Impact of living plants on the indoor air quality in a large modern building

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Abstract

The purpose of this paper is to investigate the use of living plants in enhancing the indoor air quality (IAQ) and the general indoor environment within a large modern open-plan office building with a central atrium design and a building management system (BMS) in place. Poor indoor air quality was measured within the building, primarily due to the low relative humidity during the winter months. Previous literature suggests that the incorporation of plants in buildings helps to regulate relative humidity whilst also bringing perceptual benefits and potentially reducing short-term sickness absence.

The investigation was developed through quantitative and qualitative data. The quantitative element involved the use of experimental and control zones within the building, selected on the basis of orientation, user density and users' work roles. Plants were selected based on the transpiration rates of various commercially-available species. Relative humidity was continuously monitored using data loggers with half-hourly logging intervals for a duration of six months. Carbon dioxide gas concentration was measured using a dedicated hand-held sensor. Qualitative user perception data was gathered through the use of a structured questionnaire distributed to staff members working in each of the experimental and control zones.

Initial findings suggest that the plants have not instigated the positive effects on IAQ that were expected. The recorded data on relative humidity displayed only non-significant variations between the experimental and control zones. These findings are attributed, in part, to the atrium design, which results in a substantial volume of air within the building, leading to cross-contamination and excessive dilution of the introduced humidity as a result of plant transpiration. The study extends the previous, mainly laboratory-based, investigations to a real working environment. However, this introduces a range of other experimental factors, thus impacting the results.

Implications for further research and practice include the extension of this research approach to consider a wider selection of buildings studied over a longer period of time, taking further account of seasonal fluctuations and the impact of additional variables present in real working environments. The practical value of this study is evident through the sustainability aspect provided by the potential of indoor plants to reduce carbon emissions of the general built environment through the elimination or reduction in use of energy and capital-intensive humidification air-conditioning systems.

Keywords: relative humidity, thermal comfort, air quality, indoor plants

1. Introduction

Over the past three decades, the indoor air quality in commercial and domestic buildings has been widely investigated with studies focusing on respiratory irritants such as nitrogen and sulphur dioxides and carcinogens such as asbestos, formaldehyde and other volatile organic compounds (VOCs). A number of authors have also investigated the percentage relative humidity (%*RH*) in indoor air which represents the ratio of the percentage of water vapour held by the indoor air to the equivalent saturation level at a given temperature. Arundel et al. (1986) and Nagda and Hodgson (2001) reported that indoor humidity is not typically classified as an indoor contaminant. However, a number of studies (Wyon et al., 2002; Wolkoff and Kjaergaard, 2007; Wan et al. 2009) and building design guides (CIBSE, 2005&2006) recommend an indoor %*RH* in the range of 40 to 60%. Humidity levels below 40%*RH* are undesirable due to negative health implications whilst humidity levels above the maximum recommended value are undesirable due to a combination of health and building damage implications. As reported by CIBSE (2006), humidity levels lower than 30%*RH* could only be acceptable for limited periods of time. CIBSE also reported that at these humidity levels, occupants could be prone to allergies and respiratory illnesses due to dust and other airborne particles.

At significantly low levels of indoor humidity, Bron et al. (2004) reported a change in the precorneal tear film in humans which results in a slight discomfort in the eye (dry eyes) while Doty et al. (2004) reported a sensory irritation of the upper airways. Wyon et al. (2002) reported that human skin exposed to 15%*RH* was significantly drier than the same skin exposed to 35%*RH*. Wyon et al. associated the latter health symptoms with the classic definition of sick building syndrome. More recently, Wolkoff and Kjaergarrd (2007), reported that the health implications of indoor humidity are complex and have not been widely investigated. This is due to the fact that the influence of the relative humidity on the combined impact of VOCs and other indoor contaminants is not well-understood. Low humidity levels are also associated with the susceptibility to electrostatic shocks. This is due to the fact that the body voltage is a function of the indoor air %*RH*. Therefore a drop in the %*RH* results in an increase in the body voltage (CIBSE, 2006). CIBSE reported that carpeted office buildings equipped with underfloor heating could be susceptible to electrostatic shocks due to significantly dry carpets. Hence, a lower limit of 55%*RH* is recommended for such buildings.

Higher levels of humidity are mostly the result of poor ventilation and significant evaporation from moisture sources such as bathrooms, kitchens and indoor plants. Such levels of humidity could lead to condensation on the internal walls, which could result in mould, microbial and house dust mite growth (CIBBSE, 2005). In colder climates, as typical to countries in Northern Europe, heated only buildings could experience prolonged periods where the indoor humidity falls below the recommended lower value of 40%*RH*. This happens as the ability of air to hold water vapour is a direct function of the temperature. Therefore, as the outdoor air is heated to the indoor room temperature, the ability of this air to contain water vapour is enhanced with a resultant drop in the percentage relative humidity. Consequently, humidification systems are incorporated in heating systems to top-up the resultant indoor %*RH*. However, in most European Union countries, the maintained indoor %*RH* levels are not stipulated through statutory laws or regulations and therefore, due to financial implications, most buildings do not make use of humidification systems.

