical humidification equipment (MHE) can help counter this situation, but in most

108   European Union countries, indoor %*RH* levels are not defined in statute so (due to financial

109   implications), most buildings do not make use of such. That is, mechanical humidification is

110   typically controlled by the heating and injection of steam into supply air (CIBSE, 2005); which

111   calls for significant MHE capital outlay and high running costs. Humidification also has a

112   negative impact on a building's carbon 'footprint' because for each 10 kg/hr of water vapour

113   produced, circa 7.22kWh of gas is consumed as fuel, producing 1.61 kgCO_2 (Department for

114   Environment Food and Rural Affairs, 2015).

115

116   IAQ is also a function of indoor carbon dioxide (CO_2) concentration levels (Lee *et al.*, 2002).

117   Humans exhale CO_2 so indoor spaces are characterised by higher concentrations of CO_2 than

118   are found in outdoor air. Usha *et al.* (2012) reported that high CO_2 concentrations are associated

119   with poor IAQ and, that this could lead to health issues such as headaches, mucosal irritations,

120   slower work performance, and increased employee absence. For this reason, CIBSE (2006)

121   recommended a fresh air supply in the range of 5–8 litres per second per occupant, the aim

122   being to sustain an internal CO_2 concentration in the range of 1,000 to 1,350 ppm.

123

124   Other pollutants affect IAQ, including certain building materials, furnishings, and equipment

125   – the most pertinent of which are classified as VOCs. Zuraimi *et al.* (2006) confirmed that

126   indoor VOC levels are typically higher than outdoor levels. VOCs can negatively affect

127   occupants' health by increasing the occurrence of cutaneous and mucous membrane symptoms

128   associated with sick building syndrome (Ekberg, 1994). The World Health Organisation (2010)

129   recommends that indoor levels of formaldehyde and total VOCs should be lower than 100 and

130    $300\mu g/m^3$ respectively.

131

132   *2.1 Indoor plants in office buildings*

133   The ability of indoor plants to counteract indoor air polluting chemicals was first evidenced in

134   the early 1980s and much of this research was undertaken by NASA (Wolverton *et al.*, 1989).

135   Experiments found that soil acts as a sink for removing airborne VOCs such as formaldehyde

136   (Wolverton and McDonald, 1982; Wolverton *et al.*, 1984) and benzene and carbon monoxide

137   from closed experimental chambers (Wolverton, 1986). These studies also reported a

138   significant reduction in air pollution, from within a modular structure that replicated an energy-

139   efficient building. It was found that both plant leaves and their roots help in the air purification

140   process (Wolverton, 1988).

141

142 Godish and Guindon (1989) built on these early studies, and examined the removal capabilities

143 of plants under dynamic conditions where formaldehyde was continuously generated and

144 released with varying emission rates. They found formaldehyde reduction rates of between 29-

145 50%. Wolverton and Wolverton (1996) later showed how different plants grown in the same

146 soil had significantly different formaldehyde removal abilities. Plants that culture large

147 numbers of gram-negative bacteria (such as Pseudomonas) on or around their roots, are more

148 effective at VOC removal than those that culture predominantly gram-positive bacteria. Giese

149 *et al.* (1994), added support to the idea of air decontamination by plants. In their study, spider

150 plants were put in contact with formaldehyde over a 24-hour period and this was removed by

151 the plants to below detection limits, from the atmosphere of an experimental glass chamber

152 within five hours. They suggested that a single 300g spider plant (*Chlorophytum comosum*)

153 could 'detoxify' a $100m^3$ room in six hours. Another study indicated that efficacy of

154 purification increased with greater numbers of plants, and that purification took longer with

155 increasing molecular weight of the chemical being absorbed (Oyabu *et al.*, 2003).

156

157 Recent experimental work has considered the uptake rates of various plant species concerning

158 specific VOCs, finding for example, that *Dracaena sanderiana* is highly efficient at Benzene

159 removal (Treesubsuntorn and Thiravetyan, 2012). Of 12 species tested, *Sansevieria trifasciata*

160 had the highest toluene removal rate, while the highest ethylbenzene removal rate was by

161 *Chlorophytum comosum* (Sriprapat et al., 2014). Evidence based on test chamber experiments

162 have also shown that at light CO_2 intensities (as commonly found indoors), hydroculture plants

163 are more effective at CO_2 reduction than those grown in a traditional potting mix (Irga et al.,

164 2013). (Hydroculture is where plants are grown in a static closed container system, containing

165 an inert growth medium such as perlite or expanded clay, and saturated with a controlled

166 nutrient solution). However, the rate of hydroculture VOC removal was found to be slower

than for traditional potting mix plants. This study also highlighted the need to expand these kind of chamber experiments, to real indoor spaces (Irga et al., 2013).

Living plants such as Rhapis palms and Marantas (which require regular misting) or plants with a high moisture content, can benefit offices with sustained levels of low indoor air humidity (Costa and James, 1995). Such plants can increase the *RH* of a non-air-conditioned building by about 5%, although the planting density required to achieve this, would be higher than 'normally' provided for a commercial office environment (*ibid*.). Wolverton and Wolverton (1996) suggested that due to transpiration, plants may be used instead of (or as a complement to) mechanical humidifiers to supplement humidity levels in homes and offices. During photosynthesis, plants absorb CO_2 from the atmosphere through their stomata (tiny openings on the leaves), while the roots absorb moisture from the soil. Chlorophyll and other tissue in the leaves absorb radiant energy from light sources, which is used to split water molecules into oxygen and hydrogen. Plants use the hydrogen and CO_2 to form sugars while oxygen, a by-product of photosynthesis, is released into the atmosphere (Wolverton, 1986).

Smith *et al.* (2011) reported a plant trial in an open plan office where short-term sickness absence was reduced in the planted experimental area, by approximately half of that in a control area. A saving of circa £40,000 GBP per annum was reported as a result of this. However, they acknowledged that results were limited to one building and one small sample, recommending further research in this area. Especially, given an apparent dearth of literature on indoor planting and workers' sickness absence.

Evidence also suggests that indoor plants can help reduce ambient noise levels, although it is unlikely they would act as efficiently as dedicated sound attenuation construction solutions.

192   Costa and James (1995) contended that plants might achieve acoustic quieting by absorption;

193   as did Freeman (2008) who suggested plants may absorb, diffract, and reflect sound dependent

194   upon their characteristics; such as size, shape, container, top dressing, compost, and

195   positioning. Indeed, indoor planting density commensurately increases noise reduction efficacy

196   (Costa and James, 1995). Considerable environmental psychology research has studied the role

197   of nature. For example, outdoor natural environments and vegetation have been shown to

198   provide several psychological benefits including positive feelings (Sheets and Manzer, 1991),

199   environmental awareness (Lutz *et al.*, 1999), reduced driver frustration (Cackowski and Nasar,

200   2003), reduced crime (Kuo and Sullivan, 2001) and enhanced cognitive functioning in children

201   (Wells, 2000).

202

203   While 'completely natural' office building environments may not be fully achievable, research

204   confirms that natural environment views from windows can provide restorative effects, from

205   mental fatigue (Kaplan, 1993) and job stress (Leather *et al.*, 1998). Bringslimark *et al.* (2011)

206   assessed whether office workers compensate for a lack of natural views and found that those

207   in windowless offices were approximately five times more likely to bring plants into their

208   workplace. Indoor plants at work have also been associated with improved attentiveness (Lohr

209   *et al.*, 1996), better task performance (Shibata and Suzuki, 2001) and a reduction of sick

210   building syndrome symptoms (Gou and Lau, 2012). Additionally, active interaction with

211   indoor plants can reduce physiological and psychological stress (Lee *et al*., 2015).

212

3. Methodology

214   A mixed-methods study was used that employed theoretical humidity and power consumption

215   analysis, physical data logging, and a perception questionnaire survey. This methodology is

216   described in terms of: i) the building, ii) theoretical design; iii) planting arrangements; iv)

217   relative humidity; and v) employee perceptions.

218

219   *3.1 The case study building*

220   The building was a Local Council Head Office in Southern England, responsible for a

221   population of c.270,000 people and a land area of 5,400ha (c.208 square miles). It was

222   constructed in 2011 and comprises three storeys, with a gross floor area (GFA) of 10,300m^2

223   of office space arranged predominantly in an open floor design, surrounding a central atrium.