The humidification of indoor air is typically achieved through mechanical means whereby water is heated to steam and mixed with the supply air to the building. This could result in a significant financial outlay with a further negative impact on the building's carbon footprint. In fact, for each 10kg of water vapour per hour required for humidification, circa 7.22kWh of gas is consumed, with an equivalent carbon footprint of 1.61 kgCO_2 (DEFRA, 2015).

As reported by Lee et al. (2002) the indoor air quality is also a strong function of the indoor carbon dioxide (CO_2) concentration. Humans exhale CO_2 and therefore, occupied indoor spaces are characterised with concentrations of CO_2 gas which are higher than the concentrations found in the outdoor air. Usha et al. (2012) reported that high levels of indoor CO_2 concentrations are associated with a poor indoor air quality which could lead to health issues such as headaches and mucosal irritations, slower work performance, and increased employee absence. Moreover, Wargocki et al. (2000) concluded that the perceived air quality in an office building was reported to improve with higher ventilation rates. This in turn yielded an improved occupant perception of the indoor air freshness, thus yielding better employee productivity levels as a result of the feel good factor and the reduced sensation of mouth and throat dryness. For this reason CIBSE (2006) recommended a fresh air supply per person between 5 and 8 litres per second which gives an internal CO_2 concentration in the range of 1000 and 1350 ppm. Intriguingly, Fang et al. (2004) reported that the impact on the perceived indoor air quality with lower ventilation rates (10 to 3.5 litres per second) can be counteracted with a reduction in the indoor air temperature and relative humidity (23ºC/50%*RH* to 20ºC/40%*RH*).

2. The use of indoor plants in buildings

Wolverton (1996) explained that during photosynthesis, plants absorb carbon dioxide from the atmosphere through the 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 a light source, which is used to split water molecules into oxygen and hydrogen. Hydrogen and carbon dioxide are used by the plant to form sugars, while oxygen, a by-product of photosynthesis is released into the atmosphere.

Costa and James (1995) reported that plants such as Rhapis palms and Marantas, which need regular misting, or plants with high moisture content could benefit offices with low humidity. Their study found that plants can increase the relative humidity of a non-air-conditioned building by about 5%, although the density of planting required to achieve this was higher than would normally be provided for a commercial office environment. Wolverton and Wolverton (1996) suggested that plants may be used instead of humidifiers to add moisture to homes and offices through transpiration.

Smith et al. (2011) undertook a plant trial in a large open plan office, finding that short-term sickness absence reduced by approximately 50% in the planted experimental area compared to a control area in which absence increased slightly, calculating a net saving for the organisation of approximately £40,000 (GBP). However, they also acknowledged that this trial was limited to one building and, while the results supported the theory of live plants reducing absence rates, they suggested that the true effect of plants is likely to be somewhat less than the near 50% reduction noted in that trial, recommending further research in that regard. To date, we have not unearthed any significant further research investigating the effect of plants on sickness absence.

Some evidence suggests that plants in buildings may help to reduce ambient noise levels although it is unlikely that they would act as efficiently as construction elements in this regard. Costa and James (1995) contended that they may offer acoustic quieting by absorption. Freeman (2008) also reported that plants may absorb, diffract and reflect sound and this effect will be determined by variables such as the size, species and shape of the plant, as well as its container, top dressing, compost and positioning within the room. Costa and James (1995) also recommended that increased planting densities than those currently used in the industry would be required for indoor plants to be more effective in this regard.

Considerable attention in environmental psychology research has been given to the role of nature. For example, outdoor natural environments and vegetation have been shown to provide several psychological benefits including positive feelings (Sheets and Manzer, 1991), environmental concern

(Lutz et al., 1999) and enhanced cognitive functioning in children (Wells, 2000). Whilst it may be impossible to have natural environment settings at many office buildings, research has considered that natural environment views from windows can provide restorative effects from mental fatigue (Kaplan, 1993) and the negative effects of job stress (Leather et al., 1998). Bringslimark et al. (2011) assessed whether office workers compensate for lack of nature views and found that workers in windowless offices were approximately five times more likely to bring plants into their workplace. Plants in the workplace have been associated with improved attentiveness (Lohr et al., 1996), task performance (Shibata and Suzuki, 2001) and reduction in symptoms of sick building syndrome (Gou and Lau, 2012).

3. Methodology

The building considered in the present study is the head office building of a Local Authority in the UK, located in southwest England. This detached building was constructed in 2011 and consists of three floors with a total floor area of circa 10,300 square meters of office space. The latter is predominantly arranged in an open floor design surrounding a central atrium (figure 1) with the main entrance located at the ground floor level. The building has an energy performance operational rating of ‘C’ with an annual gas and electricity consumption of 73 and 72 $kWh/m^2/year$ respectively. 13.3% of the former and 0.4% of the latter is attributed to renewable forms of energy. Gas is the main fuel used for heating whilst electricity is used for lighting and all other power requirements typical to an office building. The building services are fully linked to a central Building Management System (BMS) which controls the ventilation, heating and the opening and closing of apertures. The building design allows a significant percentage of the required ventilation to be achieved through natural stack ventilation through the atrium. Strategically located CO_2 sensors monitor the indoor air quality with the mean indoor CO_2 concentration maintained at circa 700 ppm. A central HVAC system, located on the roof top, provides heating and supplemental ventilation through floor level diffusers with the winter and summer indoor set point temperatures set at 22ºC. No cooling or humidification systems were available. As illustrated in figures 1&2, the double skin south facing façade offers sound insulation from the high-traffic road running along the south side as well as shading to minimise the solar gains during the peak summer months. There were circa 1000 adults working in the building with typical office hours between 8 am and 7 pm whilst the services offered were predominantly of a back office type.

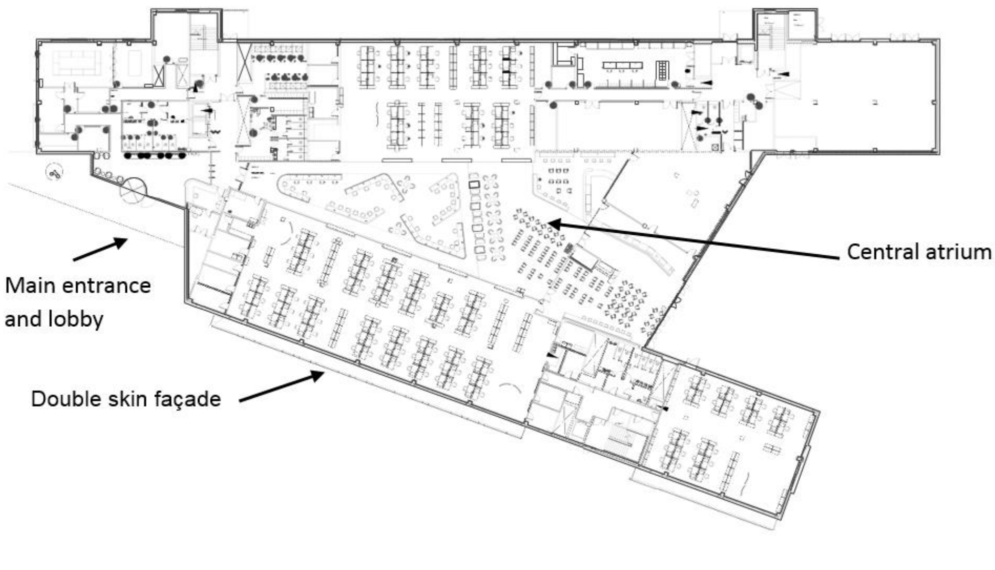

Figure 1: Plan design schematic for the ground floor

Figure 2: Central atrium design and south facing shaded façade

Live indoor plants were installed in this building within the first floor southern section of the building for a period of six months from December 2014 to June 2015. A further two control areas were designated in the ground floor southern section (directly below the experimental zone) and the first floor northern section (across the open atrium from the experimental zone). Following a similar methodology to that of Smith et al. (2011), these areas were selected due to them being of similar size and occupied by approximately the same number of people, doing similar jobs.

The plants used were selected mainly for their transpiration rate, according to Wolverton (1996) as well as factors such as ease of maintenance, light requirements, size, shape and general aesthetic qualities (Smith et al., 2011) as advised by a professional indoor planting company. They supplied and maintained the plants throughout the trial period for the reason that previous research has shown that the plants must be in the optimal condition for them to be successful in regulating the indoor climate within buildings (Costa and James, 1995; Smith and Pitt, 2011).

The plants used are detailed in table 1 and these were installed at a density a little greater than under normal commercial conditions, leading to the experimental zone being relatively densely planted. These included 30 floor-standing plants as well as a range of 24 smaller desk bowls, mainly positioned on shared furniture such as filing cabinets. The plants were all soil-grown and provided without top dressing. According to the advice of the planting company, total transpiration for the experimental zone was expected to be around 21 litres of water per 24 hours. Maintenance of the plants including watering, dusting and pest control (using natural products) was undertaken every 2 weeks.