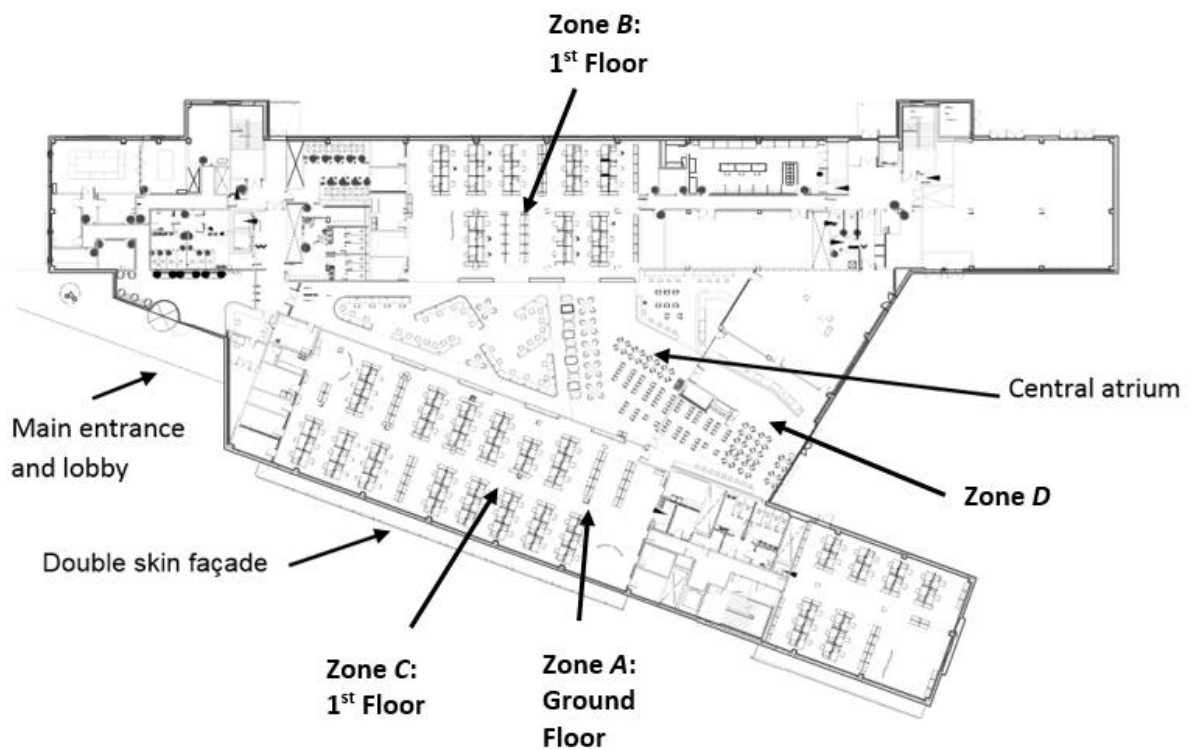224   The main entrance is located at ground floor level (Figure 1).

225

226   **Figure 1. Plan design schematic for the ground floor**

227

228   The building has an energy performance operational rating of 'C' (Department for

229   Communities and Local Government, 2015) with an annual gas and electricity consumption of

230   73 and 72 kWh/m^{2}GFA/annum respectively. Approximately, 13% of the former and 0.4% of

231   the latter is sourced from renewable energy. Gas is the main heating fuel, while electricity is

used for lighting and all other power requirements typical of an office building. Building services are fully linked to a central Building Management System, which controls lighting, ventilation, heating, and the opening and closing of apertures. The building design allows a high percentage of ventilation to be achieved via natural 'stack effect' through the atrium. Strategically located CO_2 sensors monitor IAQ with the mean indoor CO_2 concentration maintained at circa 850ppm. For this study, supplemental CO_2 readings were recorded with a handheld Solomat MP Surveyor PRO, Zwellweger Analytics CO_2 sensor. Similarly, indoor lighting and noise levels were recorded with a handheld PeakTech 5035 sensor. These sensors were calibrated by their respective suppliers prior to the commencement of the study.

A central HVAC system, located on the rooftop, provides heating and supplemental ventilation through floor level diffusers with winter and summer indoor point temperatures set at 22°C. No cooling or humidification systems are available. Figure 2 shows the central atrium and double skin south facing façade. The façade offers sound insulation from a high-volume traffic road parallel to it, as well as shading, to minimise solar gains during peak summer months. At the time of the study there were circa 1,000 adults working in the building, typically between the hours of 8am and 7pm. As illustrated in Figure 1, a single experimental zone (Zone A) and two control zones (Zones B&C) were designated. The number of employees and moisture buffering from surface finishes and furniture in each zone was assumed to be identical. Moreover, with the staff canteen and toilets (Zone D) abutting on the atrium, the exposure of each zone to moisture originating from these locations was assumed to be equal.

| 2 (a) Atrium design | 2 (b) South facing façade |

Figure 2. The office building

3.2 Theoretical calculations of mechanical humidification

The water vapour per unit volume of dry air required for the elevation of the indoor $\%RH$ to the lower recommended limit of $40\%RH$, was calculated using a psychrometric chart, based on measured indoor air temperature and $\%RH$ readings. Subsequently, the total mass of water vapour per unit time (kg/hr), required as a function of the building occupants and the mean fresh air ventilation rate, was derived from:

$$\dot{m}_m = m(3.6\rho_{air}nv_{fa}) \tag{1}$$

where: m is the mass of water vapour per kg of dry air; ρ_{air} is density of air (kg/m^3); n is the number of employees; v_{fa} is the fresh air volume flow rate (L/s) (CIBSE, 2005). A fresh air ventilation rate of 8L/s was assumed, which would yield an indoor CO_2 concentration of circa 1,000 ppm (CIBSE, 2006). The heating power required to heat fresh water from an assumed 20°C to boiling point, was calculated using:

270     $Q_w = \dot{m}_m C_p \Delta T$ **(2)**

271

272   where: Q_w is the heating power (W); $\dot{m}_m$ is the mass of water required per hour calculated from

273   equation (1); C_p is the specific heat capacity of water (J/kgK); and ΔT is the change in water

274   temperature (i.e. from 20°C to 100°C). The heating power required to evaporate water at 1Bar

275   was calculated from:

276

277     $Q_{st} = \dot{m}_m \Delta H_{vap}$ **(3)**

278

279   where: ΔH_{vap} is the enthalpy of vapourisation (kJ/kg). Hence, the total power (Q_{tot}) required

280   for the production of steam was calculated from addition of equations (2) and (3). That is:

281

282     $Q_{tot} = Q_w + Q_{st}$ **(4)**

283

284   Using a mean daily operating time of 11 hours, the energy required for production of steam per

285   month was derived from:

286

287     $E = \dfrac{Q_{tot}t}{1000}$ **(5)**

288

289   where: E is the energy consumed (kWh) and t is time (hrs). The predicted energy saving per

290   month as a result of water vapour contribution from the indoor plants, was calculated from:

291

292     $E_{sav} = \left[\dfrac{\dot{m}_{pl}}{\dot{m}_m}\right] E$ **(6)**

293

294   where $\dot{m}_{pl}$ is the mass of water vapour transpired by the plants per unit time (kg/hr).

295

296   Hence, equation (6) was used to quantify the tangible benefits of using indoor plants to

297   supplement the indoor *RH*. As discussed later, these gains take the form of financial savings

298   and environmental benefits, as a result of reduced gas consumption.

299

300   *3.3 Planting arrangements*

301   Live indoor plants were installed in the building among the first floor southern section of the

302   building (refer Figure 1) for a period of 6 months. These areas were chosen because they are

303   of similar size and are occupied by approximately the same number of people, doing similar

304   jobs (Smith *et al.*, 2011). The plants were selected mainly for their transpiration rates according

305   to Wolverton (1996) as well as factors such as: ease of maintenance, light requirements, size,

306   shape and general aesthetic qualities (Smith *et al.*, 2011). This was all in accordance with the

307   advice of a professional indoor planting company, who also supplied and carefully maintained

308   the plants throughout the trial period. Maintenance is important because plants must be in

309   optimal condition, for them to be successful in regulating indoor climate (Costa and James,

310   1995; Smith and Pitt, 2011) – this included watering (volumes recorded), dusting, and pest

311   control (using natural products) every 2 weeks.

312

313   The plants are detailed in Table 1. They were installed at a density of one plant per 10m^2, a

314   density slightly higher than under 'normal' commercial conditions. They included 30 floor-

315   standing varieties and a range of 24 smaller desk bowls, mainly positioned on shared furniture,

316   such as filing cabinets. The plants were all soil-grown and without top dressing. In line with

317   the planting company's advice, the total transpiration for the experimental zone was calculated

318   to be approximately 21 litres of water per 24 hours.