Table 1: Plant species installed in the experimental zone

Number	*Container*	*Plant*	*Plant height (m)*
12	*Plastic trough (40cm x 18cm)*	*Spathiphyllum Sensation (Peace Lily)*	*0.35*
12	*Plastic trough (40cm x 18cm)*	*Nephrolepsis (Boston Fern)*	*0.40*
20	*Round plastic (40cm x 43cm)*	*Areca Palm*	*1.80*
10	*Round plastic (40cm x 43cm)*	*Dracaena Janet Craig*	*1.80*

3.1 Relative Humidity

The relative humidity, measured by two column-mounted HOBO UX100-003 humidity sensors in each zone (six sensors in total) with accuracy of $\pm$3.5%, represents the ratio of the actual water vapour density to the saturation vapour density given in equation (1). Readings were taken at half-hourly intervals at each logging point. As illustrated in figure (3), the saturation vapour density is a strong function of the air temperature. Therefore, a unit increase in the air temperature results in an exponential rise in the capacity of air to hold water vapour. Hence, if no extra water vapour is added to the heated air, the %*RH* drops.

$$\%RH = \frac{\rho_{actual}}{\rho_{saturation}} \quad \textbf{(1)}$$

where ρ is the density at actual and saturation conditions in kg/m^3

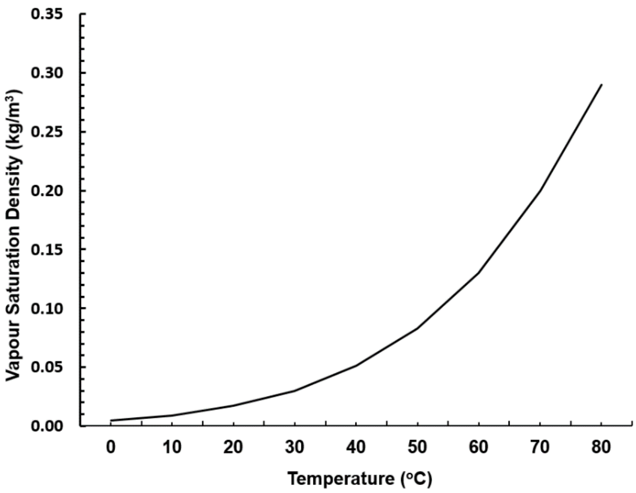

Figure 3: Vapour saturation density with temperature

3.2 Employee perceptions

Employee perceptions were tested using an online questionnaire, which was completed by occupants of the experimental zone as well as the two control zones. The questionnaire asked respondents to consider whether any of the following issues have changed since the beginning of the plant trial with options of improved, stayed the same or got worse:

- Humidity;
- Temperature;
- Background noise levels;
- Light levels;
- Personal space;
- Work area design and layout;
- Privacy;
- Work environment aesthetics.

The questionnaire remained open for a period of two weeks towards the end of the trial in June 2015. Of the respondents who completed the questionnaire, 61 (55.45%) were located in the two control zones, while 49 (44.54%) were located in the experimental zone, giving a total of 110 respondents.

4. Discussion

Figure 4 illustrates the data for the indoor relative humidity and temperature in relation to the outdoor conditions. The total water supplied to the plants over the experimental period was measured as 3822 litres. With a total foliage area of circa 40m^2, this results in a transpiration rate of circa 21.8 g/hr m^2. Contrary to the expectations of the present study, no significant differences in the relative humidity were measured in the experimental and control zones. This could be attributed to the building design which resulted in significant cross-contamination of the indoor air. Therefore, the open plan atrium design resulted in the mixing of the air in the experimental and control zones. This yielded a significant dilution of the water vapour transpired by the indoor plants located in the experimental zone. Therefore, considering the building design adopted in the present study, our data shows that it will be necessary to populate all the indoor areas with plants in order to achieve tangible results for indoor humidity levels. Furthermore, the recorded mean indoor CO_2 gas concentration was in the range of 850 to 1000 ppm. As reported by Lee et al. (2002) and Usha et al. (2012) such concentrations are considered as indicative of good indoor air quality levels. In fact, CIBSE (2006) recommends a ventilation rate yielding an indoor CO_2 concentration in the range of 1000-1350 ppm. Therefore, our data shows that the results of the present study cannot be attributed to overventilation.