319

320   **[Insert Table 1 here].**

321

322   **Table 1. Plant species installed in the experimental zone**

323

324   *3.4 Relative humidity*

325   Two newly calibrated column-mounted HOBO UX100-003 humidity sensors (accuracy +/-

326   3.5%) were mounted in each zone (six sensors in total); at a height of circa 1.6 m above floor

327   level on support columns located in the central part of the monitored zones. Their readings

328   were automatically logged at half-hourly intervals and resulting ratios of actual water vapour

329   density to the saturation vapour density were calculated from:

330

331     $\%RH = \dfrac{\rho_{actual}}{\rho_{saturation}}$ **(7)**

332

333   Figure 3 shows that saturation vapour density is directly related to air temperature, such that a

334   unit increase in air temperature results in an exponential rise in its ability to hold water vapour.

335   Hence, if supplemental water vapour is not added to heated indoor air, its $\%RH$ decreases

336   appreciably. Testing for VOCs used ISO 16000-4-2004 standard formaldehyde and Total VOC

337   testing kits. Two samples were logged for each of the three zones, with the first sample taken

338   during February and the final sample taken during June.
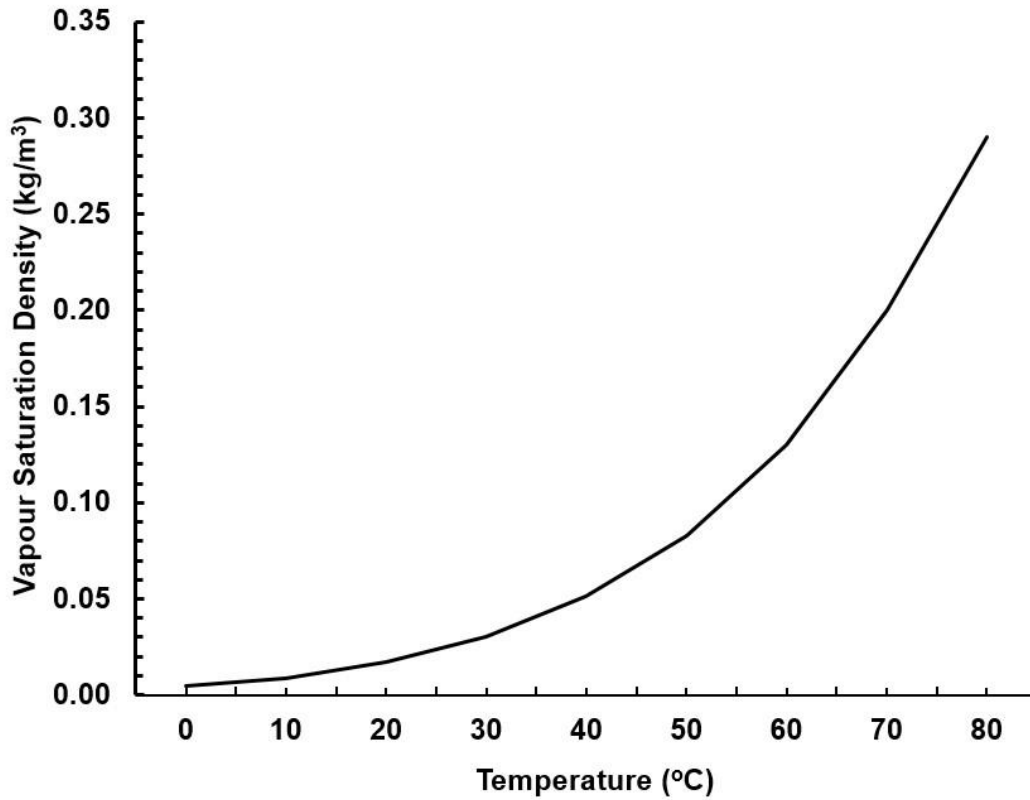
339

Figure 3. Vapour saturation density with temperature

The water vapour volume that evaporated from the 54 indoor plants was calculated from:

$$\dot{m}_{pl} = TR(n_{pl}A) \qquad\qquad (8)$$

where: TR is the mean transpiration rate of 0.0218 kg/hr/m^2 (Hussarang *et al.*, 2011); n_{pl} is the number of plants; and A is a mean foliage area of 0.906m^2 per plant (*ibid.*). By way of checking, the total water vapour volume mass produced, was compared to that of water supplied to the plants over the duration of the project. The outcome was validated with the supply value being +/-10% of $\dot{m}_{pl}$.

3.5 Employee perceptions

354 During the last two weeks of the trial period (June 2015), employees' perceptions of their

355 working environment were sampled among both the 'trial' and 'control' zones, using an online

356 questionnaire. This method was chosen for ease of distribution (Heiervang and Goodman,

357 2009); efficiency (Hardigan *et al.*, 2012); and convenient data export (Archer, 2003). It also

358 encouraged employees, to complete the survey via their desk terminal while within the survey

359 (work) environment. The questionnaire asked employees to consider whether any of four

360 environmental aspects had 'improved', 'stayed the same', or 'got worse' since the plant trial

361 had commenced. These aspects were: humidity; temperature; background noise levels; and

362 environment aesthetics.

363

364 Among the control zones there were 61 (55%) respondents. The remainder ($n = 49$, or 45%) of

365 the sample were from the trial zone. The total 110 respondents formed a reliable sample given

366 their proportion of the original population, and because where $n>30$ normality can be

367 tentatively assumed – even more so, as n increases thereafter (Mordkoff, 2011). Data were

368 analysed using real numbers and percentages, to create graphical categorical comparisons –

369 methods appropriate for interpretation of results among nominal or interval data (Holt, 2014).

370

4. Results and discussion

372 Figure 4 shows the %RH and indoor temperatures during a week in February (a) and another

373 in June (b). In contrast to expectations, the %RH in the experimental zone was quasi-identical

374 to those in the control zones. Moreover, the data suggest that the %RH (in all zones) is highest

375 during the late morning/early afternoon, which may be attributed to the peak number of

376 employees in the building at about this time.

377

378   Figure 5 presents the average measured external temperature, internal temperatures and %*RH*

379   (combined for all zones) over the trial period. In agreement with concerns reported by the

380   building's facilities management, indoor %*RH* during the months of January to April was

381   below the recommended CIBSE minimum of 40% (CIBSE, 2005; Wan *et al.*, 2009). The

382   lowest indoor *RH* levels were recorded during February while the highest levels were recorded

383   during late spring months. These results can be directly associated with corresponding outdoor

384   temperatures. For example, during February outside cold air contained much less water vapour

385   at saturation conditions, so the heating of this air to room temperature yielded a significant drop

386   in indoor *RH*.