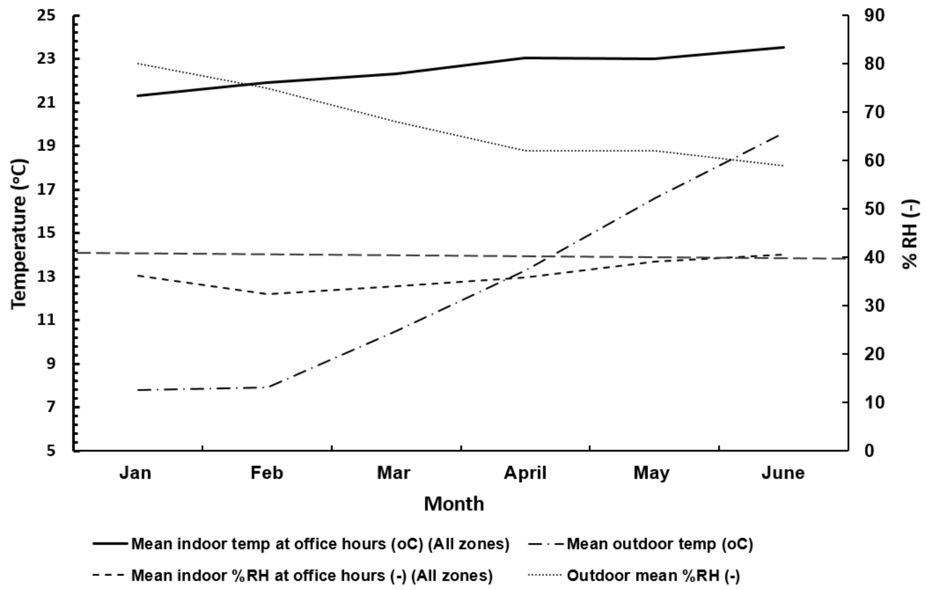

Figure 4: Indoor and outdoor temperature and %RH with the target 40% indoor RH highlighted by the horizontal dotted line

Figure 4 illustrates the trend where the lowest relative indoor humidity levels were recorded during the month of February whilst the highest indoor humidity levels were recorded during the late spring months. As illustrated in figure 3, this trend can be directly related to the relevant outdoor temperatures. Hence, during the month of February, the outside cold air could only hold a small fraction of water vapour at saturation conditions, and therefore, the warming up of this air to room temperature resulted in a significant drop in the indoor relative humidity. As reported by Wan et al., 2009 and CIBSE 2005, the indoor humidity levels should be in the range of 40-60 %*RH*. Therefore, it is evident that during the first four months of the year this minimum threshold was not satisfied.

As anticipated, the qualitative data from the staff survey yielded a noticeable shift in perception within the experimental zone regarding improved indoor relative humidity, although this is at odds with the measured quantitative data. Approximately 27% of respondents in the experimental zone perceived that %*RH* had improved and 65% felt that it had remained the same, with a minority of approximately 4% believing that it had got worse. In the control zones, the majority of respondents reported that relative humidity had remained the same (97%) as shown in figure 5. In accordance with Wargocki et al. (2000) this perceived air quality improvement may yield an improved occupant perception of the indoor air freshness, leading to improved employee productivity levels. A similar trend was noted in regard to temperature, with the experimental zone respondents perceiving improvements in temperature, which is also at odds with the measured data. However, the majority of respondents in all areas perceived that temperature remained the same as shown in figure 6.