387

388

389   4 (a) February

390

391   4 (b) June

392
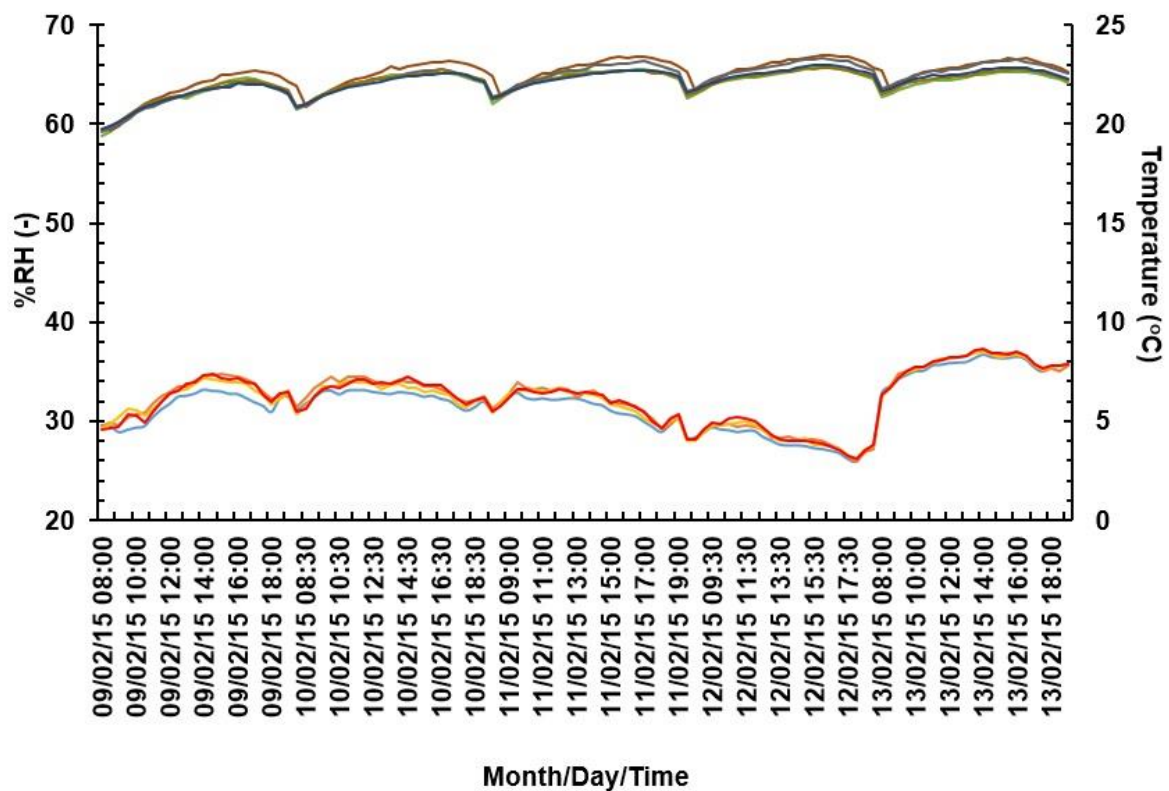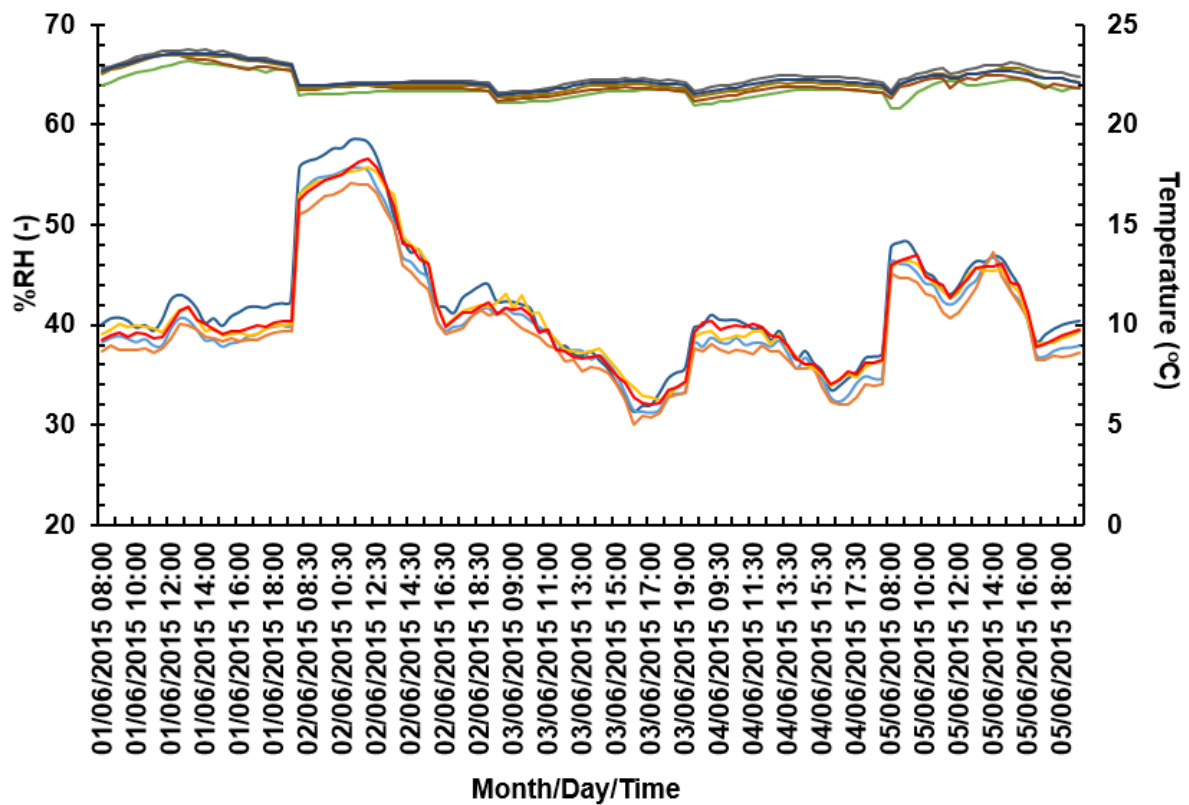
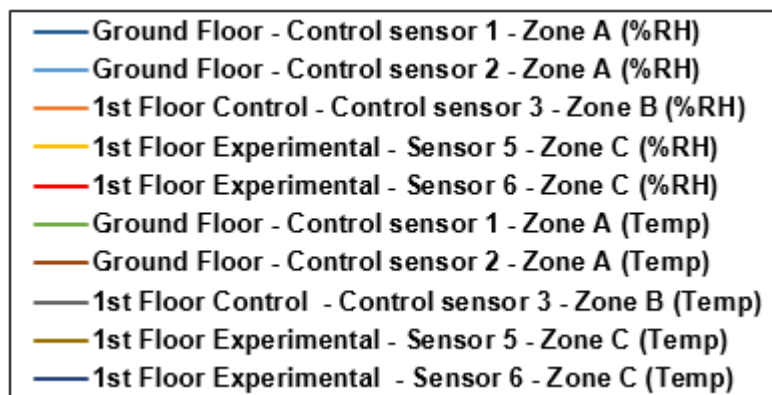393   **Figure 4.** ***%RH*** **and indoor temperature with time (office hours) during a week in**

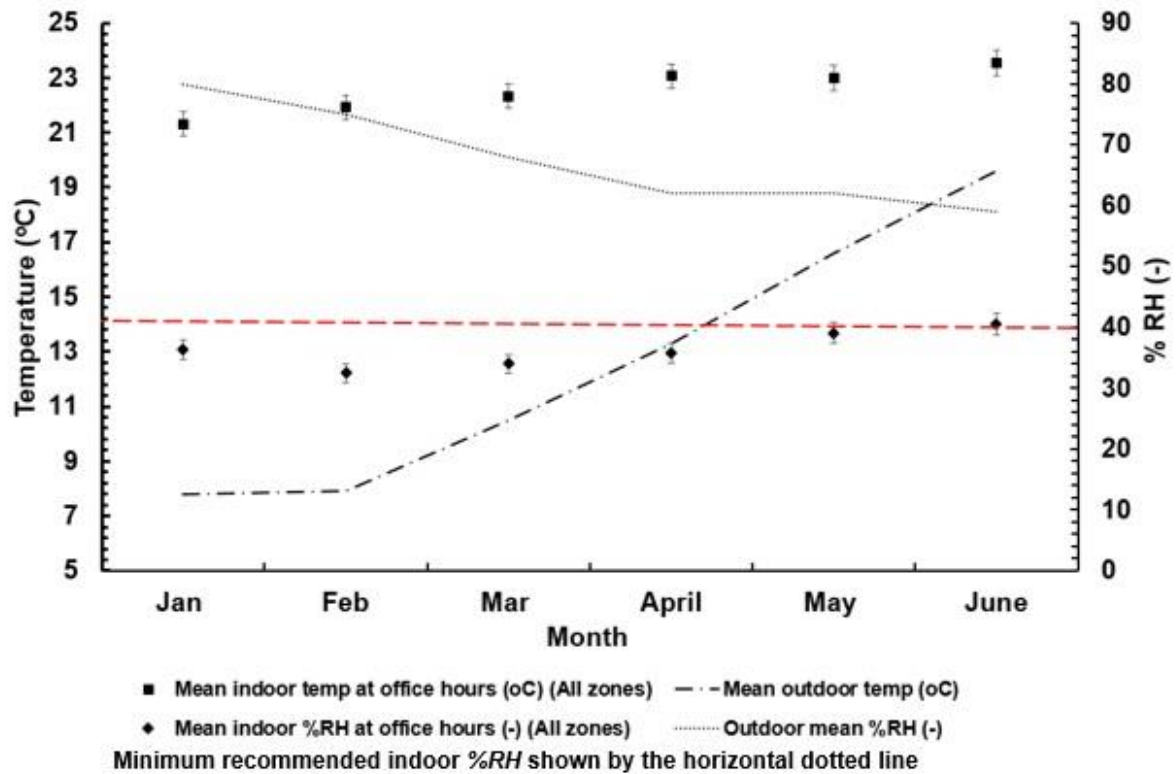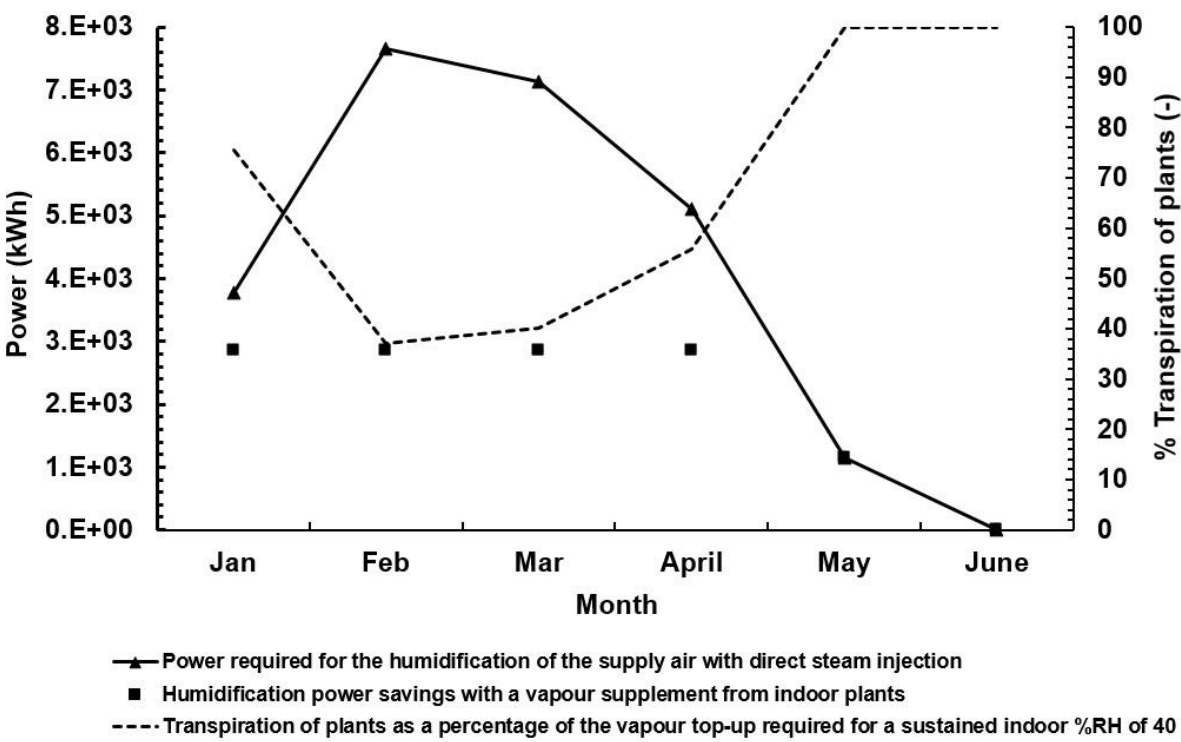394   **February (a) and June (b)**

395

396

Figure 5. Average measured indoor temperatures, outdoor temperatures and *%RH*

Indoor %*RH* values for the experimental and control zones were quasi-identical, and so are grouped together in Figure 5. These findings contrast a-priori expectations – given that a total volume of 3,822 litres of water were supplied to the plants during the six month trial period. Moreover, with a total foliage area of circa 49m^2, a mean transpiration rate of circa 18g/hr/m^2 was calculated [in reasonable agreement with the transpiration rate of 21.8g/hr/m^2 reported by Hassarang *et al.* (2011)]. Figure 6 shows how these transpiration rates were expected to significantly reduce mechanical humidification energy demands. For a sustained indoor 40%*RH*, mechanical humidification with no indoor plants, was calculated to increase gas consumption by 7%. Hence, during January and February, the plants were predicted to reduce mechanical humidification energy by 75 and 38 per cent respectively (a saving of circa 6,000 kWh over the period). For the trial period, a total CO_2 reduction of 2,200kg (Figure 7) was calculated (Department for Environment Food and Rural Affairs, 2015).

412

Power required for the humidification of the supply air with direct steam injection

■ **Humidification power savings with a vapour supplement from indoor plants**

---- **Transpiration of plants as a percentage of the vapour top-up required for a sustained indoor %RH of 40**

413

414 **Figure 6. Theoretical power consumption with indoor air-humidification provision and**

415 **potential power savings with a vapour supplement from indoor plants**

416
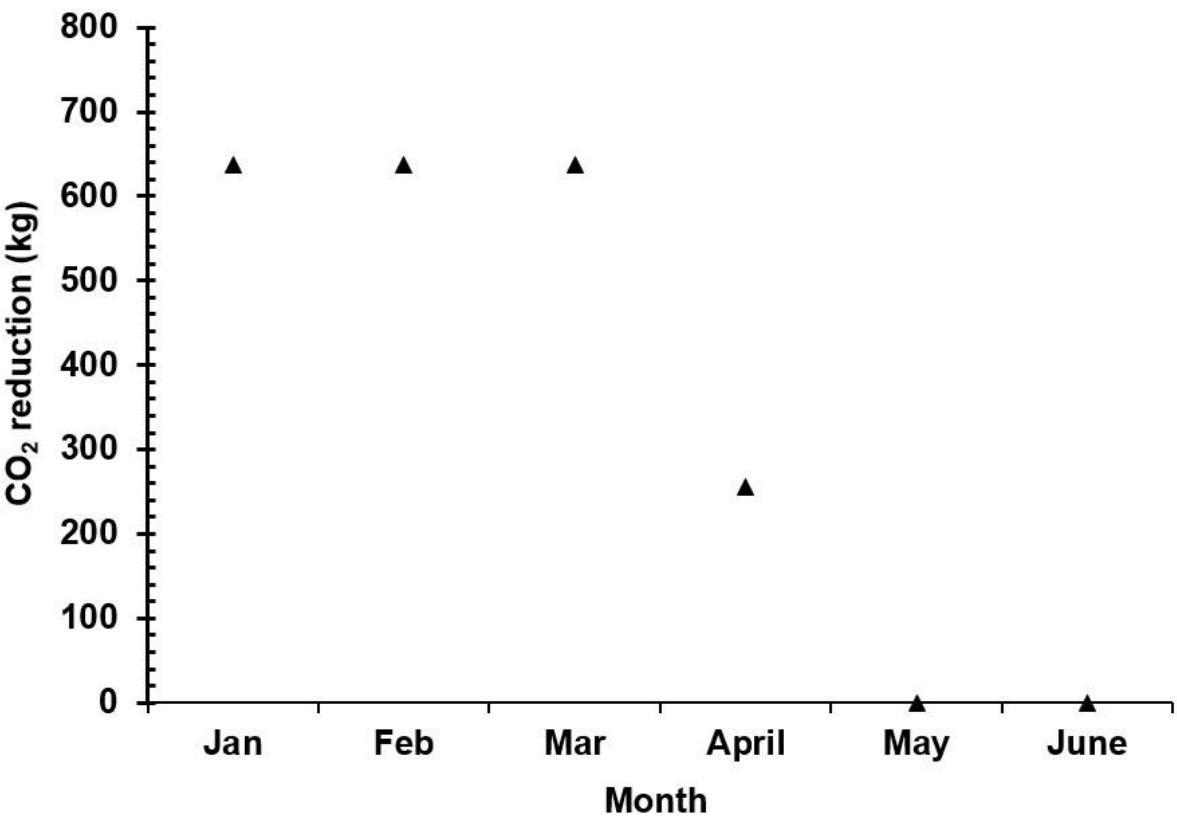
417   **Figure 7. Theoretical CO2 gas reduction with indoor plants**

418

419   The marked differences between measured and predicted %*RH* may be attributed to building

420   design, which it is assumed, allowed cross-contamination of indoor air between the

421   experimental and control zones. It is logical to infer that this resulted in some dilution of the

422   concentration of water vapour, transpired by the plants located in the experimental zone. A

423   corollary of this suggests it will be necessary to populate all of the building's indoor areas with

424   plants, to achieve enhanced indoor humidity levels. Moreover, indoor CO_2 gas concentration

425   data suggest that results were not attributable to over-ventilation. Recorded mean indoor CO_2

426   concentration was in the range of 850-1000ppm, this being indicative of good IAQ (Usha *et*

427   *al.*, 2012). This suggests an approximate ventilation rate of 8-10 L/s per person (CIBSE, 2006).