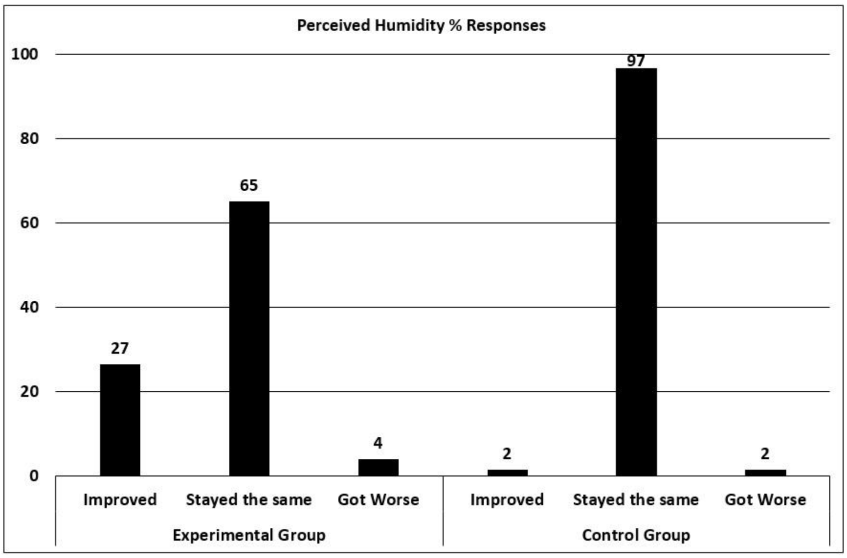

Figure 5: Perceived changes in humidity during the trial

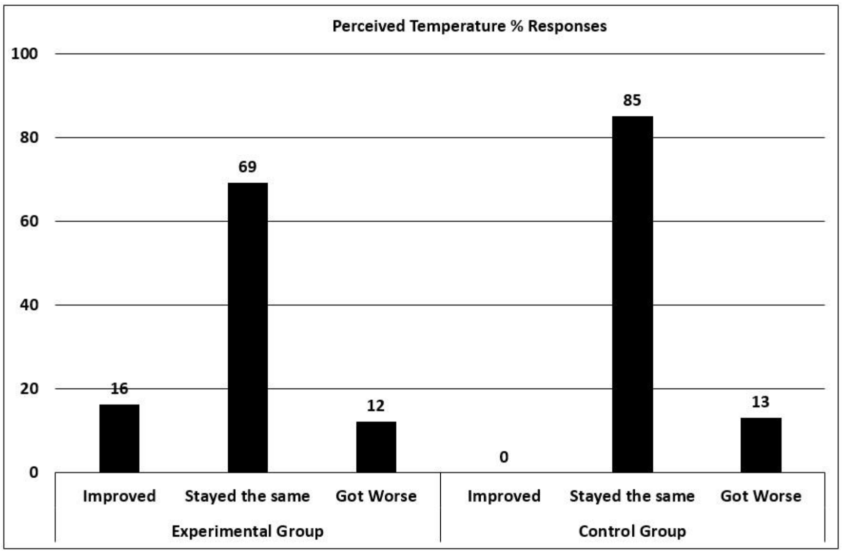

Figure 6: Perceived changes in temperature during the trial

In accordance with research by Costa and James (1995) and Freeman (2008), results suggest an improvement in perceived background noise levels within the experimental area. Although physical measurements of noise levels were not carried out in this research, this may provide an indication of the sound absorption properties of plants in buildings. Of the respondents in the experimental area, 22% perceived an improvement in background noise levels, compared to 0% noting improvement in the control areas as shown in figure 7.

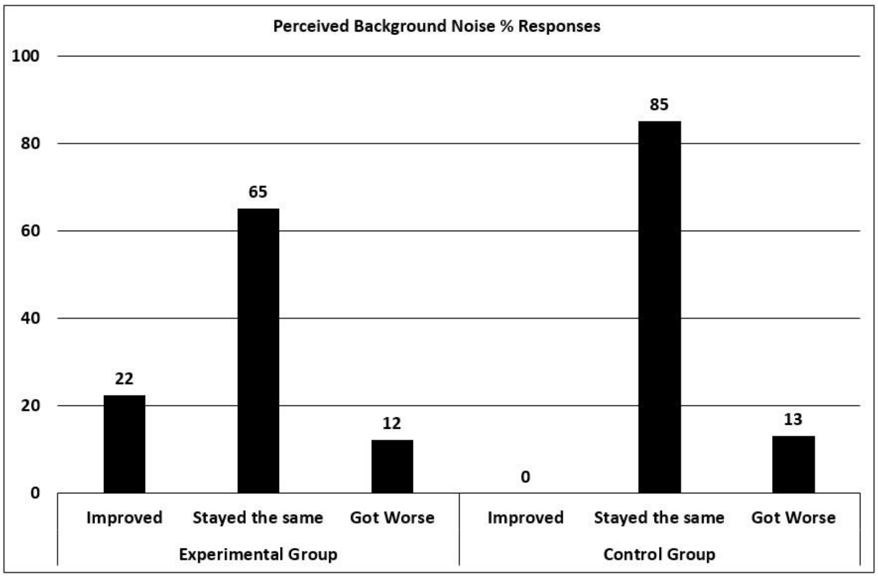

Figure 7: Perceived changes in background noise during the trial

The most significant improvement rate in the experimental area regards office aesthetics as shown in figure 8, with the majority of respondents in the experimental area (45%) perceiving an improvement, although a relatively significant response rate of 20% of respondents in the experimental area also felt that aesthetics got worse, reflecting the subjective nature of office design considerations. This result also supports previous research, which identified a general preference for plants (Smith and Pitt, 2008).