428

429   Figure 8 shows the measured concentrations for TOTAL VOCs (TVOCs) and formaldehyde,

430   at μg/m^3 among the control and experimental areas. Both sets of data show concentrations

431   much lower than the recommended maximum of 100 and 300 µg/m^3 for formaldehyde and

432   TVOCs respectively (World Health Organisation, 2010). This additionally suggests no

433   substantial differences in the concentrations of experimental vis-à-vis control zones. However,

434   it is evident that during June, the TVOC concentrations were consistently lower than during

435   January. Given that formaldehyde concentration and CO_2 readings were consistent for both

436   months, these results do not appear due to higher ventilation rates, and so remain indeterminate.
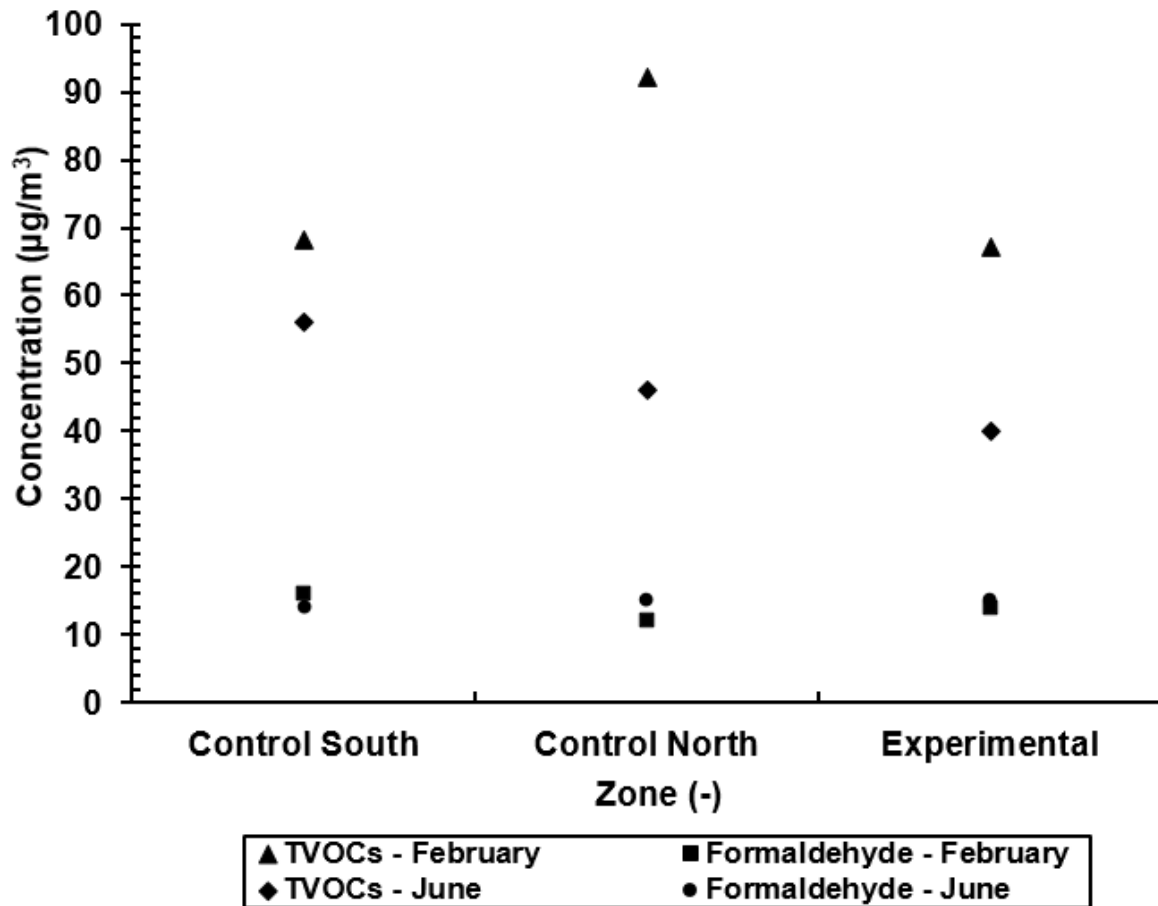
437

Figure 8. VOC measurements for the experimental and control zones

The questionnaire survey found a noticeable shift in perceptions within the experimental zone; approximately one-quarter of respondents felt that indoor *RH* had improved. This contradicts actual *RH* measurements and so suggests a misperception. While beyond the remit of this study, reasons for misperception include distortion from an array of cognitive, perceptual and motivational biases [reasoning error; experientially influenced perception; and personal or situational leanings, respectively (Pronin, 2007)]. In this instance, maybe from optimism bias, which is the tendency to underestimate the likelihood of being affected by adverse events or conditions (Moss, 2016); or acquiescence bias, which is the tendency to respond affirmatively to survey items irrespective of substantive content (Watson, 1992). Notably, almost all respondents from the control groups felt that *RH* had not changed. Figure 9(a) shows all results

451   between both groups in terms of *RH* perceptions. A similar condition was reported regarding

452   temperature, with almost one-third of experimental zone respondents perceiving change in

453   temperature, which again contradicts actual temperature readings. The majority of respondents

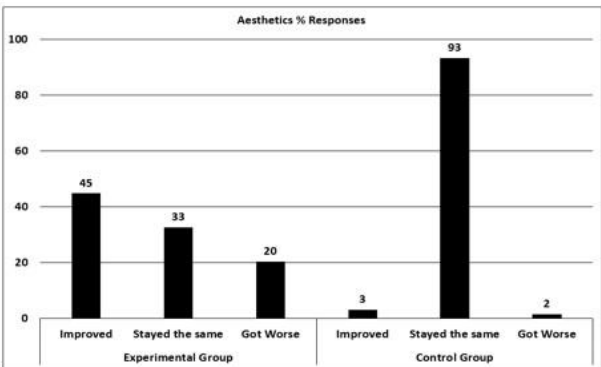454   in all areas perceived that temperature remained the same (Figure 9(b)).

455
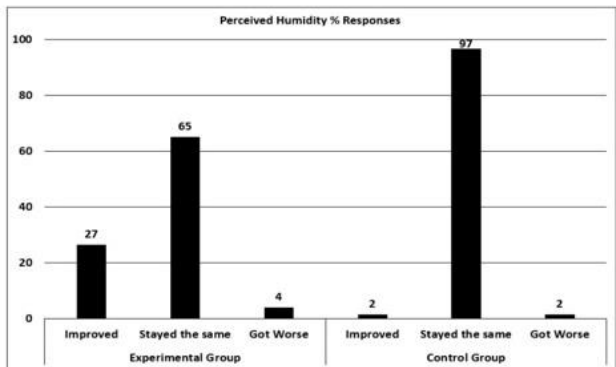
(a) Humidity perceptions
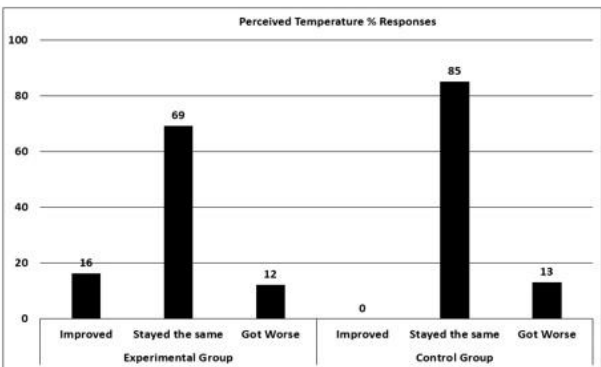
(b) Temperature perceptions
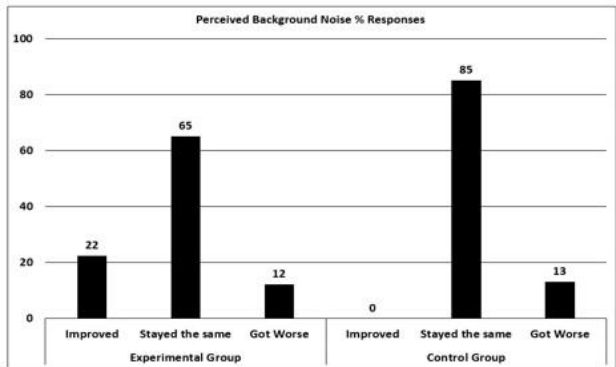
(c) Background noise perceptions

(d) Aesthetic perceptions

456

457   **Figure 9. Results of the questionnaire survey**

458

459   In accordance with research by Costa and James (1995) and Freeman (2008), the questionnaire

460   results suggest a perceived improvement in background noise levels, within the experimental

461   area. Although this contradicts physical measurements (mean noise levels of 45-55dB were

462   measured among all zones), it may provide an indication of the sound absorption properties of

463   plants in buildings (or a reduction in reverberation times that was perceived as reduction in

464   noise). Twenty-two per cent of experimental area respondents reported this improvement,

465   compared to none in the control areas (Figure 9(c)).

466

467 The most marked perceived improvement was for aesthetics within the experimental area.

468 Figure 9(d) shows that almost half of respondents reported this, although one-fifth of

469 experimental area respondents suggested that aesthetics got worse. This reflects the subjective

470 nature of office design considerations and individuals' differing opinions as to the addition of

471 indoor plants at work. Nonetheless, these results concur with Smith and Pitt (2008) who found

472 a general preference for plants in this context.