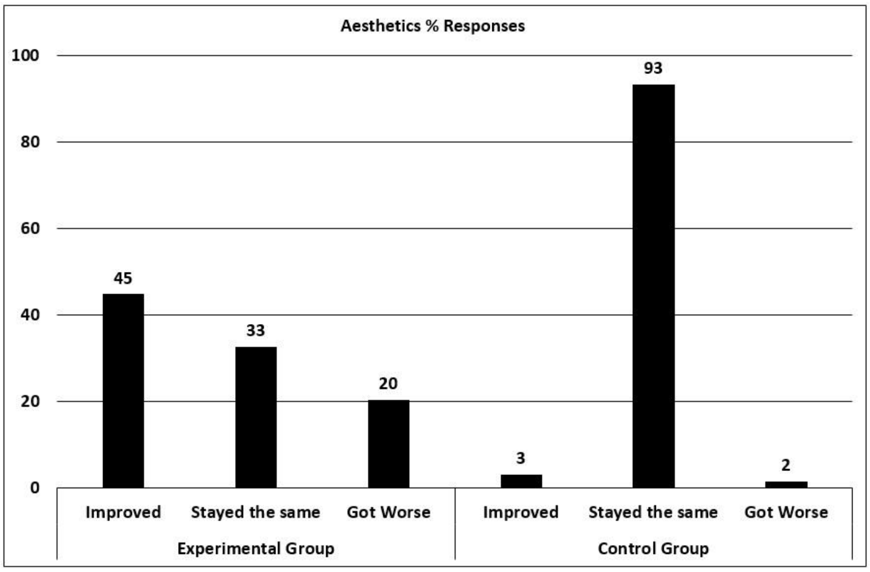

Figure 8: Perceived changes in aesthetics during the trial

Some of the more negative responses regarding plants concerned light levels and personal space, with significant responses from the experimental area suggesting that these had got worse since the beginning of the plant trial, 47% in the case of light and 39% in the case of personal space. This is perhaps unsurprising, given that many of the plants were relatively large, providing shading and potentially reducing natural and artificial light, at the same time as taking up floor and surface space.

Regarding design and layout, the majority of respondents in the experimental area and control areas perceived that this had stayed the same (67% and 93% respectively), perhaps suggesting that the plants were not regarded as a design and layout aspect. However, 27% of respondents in the experimental area perceived that this had got worse, possibly in line with the question on personal space.

The result on privacy perceptions was inconclusive for the experimental area, with the majority (76%) perceiving that it had stayed the same and 12% noting an improvement, which may have been due to the plants. However, 10% considered that privacy had got worse. The reason for this is not clear, although results on this question are possibly dependent on location of the respondents in relation to the positioning of the plants. Within the control group, 92% perceived that it had remained the same, while 7% felt it had got worse. As with the experimental group, it is not clear why privacy may have got worse and we are not aware of any further interventions within the office space.

5. Conclusions

The current study has shown that the use of plants to enhance the indoor air quality is a feasible option which could result in both tangible and intangible benefits. In spite of the fact that the measured relative humidity data for the experimental zone failed to suggest a significant rise in the indoor humidity levels, the water supplied to the plants over the test period, together with the typical indoor plant transpiration rates reported in literature, suggests that the transpiration rates are significant. Therefore, when coupled with an improved control of the indoor air flow, the plants have the potential to supplement the indoor relative humidity, thus improving the building comfort and potentially yielding energy savings where humidification systems are installed.

These results also need to be considered in the context of the potential perceptual or psychological effects of plants uncovered in previous studies and supported in this study. Perceived improvements were noted in regard to perceived indoor relative humidity (%*RH*), temperature, background noise levels and aesthetics. However, perceptions of light levels, personal space and privacy got worse in this study.

Further work will be undertaken on the analysis of the air flow patterns in the building through computational fluid dynamics (CFD) techniques. Funding will also be sought for the installation of plants in all the indoor zones. The evaluation of the potential energy savings through the use of plants as a replacement to traditional humidification systems will also be developed. This will be done through the concurrent analysis of the potential transpiration of plants in relation to the water vapour top-up required during the winter months.

References

Arundel A, Sterling E, Biggin J and Sterling T (1986) “Indirect health effects of relative humidity in indoor environments” *Environmental Health Perspectives* **65**: 351-361.

Bringslimark T, Hartig T and Grindal Patil G (2011) "Adaptation to windowlessness: Do office workers compensate for a lack of visual access to the outdoors?" *Environment and Behavior* **43** (4): 469-487.

Bron A, Tiffany J, Gouveia S, Yokoi N and Voon L (2004) "Functional aspects of the tear film lipid layer." *Experimental Eye Research* **78**: 347-360.

Chartered Institution of Building Services Engineers (CIBSE) (2005) *Heating, ventilation, air-conditioning and refrigeration – CIBSE Guide B*, 1st Edition, Norwich, United Kingdom.

Chartered Institution of Building Services Engineers (CIBSE) (2006) *Environmental design – CIBSE Guide A*, 7th Edition, Norwich, United Kingdom.

Costa P and James R (1995) "Constructive use of vegetation in office buildings", *Plants for People Symposium*, 23 November 1995, The Hague, Netherlands.

Department for Environment Food and Rural Affairs (DEFRA) (2015) *UK Government Carbon conversion factors for government reporting*, (available online http://www.ukconversionfactorscarbonsmart.co.uk/ [accessed on 09/10/2015])

Doty R, Cometto-Muniz J, Jalowayski A, Dalton P, Kendall-Reed M and Hodgson M (2004) "Assessment of upper respiratory tract and ocular irritative effects of volatile chemical in humans." *Critical Review Toxicology* **34**: 85-142.

Fang L, Wyon D, Clausen G, Fanger P (2004) Impact of indoor air temperature and humidity in an office on perceived air quality, SBS symptoms and performance, *Indoor Air*, **14** (7): 74-81

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

Gou Z and Lau S (2012) "Sick building syndrome in open-plan offices: Workplace design elements and perceived indoor environmental quality." *Journal of Facilities Management* **10** (4): 256-265.

Hodgson M (2002) "Indoor environment exposure and symptoms." *Environment Health Perspective* **110**: 663-667.

Kaplan R (1993) "The role of nature in the context of the workplace." *Landscape and Urban Planning* **26** (1 – 4): 193 - 201.

Leather P, Pyrgas M, Beale D and Lawrence C (1998) "Windows in the workplace: Sunlight, view and occupational stress." *Environment and Behavior* **30** (6): 739-762.

Lee S, Li W and Ao C (2002) "Investigation of indoor air quality at residential homes in Hong Kong – A case study." *Atmospheric Environment* **36**: 225-237.

Lohr V, Pearson-Mims, C and Goodwin G (1996) "Interior plants may improve worker productivity and reduce stress in a windowless environment." *Journal of Environmental Horticulture* **14** (2): 97 – 100.

Lutz A, Simpson-Housley P and De Man A (1999) "Wilderness: Rural and urban attitudes and perceptions." *Environment and Behavior* **31** (2): 259 – 266.

Nagda N and Hodgson M (2001) "Low relative humidity and aircraft cabin air quality." *Indoor Air* **11**: 200-214.

Sheets V and Manzer C (1991) "Affect, cognition and urban vegetation: Some effects of adding trees along city streets." *Environment and Behavior* **23**: 285 – 304.

Shibata S and Suzuki N (2001) "Effects of indoor foliage plants on subjects' recovery from mental fatigue." *North American Journal of Psychology* **3** (2): 385 - 396.

Smith A and Pitt M (2008) "Preference for plants in an office environment," *Proceedings of the CIB W70 Conference in Facilities Management: Healthy and Creative Facilities*, 16-18 June 2008, Heriot-Watt University Edinburgh, UK.

Smith A and Pitt M (2011) "Healthy workplaces: Plantscaping for indoor environmental quality." *Facilities*, **29** (3/4): 169-187.

Smith A, Tucker M and Pitt M (2011) "Healthy, productive workplaces: towards a case for interior plantscaping." *Facilities*, **29** (5/6): 209-223.

Usha S, Mendell M, Shekhar K, Hotchi T, Sullivan D, Streufert S and Fisk W (2012) "Is CO2 an indoor pollutant? Direct effects of low-to moderate CO_2 concentrations on human decision-making performance" *Environment Health Perspectives*: doi: 10.1289/ehp.1104789.

Wan J, Yang K, Zhang W and Zhang J (2009) "A new method of determination of indoor temperature and relative humidity with consideration of human thermal comfort." *Building and Environment* **44**: 411-417.

Wargocki P, Wyon D, Sundell J, Clausen G, Fanger P, (2000) The effects of outdoor air supply rate in an office on perceived air quality, sick building syndrome symptoms and productivity, *Indoor Air*, **10**: 222-236

Wells M (2000) "At home with nature: Effects of 'Greenness' on children's cognitive functioning." *Environment and Behaviour* **32** (6): 775 – 795.

Wolkoff P and Kjaergaard S (2007) "The dichotomy of relative humidity on indoor air quality." *Environment International* **33**: 850-857.

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

Wolverton B and Wolverton J (1996) "Interior plants: Their influence on airborne microbes inside energy-efficient buildings." *Journal of the Mississippi Academy of Sciences* **41** (2): 99 – 105.

Wyon D, Fang L, Meyer H, Sundell J, Weirsoe C, Sederberg-Olsen N, Tsutsumi H, Agner T and Fanger P (2002) "Limiting criteria for human exposure to low humidity indoors", *Proceedings of the 9th International Conference on Indoor Air Quality and Climate: Indoor Air 2002,* Monterey, USA.