473

474 ## 5. Conclusions

475 The study has presented a mix of numerical and qualitative investigations regarding the impact

476 of living plants on IAQ. The measured indoor RH suggests that despite what theoretical

477 calculations predicted, in practice the humidification effect of the plants was not discernible.

478 The research team feel that this is mainly due to the open plan design of the building, which

479 allowed cross-contamination of air between those zones studied. The volume of water supplied

480 to the plants over the investigation period, together with calculations of their typical

481 transpiration rates based on the literature, suggests that during winter months, indoor plants

482 offer the potential to reduce mechanical humidification power requirements by up to 75%.

483 These savings were calculated based on a minimum indoor RH of 40% (a comfortable and

484 healthy indoor environment for the building's occupants).

485

486 Changes in perception were shown to contrast those physical data measured in relation to

487 indoor RH, temperature, and background noise levels. This misperception probably results

488 from optimism or acquiescence bias, and suggests that future perception surveys of indoor

489 planting need to account for this, in questionnaire design. The most marked improvement

490   related to aesthetics in the experimental zone where the plants were located, supporting an

491   argument that office occupants appreciate the presence of natural elements such as plants.

492

493   This research suggests that analysis of airflow patterns within the building using computational

494   fluid dynamics would be beneficial, in order to study the degree to which inter-zone mixing of

495   air can affect positive *RH* gains from indoor planting. Linked to this, future work will also

496   assess the effect of indoor planting throughout *all* of the building. This in addition, will further

497   knowledge of zonal air interfaces in the present context; and equally compare occupants'

498   perceptions of those indoor environmental criteria used in the present study.

499
500
501

References

503
504   Archer, T.M. (2003), "Web-based Surveys", *Journal of Extension,* Vol. 41 No. 4. Available at:
505   http://www.joe.org/joe/2003august/tt6.php (accessed 23 April 2016).
506   Baur, X., Bakehe, P., Vellguth, H. (2012), "Bronchial Asthma and COPD due to irritants in the
507   workplace: an evidence-based approach", *Journal of Occupational Medicine and
508   Toxicology*, Vol. 7, No. 19, p. 19.
509   Bringslimark, T., Hartig, T., Patil, G. (2011), "Adaptation to windowlessness: Do office workers
510   compensate for a lack of visual access to the outdoors?", *Environment and Behavior,* Vol.
511   43, No. 1, pp. 469–487.
512   Bron A.J., Tiffany J.M., Gouveia S.M., Yokoi N., Voon L.W. (2004), "Functional aspects of the tear
513   film lipid layer", *Experimental Eye Research,* Vol. 78, No. 3, pp. 347-360.
514   Cackowski, J.M., Nasar, J.L. (2003), "The restorative effects of roadside vegetation: Implications for
515   automobile driver anger and frustration", *Environment and Behavior,* Vol. 35, No. 6, pp.
516   736–751.
517   Chao, C.Y.H. (2001), "Comparison between indoor and outdoor air contaminant levels in residential
518   buildings from passive sampler study", *Building and Environment*, Vol. 36, pp. 999-1007.
519   Chartered Institution of Building Services Engineers (CIBSE) (2005), *Heating, ventilation, air-
520   conditioning and refrigeration – CIBSE Guide B, 7th Edition, 1st Edition,* CIBSE
521   Publications, Norwich, United Kingdom.
522   Chartered Institution of Building Services Engineers (CIBSE) (2006), *Environmental design – CIBSE
523   Guide A, 7th Edition,* CIBSE Publications, Norwich, United Kingdom.
524   Costa, P., James, R.W. (1995), "Constructive use of vegetation in office buildings", paper presented at
525   Plants for People Symposium, 23 November, The Hague, Netherlands, available at:
526   http://www.healthygreennatwork.org/index_en.cfm?act=artikelen.details&varart=18
527   (accessed 15 May 2016).

528 Doty R.L., Cometto-Muniz J.E., Jalowayski A.A., Dalton P., Kendall-Reed M., Hodgson M. (2004),
529   "Assessment of upper respiratory tract and ocular irritative effects of volatile chemical in
530   humans", *Critical Review Toxicology,* Vol. 34, No. 2, pp. 85-142.

531 Department for Environment Food and Rural Affairs (2015), "UK Government Carbon conversion
532   factors for government reporting", available at:
533   http://www.ukconversionfactorscarbonsmart.co.uk (accessed 15 May 2016).

534 Department for Communities and Local Government (2015), "Display energy certificates and
535   advisory reports for public buildings" available at:
536   https://www.gov.uk/government/publications/display-energy-certificates-and-advisory-
537   reports-for-public-buildings (accessed 15 May 2016).

538 Ekberg L.E., (1994), "Volatile organic compounds in office buildings", *Atmospheric Environment,*
539   Vol. 28, No. 22, pp. 3571-3575.

540 Freeman, K. (2008), "Plants in Green Buildings", Unpublished Manuscript, Ambius White Paper –
541   01, Ambius University, Buffalo Grove, USA.

542 Giese, M., Bauer-Doranth, U., Langebartels, C., Sandermann Jr., H. (1994), "Detoxification of
543   formaldehyde by the spiderplant (Chlorophytum comosum L.) and by soybean (Glycine max
544   L.) cell-suspension cultures", *Plant Physiology*, Vol. 104, No. 4, pp. 1301–1309.

545 Godish, T., Guindon, C. (1989), "An assessment of botanical air purification as a formaldehyde
546   mitigation measure under dynamic laboratory chamber conditions", *Environmental
547   Pollution,* Vol. 62, No. 1, pp. 13-20.

548 Gou, Z., Lau, S. (2012), "Sick building syndrome in open-plan offices: Workplace design elements
549   and perceived indoor environmental quality", *Journal of Facilities Management*, Vol. 10,
550   No. 4, pp. 256–265.

551 Hardigan P.C., Succar, C.T. and Fleisher, J.M. (2012), "An Analysis of Response Rate and Economic
552   Costs between Mail and Web-Based Surveys among Practicing Dentists: A Randomized
553   Trial", *Journal of Community Health*, Vol. 37, No. 2, pp. 383-394.

554 Heiervang, E., Goodman, R. (2009), "Advantages and Limitations of Web-based Surveys: Evidence
555   from a Child Mental Health Survey", *Social Psychiatry and Psychiatric Epidemiology,* Vol.
556   46, No. 1, pp. 69-76.

557 Hetreed, J. (2008). *The Damp House: A Guide to the Causes and Treatment of Dampness.* Wiltshire:
558   The Crowood Press Ltd.

559 Holt, G. D. (2014), Guest Editorial – "Asking Questions, Analysing Answers: Relative Importance
560   Revisited", *Construction Innovation: Information, Process, Management,* Vol. 14, No. 1,
561   pp. 2-16.

562 Hussarang O., Boonkorkaew P., Kasemsap P. (2011), "Study on transpiration of indoor decorative
563   plants", in *Proceedings of the 49th Kasetsart University Annual Conference*, Kasetsart
564   University, Thailand, 1-4 February 2011, Vol. 1, pp. 272-281.

565 Irga, P.J., Torpy, F.R., Burchett, M.D. (2013), "Can hydroculture be used to enhance the performance
566   of indoor plants for the removal of air pollutants?", *Atmospheric Environment*, Vol. 77, pp.
567   267-271.

568 Kaplan, R. (1993), "The role of nature in the context of the workplace", *Landscape and Urban
569   Planning,* Vol. 26, Nos. 1-4, pp. 193-201.

570 Kuo, F.E., Sullivan, W.C. (2001), "Environment and crime in the inner city: Does vegetation reduce
571   crime?", *Environment and Behaviour,* Vol. 33, No. 3, pp. 343–367.

572 Latif, M.T., Baharudin, N.H., Velayutham, P., Awang, N., Hamdan, H., Mohamad, R., Mokhtar, M.B.
573   (2011) "Composition of heavy metals and airborne fibers in the indoor environment of a
574   building during renovation", *Environmental Monitoring and Assessment*, Vol. 181, No. 1-4,
575   pp. 479-490.

576 Lee S.C., Li W., Ao C.H. (2002) "Investigation of indoor air quality at residential homes in Hong
577   Kong – A case study", *Atmospheric Environment*, Vol. 36, No. 2, pp. 225-237.
578 Lee, M., Lee, J., Park, B., Miyazaki, Y. (2015), "Interaction with indoor plants may reduce
579   psychological and physiological stress by suppressing autonomic nervous system activity in
580   young adults: a randomized crossover study", *Journal of Physiological Anthropology*, Vol.
581   34, pp. 21–26.
582 Leather, P., Pyrgas, M., Beale, D., Lawrence, C. (1998), "Windows in the workplace: Sunlight, view
583   and occupational stress", *Environment and Behaviour,* Vol. 30, No. 6, pp. 739-762.
584 Lohr, V.I., Pearson-Mims, C.H., Goodwin, G.K. (1996), "Interior plants may improve worker
585   productivity and reduce stress in a windowless environment", *Journal of Environmental
586   Horticulture*, Vol. 14, No. 2, pp. 97–100.
587 Lutz, A.R., Simpson-Housley, P., De Man, A.F. (1999), "Wilderness: Rural and urban attitudes and
588   perceptions", *Environment and Behaviour,* Vol. 31, No. 2, pp. 259 – 266.
589 Meininghaus, R., Kouniali, A., Mandin, C., Cicolella, A. (2003), "Risk assessment of sensory irritants
590   in indoor air – a case study in a French school", *Environment International*, Vol. 28, No. 7,
591   pp. 553-557.
592 Mordkoff, J.T. (2011), "The Assumption(s) of Normality*",* available at:
593   http://www2.psychology.uiowa.edu/faculty/mordkoff/GradStats/part%201/I.07%20normal.p
594   df (accessed 15 May 2016).
595 Moss, S. (2016), "Optimism bias", available at: http://www.sicotests.com/psyarticle.asp?id=238
596   (accessed 12 December 2016).
597 Nagda N.L., Hodgson M.H. (2001), "Low relative humidity and aircraft cabin air quality", *Indoor Air,
598   Vol. 11, No. 3, pp. 200-214.
599 Oyabu, T., Sawada, A., Onodera, T., Takenaka, K., Wolverton, B. (2003), "Characteristics of potted
600   plants for removing offensive odors", *Sensors and Actuators B,* Vol. 89, Nos. 1-2, pp. 131–
601   136.
602 Oxley, T.A. and Gobert, E.G. (2011). *Dampness in Buildings. Diagnosis, Treatment and Instruments.*
603   Abingdon, Oxon: Spon Press.
604 Pronin, E. (2007), "Perception and misperception of bias in human judgment", *Trends in Cognitive
605   Sciences*, Vol.11, No.1, pp. 37-43.
606 Reynolds, S., Kreiger, R., Bohn, J., Fish, D. (1994) "Factors affecting airborne concentrations of
607   asbestos in a commercial building", *American Industrial Hygiene Association Journal*, Vol.
608   55, No. 9, pp. 823-828.
609 Rios, J., Boechat, J., Gioda, A., Santos, C., Neto, F., Silva, J. (2009) "Symptoms prevalence among
610   office workers of a sealed versus a non-sealed building: Associations to indoor air quality",
611   *Environment International*, Vol. 35, No. 8, pp. 1136-1141.
612 Salonen, H., Pasanen, A-L., Lappalainen, S., Riuttala, H., Tuomi, T., Pasanen, P., Back, B., Reijula,
613   K. (2009), "Volatile Organic Compounds and Formaldehyde as explaining factors for
614   sensory irritation in office environments", *Journal of Occupational and Environmental
615   Hygiene*, Vol. 6, No. 4, pp. 239-247.
616 Sheets, V.L., Manzer, C.D. (1991), "Affect, cognition and urban vegetation: Some effects of adding
617   trees along city streets", *Environment and Behaviour,* Vol. 23, No. 3, pp. 285–304.
618 Shibata, S., Suzuki, N. (2001), "Effects of indoor foliage plants on subjects' recovery from mental
619   fatigue", *North American Journal of Psychology,* Vol. 3, No. 2, pp. 385-396.
620 Smith, A., Pitt, M. (2011), "Healthy workplaces: Plantscaping for indoor environmental quality",
621   *Facilities*, Vol. 29, Nos. 3/4, pp. 169-187.
622 Smith, A., Tucker, M., Pitt, M. (2011), "Healthy, productive workplaces: Towards a case for interior
623   plantscaping", *Facilities*, Vol. 29, Nos. 5/6, pp. 209–223.

Sriprapat, W., Suksabye, P., Areephak, S., Klantup, P., Waraha, A., Sawattan, A., Thiravetyan, P. (2014), "Uptake of toluene and ethylbenzene by plants: Removal of volatile indoor air contaminants", *Ecotoxicology and Environmental Safety*, Vol. 102, pp. 147–151.

Taylor, A. (1996), "Respiratory irritants encountered at work", *Thorax*, Vol. 51, pp. 541-545.

Treesubsuntorn, C., Thiravetyan, P. (2012), "Removal of benzene from indoor air by Dracaena sanderiana: Effect of wax and stomata", *Atmospheric Environment*, Vol. 57, pp. 317–321.

Usha S., Mendell M.J., Shekhar K., Hotchi T., Sullivan D., Streufert S., Fisk W. (2012), "Is CO_2 an indoor pollutant? Direct effects of low-to moderate CO_2 concentrations on human decision-making performance", available at: http://ehp.niehs.nih.gov/1104789 (accessed 15 May 2016).

Wan J.W., Yang K., Zhang W.J., Zhang J.L. (2009), "A new method of determination of indoor temperature and relative humidity with consideration of human thermal comfort", *Building and Environment,* Vol. 44, No. 2, pp. 411-417.

Watson, D, (1992) "Correcting for acquiescent response bias in the absence of a balanced scale: An application to class consciousness", *Sociological Methods Research*, Vol. 21, No. 1, pp. 52-88.

Wells, M. (2000), "At home with nature: Effects of 'Greenness' on children's cognitive functioning", *Environment and Behavior*, Vol. 32, No. 6, pp. 775–795.

Wolkoff P., Kjaergaard S.K., (2007), "The dichotomy of relative humidity on indoor air quality", *Environment International,* Vol. 33, No. 6, pp. 850-857.

Wolverton, B.C., McDonald, R.C. (1982), "Foliage plants for removing formaldehyde from contaminated air inside energy-efficient homes and future space stations. National Aeronautics and Space Administration, Report No. TM-84674", available at: http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19860065907_1986065907.pdf (accessed 15 May 2016).

Wolverton, B.C., McDonald, R.C., Watkins Jr., E.A. (1984), "Foliage plants for removing indoor air pollutants from energy-efficient homes", *Economic Botany,* Vol. 38, No. 2, pp. 224–228.

Wolverton, B.C. (1986), "Houseplants, indoor air pollutants and allergic reactions. National Aeronautics and Space Administration, Report No. TM-108057", paper presented at Otolaryngology, Orthodontics and Sleep Disorders Conference, 13-14 December, Pass Christian, MS, available at: http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19930072972_1993072972.pdf (accessed 15 May 2016).

Wolverton, B.C. (1988), "Foliage plants for improving indoor air quality. National Aeronautics and Space Administration, Report No. TM-108055*",* paper presented at National Foliage Foundation Interiorscape Seminar, July 19, Hollywood, FL, USA, available at: http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19930073015_1993073015.pdf (accessed 15 May 2016).

Wolverton, B.C., Johnson, A., Bounds, K. (1989), "Interior landscape plants for indoor air pollution abatement: Final Report. National Aeronautics and Space Administration, Report No. TM-101768", available at: http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19930073077_1993073077.pdf (accessed 14 January 2008).

Wolverton, B.C. (1996), *How to grow fresh air: 50 houseplants that purify your home or office*, Weidenfeld and Nicolson, London.

669 Wolverton, B.C., Wolverton, J.D. (1996), "Interior plants: Their influence on airborne microbes
670   inside energy-efficient buildings", *Journal of the Mississippi Academy of Sciences,* Vol. 41,
671   No. 2, pp. 99–105.
672 World Health Organisation (2010), "WHO guidelines for indoor air quality – Selected Pollutants",
673   available at: http://www.who.int/indoorair/publications/9789289002134/en/ (accessed 15
674   May 2016).
675 Wyon D.P., Fang L., Meyer H.W., Sundell J., Weirsoe C.G., Sederberg-Olsen N., Tsutsumi H., Agner
676   T., Fanger P.O. (2002), "Limiting criteria for human exposure to low humidity indoors", in
677   *Proceedings: Indoor Air: 2002, 9th International Conference on Indoor Air Quality and
678   Climate,* pp. 400-405. Monterey, USA: International Academy of Indoor Air Science.
679 Zuraimi M.S., Roulet C.A., Tham K.W., Sekhar S.C., Cheong K.W., Wong N.H., Lee K.H. (2006),
680   "A comparative study of VOCs in Singapore and European office buildings", *Building and
681   Environment*, Vol. 41, No. 3, pp. 316-329.